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EDITORIAL

Mesoamericana es la revista científica de la Sociedad Mesoamericana para la Biología y la Conservación, conformada por México, Belice, Costa Rica, Honduras, Guatemala, El Salvador, Nicaragua, Colombia y Panamá. Es una revista alojada en la plataforma de revistas de la Universidad de Panamá y se publica semestralmente (septiembre-febrero, marzo-agosto). La Revista Mesoamericana, medio de publicación científica y especializada va dirigida a un público interesado en áreas específicas del conocimiento científico propias de la cobertura de la revista, siendo estas Biología, Ciencias ambientales y Conservación del Medio Ambiente. En esta ocasión la Revista Mesoamericana se complace en presentarles el segundo (2) número del vigésimo octavo (28) volumen, del 2026 el cual cuenta con un total de siete (10) contribuciones originales en materia de investigación desarrollados en diferentes campos de la Biología y la Conservación; como guía, en esta entrega se ha priorizado la temática como, revisión del género norteamericano *Arigomphus needgmam*, 1897 (Odonata: Anisoptera: Gomphidae); aplicación de inteligencia artificial generativa en biología y gestión ambiental para la conservación sostenible; Monitoreo de depredación de modelos artificiales de ranas (*Dendrobates auratus*) en bosque secundario utilizando cámaras trampa; prevalencia de Coccidae (hemiptera) en cultivos de traspatio en Cerro Punta – Chiriquí, Panamá; dinámica poblacional, crecimiento somático y patrones de mortalidad de *Leukoma asperrima* (Bivalvia: Veneridae) en el Pacífico Panameño; reporte del éxito reproductivo de una pareja de *ara severus* (linnaeus, 1758) utilizando un árbol muerto de cuipo (*cavanillesia platanifolia*) en Darién, Panamá; distriución de los escorpiones (Arachnida: Scorpiones) según las observaciones de iNaturalist en Panamá; y ecología reproductiva, ciclo gametogénico y dinámica del desove de *Leukoma asperrima* (Sowerby, 1835) en el Golfo de Panamá.

En esta ocasión deseo extender mis más sinceros agradecimientos a los lectores, autores, revisores y en especial, al equipo editorial de la revista Mesoamericana, por todo el apoyo brindado durante la conformación de este volumen. De igual forma a todos los miembros de la Oficina de Publicaciones Científicas y Académicas de la Vicerrectoria de Investigación, de la Universidad de Panamá.

Esperando que este número despierte el interés de todos los lectores y autores.

Profesor, Alonso Santos Murgas, PhD.
Editor jefe, Revista Mesoamericana

ÍNDICE GENERAL

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación
Vol.28, No.2, septiembre 2026-febrero 2027, pp.10-16

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A brief revision of the north american genus *arigomphus* needgmam, 1897 (odonata: anisoptera: gomphidae)

Una breve revisión del género norteamericano arigomphus needgmam, 1897 (odonata: anisoptera: gomphidae)

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INFORMACIÓN SOBRE EL ARTÍCULO

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Editor: Dr. Alonso Santos Murgas

ABSTRACT. A morphological and taxonomic revision of the North American genus *Arigomphus* Needham is presented, with an emphasis on the generic delimitation and diagnostic characterization of its seven species. A detailed diagnosis is provided for the genus and for each species, based on external morphological characters of adults. Diagnostic characters relevant for species identification are illustrated using comparative figures.

KEYWORDS. abdomen, cerci, pond, hamulae, morphology, Nearctic.

RESUMEN. Se presenta una revisión morfológica y taxonómica del género norteamericano *Arigomphus* Needham, con énfasis en la delimitación genérica y la caracterización diagnóstica de las siete especies que lo conforman. Se incluye una diagnosis detallada para el género y para cada especie basada en caracteres morfológicos externos de adultos. Los caracteres diagnósticos relevantes para la identificación específica se ilustran mediante figuras comparativas.

PALABRAS CLAVE: abdomen, cercos, estanque, hámulas, morfología, neártico.

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MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

INTRODUCTION

The genus *Arigomphus* was proposed by Needham (1897) to replace the provisional name Orcus proposed by Cockerell (1895), due to the risk of homonymy with *Orcus* Culsant (Coleoptera: Coccinaelidae). Needham based the genus primarily on the species *Gomphus pallidus* Rambur, 1842, without explicitly designating it as the type species. During the first half of the 20th century, between approximately 1900 and 1950, some authors, including Needham himself, considered *Arigomphus* to be a subgenus within *Gomphus* (Kennedy 1917, Needham & Heywood 1929, Byers 1939, Walker 1953), maintaining a conservative view of its taxonomic status. Subsequently, more detailed morphological and ecological studies revealed clear and consistent differences that justified its revalidation as a genus (Needham *et al*. 2000). Recently, molecular and phylogenetic analyses confirmed that, to maintain monophyly within the tribe Gomphini, *Arigomphus* must be considered a valid genus, thereby avoiding the paraphyly of *Gomphus sensu lato* (Ware *et al*. 2017). *Arigomphus* species are found exclusively in North America, from southern Canada to the southeastern United States, with the greatest diversity recorded in the eastern and central regions of the country. They inhabit primarily lentic freshwater bodies such as lakes, ponds, lagoons, and slow-moving sections of rivers, preferably with sandy or muddy bottoms and moderate riparian vegetation. Unlike other gomphids associated with fast-flowing streams, *Arigomphus* larvae exhibit morphological and behavioral adaptations typical of calmer environments, such as shallow, warm water bodies (Needham *et al*. 2000). Adults are typically found perched on low vegetation or on the bare substrate near the water, being active during the day under sunny conditions. This set of ecological traits has been considered relevant in defining the genus and distinguishing it from other related groups within Gomphidae (Ware *et al*. 2017).

Materials and Methods

Photographs of type specimens from international collections were requested, and databases from various collections were also consulted. The following information is provided: the collection's acronym, the collection's name, the address, and the person who assisted in providing the photographs of the requested types.

CUIC	Cornell University Insect Collection, Ithaca, Nueva York, USA (Jason Dombroskie).
INHS	Illinois Natural History Survey Insect Collection, Illinois, USA (Michele M. Kohler).
MNHN	Muséum national d'Histoire naturelle, Paris, French.
BMNH	British Museum of Natural History, London, United Kingdom.
OSUC	The Ohio State University Collection, Ohio, USA.

The information on the labels is presented verbatim; double slashes "//" indicate different labels; label characteristics or details are presented in square brackets "[ ]"; the collection data detailed on the labels are enclosed in quotation marks (" "). The illustrations were created using Adobe Illustrator 2025 software. The photographs were processed and edited using Adobe Photoshop 2025.

Taxonomy

Order **Odonata** Fabricius, 1793
Suborder **Anisoptera** Selys, 1854
Family **Gomphidae** Rambur, 1842
Genus ***Arigomphus*** Needgam, 1897: 181

Type species. *Gomphus pallidus* Rambur, 1842: 163, designation by monotype.
Gomphus pilipes Hagen in Selys, 1858: 408–410. synonymy

Diagnosis. Head: Post frons approximately three times as wide as it is long (3:1); females lack prominent tubercles or a pyramidal projection on the posterior surface of the cephalic capsule; tubercles and a pyramidal projection are present in males. **Abdomen:** Average dorsal length of abdominal segment VIII approximately equal to that of

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

segment IX; segments VII (S7) to IX (S9) of the male abdomen barely expanded; in the female, the subgenital plate measures between 1/4 and 2/5 of the length of the ninth sternite, is laterally convex, with parallel tips, generally blunt and contiguous. **Legs:** Metafemur approximately 1.1 times longer than the maximum width of the head and without unusually long spines. Nymphs with burrowing hooks on the protibiae. **Genitalia:** Male cerci generally straight in lateral view (slightly curved in *A. furcifer*), basolateral margin not keeled, frequently with a distinctive lateral angulation and/or a ventral spine or protuberance (absent or poorly developed in *A. lentulus*, *A. maxwelli*, and *A. villosipes*); anterior hamulae not clavate, each with a small terminal hook directed backward; first segment of the male genitalia elongated-pyramidal in shape, with a medioventral groove (penis receptor) extending across the posteroventral edge of the hood; in lateral view, the posterior margin of the vesicle is concave and the anterior margin has a strong constriction at the base of the hood (*sensu* Ware *et al*. 2017).

Etymology. *Arigomphus* is derived from the Greek "ari-" (ἀρι-), meaning "very" or "prominent," and "gomphos" (γομφος), meaning "mace" or "pin," thus meaning "with a prominent mace," a reference to the characteristic terminal expansion of the abdomen typical of the genus.

Distribution. *Arigomphus* is a genus from North America (Canada and USA).

Arigomphus cornutus (Tough, 1900)
Fig. 1a

Gomphus cornutus Tough, 1900: 17–18 (original combination).

Type Material. According to Tough (1900: 18), the specimens are housed at The Ohio State University (OSUC), USA.

Diagnosis. ***Body length***: 40–44 mm. **Head:** Blue-green eyes; olive-green clypeus and frons with slight black tinging along the sutures; dark vertex. **Thorax:** Olive-green with thick, dark, distinct antehumeral bands; black thoracic sutures. **Abdomen:** Slender, straight; segments with a prominent dark dorsal pattern; male cerci with a broad, divergent, horn-shaped internal projection. **Legs:** Coxae, femora, and tibiae uniformly dark brown; tarsomeres black; bristles sparse.

Distribution. Widely distributed throughout the northern Midwest of the United States (Minnesota, Wisconsin, Michigan, Iowa, Illinois, Indiana, Ohio) and southern Ontario, Canada.

Biology. *Arigomphus cornutus* is commonly found in ponds with marshy shores, small lakes with wet vegetation, slow moving streams, and rivers.

Arigomphus furcifer (Hagen in Selys, 1878)
Fig. 1b

Gomphus furcifer Hagen in Selys, 1878: 458–459 (original combination).

Diagnosis. Body length: 38–41 mm. Head: Light green eyes; olive-green frons and labium; brown nape; black vertex. **Thorax:** Yellowish green with broad, dark antehumeral bands. **Abdomen:** Slender, segments 1–7 with a continuous dark dorsal band; cerci long, forked, with curved, diverging branches. **Legs:** Medium brown; tarsomeres dark; setae short.

Distribution. Widely distributed in the northeastern United States, in the states of New York, Massachusetts, Connecticut, Vermont, New Hampshire, Maine, and Pennsylvania, and, to a lesser extent, in New Jersey. Its range also includes southeastern Canada, particularly southern Quebec and Ontario (Nukela *et al*. 2003).

Biology. *Arigomphus lentulus* inhabits calm waters with floating and aquatic vegetation, ponds, and lakes surrounded by marshes and slow-moving streams. Adults hunt along forest edges, perching on the ground, rocks, and, occasionally, broad leaved vegetation. At breeding sites, males perch along the shore and on floating vegetation, such as water lilies. Females lay eggs by tapping the water with their abdomen (Nukela *et al*. 2003).

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Arigomphus lentulus (Needham, 1902)
Figs. 1c, 2

Gomphus lentulus Needham, 1902: 275–276 (original combination).
Gomphus subapicalis Williamson, 1914: 54–56. synonymy

Type material. Male (♂) holotype of *Gomphus lentulus* at INHS, labeled: "[yellow label with red border] Gomphus lentulus type [illegible text] // (QR code) INHS Insect Collection 1077288 // [red label] Type ♂ Gomphus lentulus Needham".

Diagnosis. Body length: 40–43 mm. Head: Bluish eyes; clypeus and frons medium green with a slight dark spot in the center of the clypeus; occiput brown. Thorax: Olive green with well-defined dark antehumeral lines; sutures clearly delineated. Abdomen: Broad and flattened; dark dorsal markings extending to the ninth segment; cerci straight, slightly divergent (Fig. 1c). Legs: Yellowish brown with black tarsomeres; short setae.

Distribution. *Arigomphus lentulus* is distributed in the southeastern United States, with records in the states of Florida, Georgia, South Carolina, Alabama, and Mississippi.

Biology. *Arigomphus lentulus* is associated with ponds, lagoons, marshes, and lower reaches of streams, with sandy or silty bottoms and abundant riparian vegetation. The larvae inhabit the soft substrate and develop in warm environments. Adults typically rest on low vegetation or directly on open ground; they are active during the warm months, with peak activity observed in spring and early summer. The territorial behavior of males has been poorly documented, and details regarding the duration of the larval cycle or reproductive preferences are unknown (Needham *et al*., 2000; Paulson 2011).

Remarks. Needham (1902) described this species based on a single male specimen collected by J. F. Garber from the Little Wabash River in southeastern Illinois (USA). Needham places *G. lentulus* (= *Arigomphus lentulus*) within the subgenus *Arigomphus*, noting that *G. pallidus* (= *Arigomphus pallidus*) is the species most morphological similar.

Arigomphus maxwelli (Ferguson, 1950)
Figs. 1d, 3

Gomphus maxwelli Ferguson, 1950: 93–96 (original combination).

Type material. Male holotype (♂) of *Gomphus maxwelli* deposited at CUIC, labeled: "Arigomphus group ♂ Gomphus maxwelli n.s. #1 Holotype 1950 Alt7. limosus not villosipes Hardin Co., Texas 11 V 40 R.E. Maxwell // [red label] HOLOTYPE Cornell U. No. 3100 // Gomphus maxwelli Ferguson HOLOTYPE No. 3100". 2 male paratypes of *Gomphus maxwelli* (♂♂) deposited at CUIC, labeled: (1♂) "Arigomphus group ♂ Gomphus maxwelli n.s. 1950 Hardin Co., Texas 11 V 40 #2 R.E. Maxwell // Gomphus maxwelli Ferguson PARATYPE No. 3100.1 // Gomphus Hardin Co 11 V 40 R.E. Maxwell 1ex Alice Ferguson // [light blue label] PARATYPE Cornell U. No. 3100.1 // [QR code] CUIC 000065418". (1♂) "(Gomphinae) maxwelli Gomphus lentulus ♂ Det. By A.M.F. 1944 Dallas, Denton, or Caddo Lake Texas 1938 – Spring (S.M.U. collection) //[QR code] CUIC 000065419".

Description. _Body length_: 40–43 mm. **Head:** Eyes green; frons and clypeus olive-brown; nape brown; vertex black. **Thorax:** Olive-green with thin, defined brown-black antehumeral bands; sutural bands light brown. **Abdomen:** More robust than in *A. pallidus*; abdominal segments with defined black markings; cerci straight, elongated, and slightly divergent, without sinuation. Legs. Uniform yellowish brown; tarsomeres black; setae visible but sparse.

Distribution. *Arigomphus maxwelli* is distributed throughout the south-central and southeastern United States, with records from Texas, Oklahoma, Arkansas, Louisiana, and Mississippi.

Biology. *Arigomphus maxwelli* inhabits muddy bottomed lakes, ponds, slow moving streams, and stagnant waters. Males perch on the shore or in low vegetation. They patrol at low altitude with their abdomen slightly turned upward. Females lay eggs by flying slowly over the water and tapping their abdomen against the surface to release the

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

eggs. This species appears to tolerate degraded habitats better than most other *Arigomphus* species (Nukela *et al*. 2003).

Arigomphus pallidus (Rambur, 1842)
Fig. 1e

Gomphus pallidus Rambur, 1842: 163 (original combination).

Description. ***Body length*:** 39–42 mm. **Head:** Bright green eyes; occiput, frons, clypeus, and labrum pale green, unmarked; vertex black. **Thorax:** Pale green to yellowish-green, with diffuse pale brown antehumeral and sutural lines. **Abdomen:** Slender abdomen, thickening distally; first seventh segments pale green, with reduced or absent black spots; last abdominal segments testaceous brown; abdominal cerci subtriangular, with slightly sinuous lateral margins as in Fig. 2e. **Legs:** Coxa, femur, and tibiae dark brown; tarsomeres black; legs with short setae.

Distribution. *Arigomphus pallidus* is found in the southeastern United States (Alabama, North Carolina, South Carolina, Florida, Kentucky).

Biology. *Arigomphus pallidus* inhabits lakes, ponds, and calm bodies of water with vegetation. Its nymphs live partially buried in the soft substrate and are predators, as are the adults, which capture insects in flight. They are active from spring through early summer (Needham *et al*. 2000; Paulson 2011).

Remarks. Rambur described the species based on an unspecified number of specimens; it is presumed that the syntypes may be deposited at the MNHN (Muséum national d'Histoire naturelle, France), however, they could not be found in the collection's database.

Arigomphus submedianus (Williamson, 1914)
Fig. 1f

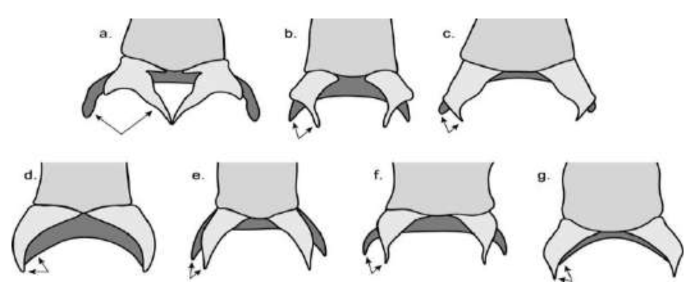
Gomphus submedianus Williamson, 1914: 56-57 (original combination).

Description. ***Body length*:** 38–41 mm. **Head:** Blue-green eyes; frons and clypeus light green with a faint brown spot in the center of the labrum; vertex black. **Thorax:** Pale green with visible submedian bands and complete, well-marked antehumeral lines. **Abdomen:** Slender, with black lateral markings and a broken dorsal line; cerci similar in shape to those of *A. pallidus*, but shorter and with black pigmented inner margins. **Legs:** Light brown; tarsomeres dark, setae fine.

Distribution. Widely distributed in the central and eastern United States. Its range extends from southern Ontario (Canada) south to Texas and Florida, and west to Nebraska and Kansas. It has been recorded in at least 20 states, including Ohio, Indiana, Illinois, Missouri, Kentucky, Tennessee, and the Carolinas.

Biology. *Arigomphus submedianus* inhabits still waters with soft bottoms; the larvae live buried in the substrate. Adults are active in spring and summer, resting on low vegetation or the ground near the water (Needham *et al*. 2000).

Figure 1.
Dorsal view of the abdominal cerci of Arigomphus species. a) A. cornutus. b) A. furcifer. c) A. lentulus. d) A. maxwelli. e) A. pallidus. f) A. submedianus. g) A. villosipes.



Arigomphus villosipes (de Selys, 1854)
Fig. 1g

Gomphus villosipes de Selys, 1854: 53 (original combination).

Vol. 28, No.2, septiembre 2026-febrero 2027, pp.10-16

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Type specimen. Syntypes deposited in the Selys Collection at the BMNH.

Diagnosis. ***Body length***: 40–44 mm. **Head:** Blue-green eyes; olive-green frons and clypeus; dark brown occiput; black vertex. **Thorax:** Brown with broad green dorsal stripes forming a "W" pattern; lateral margins grayish-green; antehumeral region and sutures well pigmented. **Abdomen:** Slender, with greenish-brown segments and dark dorsal spots; cerci thick, straight, slightly divergent; blackish with yellow dorsal stripes on S1–S7 (occasionally a small dorsal spot on S8 and/or S9), rust-colored on the sides of S8–S9, and mostly yellow on S10 and appendages. **Legs:** Legs notably hairy; femora with long, dense bristles, from which the name derives; tibiae with pale yellow stripes; tarsomeres black. Female similar to male but with more yellow on the lateral part of the abdomen.

Distribution. *Arigomphus villosipes* is found in the southeastern and south-central United States, with records from states such as Texas, Louisiana, Arkansas, Mississippi, Alabama, and Georgia.

Biology. It inhabits muddy-bottomed lakes, ponds, slow-moving streams, and stagnant waters. Males rest on the shore or in low vegetation. They patrol at low altitude with their abdomen slightly turned upward. Females lay eggs by flying slowly over the water and tapping their abdomen against the surface to release the eggs. This species appears to tolerate degraded habitats better than most other springtails (Nukela *et al*. 2003).

Remarks. The species was described based on an unspecified number of males and females from a locality identified only as "United States".

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Figure 2.
Male holotype of Gomphus lentulus Needham deposited at the INHS. Photographs courtesy of Michele M. Kohler (Illinois Natural History Survey Insect Collection, Illinois, USA).

Figure 3.
Male holotype of Gomphus maxwelli Ferguson deposited at CUIC. Photographs courtesy of Jason Dombroskie (Cornell University Insect Collection, USA).

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

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MESOAMERICANA
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Aplicación de inteligencia artificial generativa en biología y gestión ambiental para la conservación sostenible

Application of generative artificial intelligence in biology and environmental management for sustainable conservation

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RESUMEN. La presente investigación analizó el uso de la inteligencia artificial generativa en biología y gestión ambiental, con énfasis en su aporte a la conservación sostenible de los ecosistemas. El estudio se desarrolló desde un enfoque cualitativo, mediante una investigación documental de alcance descriptivo sustentada en la revisión sistemática de literatura científica reciente relacionada con modelos generativos, monitoreo ambiental y análisis de datos biológicos. Inicialmente se localizaron 96 publicaciones en bases de datos indexadas; posteriormente, tras aplicar criterios de pertinencia temática, actualidad y relación directa con la sostenibilidad ecológica, se seleccionaron 50 documentos para el análisis final.

Los hallazgos evidenciaron que las herramientas basadas en inteligencia artificial optimizan el procesamiento de información ecológica, favorecen la predicción de cambios ambientales y fortalecen la toma de decisiones en programas de conservación. También se observó que estas tecnologías facilitan la automatización de procesos científicos y el desarrollo de modelos predictivos aplicados a la protección de la biodiversidad. En conjunto, los resultados mostraron que la integración de inteligencia artificial generativa en la gestión ambiental representa una alternativa tecnológica con amplio potencial para apoyar estrategias sostenibles frente a los desafíos ecológicos actuales. Se concluyó que su implementación responsable puede contribuir al fortalecimiento de la sostenibilidad ambiental y a la preservación de los recursos naturales.

PALABRAS CLAVE. biología, conservación de la naturaleza, desarrollo sostenible, gestión ambiental, inteligencia artificial.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

ABSTRACT. This research analyzed the use of generative artificial intelligence in biology and environmental management, with an emphasis on its contribution to the sustainable conservation of ecosystems. The study was developed using a qualitative approach, through a descriptive documentary research based on a systematic review of recent scientific literature related to generative models, environmental monitoring, and biological data analysis. Initially, 96 publications were in indexed databases; subsequently, after applying criteria of thematic relevance, currency, and direct relationship to ecological sustainability, 50 documents were selected for the final analysis. The findings showed that artificial intelligence-based tools optimize the processing of ecological information, facilitate the prediction of environmental changes, and strengthen decision-making in conservation programs. It was also observed that these technologies facilitate the automation of scientific processes and the development of predictive models applied to biodiversity protection. Overall, the results showed that the integration of generative artificial intelligence into environmental management represents a technological alternative with broad potential to support sustainable strategies in the face of current ecological challenges. It was concluded that its responsible implementation can contribute to strengthening environmental sustainability and preserving natural resources.

KEYWORDS: artificial intelligence, biology, environmental management, nature conservation, sustainable development.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

INTRODUCCIÓN

Durante las últimas décadas, el avance de las tecnologías digitales ha transformado de manera significativa los procesos de investigación, monitoreo y análisis dentro de las ciencias biológicas y ambientales (González et al., 2021). En este escenario, la inteligencia artificial generativa ha adquirido relevancia por su capacidad para procesar grandes volúmenes de datos, construir modelos predictivos y automatizar análisis aplicados a distintos contextos científicos (Feuerriegel et al., 2023; Abrahms et al., 2025). Su incorporación en diferentes áreas del conocimiento ha ampliado las posibilidades de interpretar fenómenos relacionados con biodiversidad, cambio climático, degradación de ecosistemas y manejo sostenible de recursos naturales (Anderson et al., 2021; Zhang et al., 2023). Debido a ello, las herramientas basadas en inteligencia artificial se consideran actualmente una alternativa tecnológica con potencial para fortalecer las estrategias de conservación ambiental mediante un uso más eficiente de la información ecológica y biológica (Brown et al., 2022; Wang et al., 2024).
En la actualidad, la biología y la gestión ambiental enfrentan desafíos asociados con la pérdida acelerada de biodiversidad, la fragmentación de hábitats, la contaminación y el impacto de las actividades humanas sobre el equilibrio ecológico. Estas problemáticas han impulsado la búsqueda de métodos más precisos para comprender el comportamiento de los ecosistemas y anticipar posibles alteraciones ambientales (Johnson et al., 2023; Peterson et al., 2025).

Tradicionalmente, muchos procesos de monitoreo ecológico requerían largos periodos de observación y elevados recursos humanos y económicos, limitando la capacidad de respuesta ante escenarios críticos. Frente a esta situación, la inteligencia artificial generativa comenzó a consolidarse como una herramienta capaz de optimizar la recopilación, clasificación e interpretación de información ambiental en tiempo real (Hernández et al., 2023; Li et al., 2022).
Diversos estudios recientes señalan que los sistemas de inteligencia artificial contribuyen al reconocimiento automatizado de especies, al análisis de imágenes satelitales y a la detección de patrones ecológicos útiles para la toma de decisiones sostenibles (Ahmed et al., 2023; Silva et al., 2024).
Los modelos generativos, además, han permitido desarrollar simulaciones predictivas relacionadas con la evolución de ecosistemas, el impacto del cambio climático y la conservación de especies en peligro de extinción (Patel et al., 2025; Kumar et al., 2025). Estas aplicaciones favorecen no solo la eficiencia científica, sino también el diseño de estrategias preventivas orientadas a disminuir impactos ambientales y promover un equilibrio entre innovación tecnológica y sostenibilidad ecológica (Chen et al., 2024; Ramírez et al., 2022).
A pesar de los avances observados, todavía persisten debates relacionados con el uso responsable de la inteligencia artificial en contextos ambientales. Entre las principales preocupaciones destacan la confiabilidad de los datos utilizados por los modelos generativos, los posibles sesgos algorítmicos y las implicaciones éticas derivadas de la automatización de procesos científicos (Lee et al., 2024; Félix et al., 2026). También existen limitaciones vinculadas con la infraestructura tecnológica, el acceso desigual a herramientas digitales y la necesidad de establecer marcos regulatorios que garanticen un uso transparente y sostenible de estas tecnologías en programas de conservación (Martínez et al., 2025; Reuters, 2026).
En el ámbito internacional, el interés por incorporar inteligencia artificial en proyectos de conservación sostenible ha aumentado considerablemente en los últimos años. Organizaciones ambientales y centros de investigación comenzaron a utilizar sistemas inteligentes en iniciativas relacionadas con monitoreo forestal, gestión hídrica, control de especies invasoras y protección de ecosistemas vulnerables (Tuia et al., 2026; Kong et al., 2025). Sin embargo, gran parte de la producción científica permanece dispersa entre distintas disciplinas, dificultando una comprensión integral sobre el verdadero alcance de la inteligencia artificial generativa en la conservación ambiental. Por ello, resulta necesario integrar y analizar críticamente la evidencia científica disponible para comprender sus aportes, limitaciones y posibilidades futuras dentro de la gestión ambiental (Islam et al., 2026; Vuilliomenet et al., 2026).
Bajo esta perspectiva, la presente investigación examinó la aplicación de la inteligencia artificial generativa en biología y gestión ambiental, considerando sus contribuciones al fortalecimiento de estrategias de conservación sostenible.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

El estudio buscó identificar cómo estas tecnologías pueden apoyar la protección de la biodiversidad, optimizar procesos de análisis ecológico y fortalecer la toma de decisiones sustentadas en evidencia científica confiable. Del mismo modo, permitió reflexionar sobre las implicaciones éticas, técnicas y ambientales derivadas de la incorporación de sistemas inteligentes en escenarios ecológicos contemporáneos.

La investigación se desarrolló a partir de la siguiente pregunta científica: ¿de qué manera la inteligencia artificial generativa contribuye a la biología y la gestión ambiental para fortalecer los procesos de conservación sostenible de los ecosistemas?; En correspondencia con esta interrogante, el objetivo general consistió en analizar la aplicación de la inteligencia artificial generativa en biología y gestión ambiental para la conservación sostenible. De forma complementaria, se buscó identificar sus principales aplicaciones en el análisis biológico y ambiental, examinar los beneficios y desafíos asociados con su implementación y valorar su impacto potencial sobre la sostenibilidad ecológica y la protección de la biodiversidad.

La investigación aporta una visión integradora sobre el papel emergente de la inteligencia artificial generativa en las ciencias biológicas y ambientales, destacando su utilidad como herramienta de apoyo frente a problemáticas ecológicas complejas. Además, contribuye a ampliar la discusión académica sobre la relación entre innovación tecnológica y sostenibilidad, promoviendo una reflexión crítica acerca de la necesidad de implementar soluciones digitales responsables orientadas a la preservación de los recursos naturales y al equilibrio ambiental a largo plazo.

MATERIALES Y MÉTODOS

A La investigación se desarrolló bajo un enfoque cualitativo, ya que estuvo orientada al análisis e interpretación del alcance de la inteligencia artificial generativa en biología y gestión ambiental, especialmente en relación con los procesos de conservación sostenible. Este enfoque permitió examinar de manera integral la información científica disponible, considerando aplicaciones tecnológicas, aportes investigativos y desafíos vinculados con el uso de sistemas inteligentes en contextos ambientales contemporáneos.

El estudio mantuvo además un carácter descriptivo e interpretativo, debido a que se centró en identificar tendencias científicas, avances tecnológicos y contribuciones de la inteligencia artificial dentro de las ciencias biológicas y ambientales.

El diseño metodológico correspondió a una investigación documental sustentada en la revisión sistemática y el análisis crítico de literatura científica especializada. Este tipo de estudio facilitó la recopilación, organización y evaluación de información proveniente de distintas fuentes académicas relacionadas con inteligencia artificial, biodiversidad, conservación ambiental y sostenibilidad ecológica. Al mismo tiempo, permitió integrar conocimientos procedentes de diversas disciplinas, favoreciendo una visión amplia e interdisciplinaria del fenómeno analizado.

La búsqueda documental se efectuó mediante consultas estructuradas en bases de datos indexadas y repositorios académicos de reconocimiento internacional, entre ellos Scopus, Web of Science, Google Scholar y ScienceDirect. Para garantizar la pertinencia de la información recopilada, se emplearon combinaciones de palabras clave asociadas con “inteligencia artificial generativa”, “biología”, “gestión ambiental”, “conservación sostenible”, “biodiversidad”, “ecosistemas” y “tecnologías emergentes”. Las búsquedas se realizaron en español e inglés con el propósito de ampliar la cobertura documental y acceder a investigaciones recientes de alcance internacional.

En la fase inicial se identificaron noventa y seis publicaciones científicas, incluyendo artículos arbitrados, revisiones sistemáticas y documentos técnicos relacionados con la temática estudiada. Posteriormente, se aplicaron criterios de inclusión y exclusión para seleccionar únicamente aquellos trabajos con relación directa al uso de inteligencia artificial generativa en procesos biológicos y ambientales. Entre los criterios de inclusión se consideraron publicaciones indexadas, estudios publicados durante los últimos cinco años y documentos vinculados con sostenibilidad, monitoreo ambiental, conservación ecológica o análisis de biodiversidad. Se excluyeron investigaciones duplicadas, publicaciones sin respaldo académico verificable y trabajos alejados del objetivo central del estudio.

Después del proceso de depuración documental, la muestra final quedó conformada por cincuenta publicaciones científicas utilizadas para el análisis investigativo.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

La información recopilada se organizó mediante matrices de análisis documental, lo que permitió clasificar los estudios según variables relacionadas con aplicaciones tecnológicas, áreas biológicas involucradas, herramientas de inteligencia artificial empleadas, beneficios identificados, limitaciones técnicas y aportes a la conservación sostenible. Este procedimiento facilitó la comparación de resultados entre investigaciones y ayudó a identificar tendencias emergentes, patrones comunes y vacíos existentes en la literatura revisada.

El análisis de la información se realizó mediante técnicas de análisis de contenido y revisión interpretativa. A través de este proceso se examinaron los principales aportes de la inteligencia artificial generativa en áreas como monitoreo ecológico, modelado predictivo, identificación automatizada de especies, análisis de imágenes ambientales y gestión de recursos naturales. También se consideraron las implicaciones éticas, sociales y ambientales derivadas de la implementación de sistemas inteligentes en escenarios de conservación ecológica. La interpretación de los hallazgos se desarrolló desde una perspectiva crítica y reflexiva, tomando en cuenta las contribuciones más relevantes y las limitaciones señaladas en los estudios consultados.

Para fortalecer la confiabilidad y validez del estudio, se priorizó el uso de fuentes académicas arbitradas y documentos procedentes de instituciones científicas reconocidas internacionalmente. Además, se realizó un contraste constante entre autores, enfoques teóricos y resultados investigativos, lo que permitió reducir sesgos interpretativos y mantener una visión equilibrada del fenómeno analizado. Del mismo modo, la investigación respetó principios éticos relacionados con el uso responsable de la información científica, garantizando el adecuado reconocimiento de las fuentes y el respeto a la propiedad intelectual.

La metodología aplicada permitió obtener una comprensión integral sobre las posibilidades y desafíos de la inteligencia artificial generativa en biología y gestión ambiental. Asimismo, proporcionó bases teóricas y analíticas para reflexionar sobre el impacto de las tecnologías emergentes en la conservación sostenible y en el desarrollo de estrategias orientadas a la protección de la biodiversidad y los ecosistemas

RESULTADOS

A El análisis documental permitió identificar tendencias relevantes sobre la aplicación de la inteligencia artificial generativa en biología y gestión ambiental, particularmente en los procesos orientados a la conservación sostenible. A partir de la revisión de las cincuenta publicaciones científicas seleccionadas, se reconocieron las principales áreas de aplicación tecnológica, los beneficios observados en la gestión ecológica, las herramientas de inteligencia artificial más utilizadas, los desafíos presentes en su implementación y las contribuciones potenciales a la sostenibilidad ambiental. En conjunto, los hallazgos reflejaron una incorporación cada vez más amplia de tecnologías inteligentes en investigaciones ambientales y biológicas desarrolladas durante los últimos años.

Inicialmente, se analizaron las principales áreas de aplicación identificadas en los estudios revisados. Los resultados mostraron que las investigaciones se concentraron principalmente en monitoreo ambiental, análisis de biodiversidad y modelado predictivo orientado a la conservación ecológica, como se presenta en la Tabla 1.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Tabla 1

Principales áreas de aplicación de la inteligencia artificial generativa en biología y gestión ambiental

Área de aplicación	Descripción principal	Frecuencia	Porcentaje
Monitoreo ambiental	Seguimiento automatizado de ecosistemas y variables ecológicas	15	30 %
Análisis de biodiversidad	Identificación y clasificación de especies	12	24 %
Modelado predictivo	Simulación de cambios ambientales y climáticos	10	20 %
Gestión de recursos naturales	Optimización de recursos y planificación sostenible	8	16 %
Automatización científica	Procesamiento automatizado de datos ecológicos	5	10 %

Nota. Las principales áreas de aplicación identificadas en la revisión documental. ***Fuente.*** *Elaboración propia con base en revisión documental (2026).*

La Tabla 1 evidenció que el monitoreo ambiental representó el área con mayor presencia en las investigaciones analizadas, alcanzando un 30 % del total de estudios revisados. Este resultado reflejó el interés por utilizar sistemas inteligentes capaces de procesar información ambiental en tiempo real y generar alertas relacionadas con alteraciones ecológicas. El análisis de biodiversidad también ocupó una posición importante debido al uso creciente de modelos generativos para la identificación automatizada de especies y el reconocimiento de patrones biológicos mediante imágenes y registros digitales.

El modelado predictivo mostró igualmente una presencia significativa dentro de la literatura científica revisada, destacándose por su capacidad para anticipar escenarios asociados al cambio climático, degradación de ecosistemas y pérdida de biodiversidad. De manera paralela, la gestión de recursos naturales comenzó a incorporar inteligencia artificial generativa como apoyo para la planificación ambiental y el aprovechamiento sostenible de los ecosistemas. Aunque la automatización científica presentó una frecuencia menor, los hallazgos evidenciaron un interés creciente por optimizar procesos investigativos mediante sistemas automatizados de análisis de datos ecológicos.

Posteriormente, se examinaron los principales beneficios asociados al uso de inteligencia artificial generativa en procesos biológicos y ambientales, cuyos resultados se presentan en la Tabla 2.

Tabla 2

Beneficios identificados en la aplicación de inteligencia artificial generativa para la conservación sostenible

Beneficio identificado	Aplicación observada	Frecuencia	Porcentaje
Optimización del análisis de datos	Procesamiento rápido de información ecológica	14	28 %
Mejora en la toma de decisiones	Apoyo a estrategias de conservación	11	22 %
Predicción ambiental	Anticipación de riesgos ecológicos	10	20 %
Automatización de procesos	Reducción de tareas manuales	9	18 %
Fortalecimiento de la sostenibilidad	Apoyo a políticas ambientales	6	12 %

Nota. Beneficios más frecuentes identificados en las investigaciones revisadas. ***Fuente.*** *Elaboración propia con base en revisión documental (2026).*

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Los resultados reflejados en la Tabla 2 mostraron que la optimización del análisis de datos constituyó el principal beneficio asociado a la implementación de inteligencia artificial generativa en contextos ambientales y biológicos. Las investigaciones revisadas señalaron que estas herramientas permitieron procesar grandes volúmenes de información ecológica con mayor rapidez y precisión, facilitando actividades relacionadas con monitoreo y análisis ambiental.

Otro beneficio relevante correspondió a la mejora en la toma de decisiones, debido a que los modelos inteligentes favorecieron la generación de información predictiva útil para diseñar estrategias de conservación y sostenibilidad. También se observó una importante presencia de estudios orientados a la predicción ambiental, particularmente en investigaciones relacionadas con riesgos climáticos, incendios forestales y alteraciones ecológicas.

En relación con la automatización de procesos, varios documentos destacaron la reducción de tareas manuales asociadas al procesamiento de datos biológicos. Aunque el fortalecimiento de la sostenibilidad ambiental registró una frecuencia menor, los estudios resaltaron su relevancia estratégica para apoyar políticas de conservación y gestión responsable de recursos naturales.

Otro aspecto analizado correspondió a las herramientas tecnológicas más utilizadas en investigaciones ambientales y biológicas, tal como se presenta en la Tabla 3.

Tabla 3
Herramientas de inteligencia artificial generativa utilizadas en investigaciones ambientales

Herramienta tecnológica	**Función principal**	**Frecuencia**	**Porcentaje**
Redes neuronales artificiales	Reconocimiento y clasificación de datos	16	32 %
Modelos generativos predictivos	Simulación de escenarios ecológicos	12	24 %
Sistemas de visión computacional	Análisis de imágenes ambientales	10	20 %
Procesamiento de lenguaje natural	Interpretación documental científica	7	14 %
Plataformas automatizadas de monitoreo	Seguimiento ecológico digital	5	10 %

Nota. Resume las herramientas tecnológicas identificadas en las investigaciones analizadas. ***Fuente.*** *Elaboración propia con base en revisión documental (2026).*

La Tabla 3 mostró que las redes neuronales artificiales representaron la herramienta tecnológica con mayor presencia en los estudios revisados. Su aplicación estuvo orientada principalmente al reconocimiento automatizado de patrones biológicos, clasificación de especies y análisis de datos ambientales complejos. Estos resultados evidenciaron la capacidad de los sistemas inteligentes para fortalecer procesos de interpretación ecológica mediante algoritmos de aprendizaje automatizado.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Por otra parte, los modelos generativos predictivos mantuvieron una participación importante en investigaciones relacionadas con simulaciones ambientales y proyecciones asociadas al cambio climático y la degradación de ecosistemas. Los sistemas de visión computacional también fueron ampliamente utilizados para el procesamiento de imágenes satelitales, fotografías biológicas y monitoreo visual de hábitats naturales.

Los hallazgos evidenciaron además una incorporación progresiva del procesamiento de lenguaje natural en investigaciones orientadas al análisis automatizado de documentación ambiental y generación de reportes técnicos. Finalmente, las plataformas automatizadas de monitoreo reflejaron una tendencia emergente hacia el uso de sistemas digitales integrados para supervisar variables ecológicas de manera continua.

Además de los beneficios y aplicaciones identificadas, la investigación permitió reconocer diversos desafíos asociados a la implementación de inteligencia artificial generativa en la gestión ambiental y la conservación sostenible, como se observa en la Tabla 4.

Tabla 4

Principales desafíos asociados a la implementación de inteligencia artificial generativa

Desafío identificado	Impacto observado	Frecuencia	Porcentaje
Calidad y confiabilidad de datos	Riesgo de resultados imprecisos	13	26 %
Limitaciones tecnológicas	Infraestructura insuficiente	11	22 %
Sesgos algorítmicos	Interpretaciones parciales de información	10	20 %
Consideraciones éticas	Uso responsable de sistemas inteligentes	9	18 %
Acceso desigual a tecnologías	Brechas digitales institucionales	7	14 %

Nota. La tabla presenta los principales desafíos identificados en la implementación de inteligencia artificial generativa. ***Fuente.*** *Elaboración propia con base en revisión documental (2026).*

Los resultados presentados en la Tabla 4 evidenciaron que la calidad y confiabilidad de los datos representaron el principal desafío identificado en las investigaciones revisadas. Diversos autores señalaron que los modelos generativos dependen directamente de la precisión de la información utilizada durante el entrenamiento algorítmico, situación que puede afectar la validez de los resultados obtenidos en procesos ambientales y biológicos.

Las limitaciones tecnológicas también mostraron una presencia importante, especialmente en contextos donde la infraestructura digital resulta insuficiente para implementar sistemas avanzados de inteligencia artificial. A ello se suman los sesgos algorítmicos, considerados un problema relevante debido a la posibilidad de producir interpretaciones parciales o resultados condicionados por datos incompletos.

En cuanto a las consideraciones éticas, los estudios destacaron la necesidad de promover un uso transparente y responsable de estas tecnologías dentro de los programas de conservación ambiental. Del mismo modo, el acceso desigual a herramientas digitales evidenció la existencia de brechas tecnológicas entre instituciones científicas y regiones con diferentes niveles de desarrollo.

Finalmente, se analizaron las contribuciones potenciales de la inteligencia artificial generativa a la sostenibilidad ecológica y la conservación de la biodiversidad, como se presenta en la Tabla 5.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Tabla 5
Contribuciones de la inteligencia artificial generativa a la conservación sostenible

Contribución identificada	Aplicación ecológica	Frecuencia	Porcentaje
Protección de biodiversidad	Conservación de especies y hábitats	14	28 %
Prevención de riesgos ambientales	Detección temprana de amenazas ecológicas	12	24 %
Gestión sostenible de ecosistemas	Planificación ambiental inteligente	10	20 %
Fortalecimiento de políticas ambientales	Apoyo técnico para decisiones gubernamentales	8	16 %
Educación y sensibilización ambiental	Difusión de información ecológica	6	12 %

Nota. La tabla resume las principales contribuciones identificadas en la literatura científica revisada. ***Fuente.*** *Elaboración propia con base en revisión documental (2026).*

La información reflejada en la Tabla 5 permitió identificar que la protección de la biodiversidad constituyó la principal contribución atribuida a la inteligencia artificial generativa dentro de las investigaciones analizadas. Los estudios revisados señalaron que estas tecnologías favorecieron la identificación de especies vulnerables, el monitoreo de ecosistemas y la conservación de hábitats naturales mediante sistemas automatizados de análisis ecológico.
La prevención de riesgos ambientales mostró igualmente una presencia significativa debido al uso de modelos predictivos capaces de detectar amenazas ecológicas antes de que produzcan impactos irreversibles. Los hallazgos también evidenciaron que la gestión sostenible de ecosistemas comenzó a incorporar herramientas inteligentes para optimizar procesos de planificación ambiental y administración de recursos naturales.
En relación con las políticas ambientales, los documentos revisados destacaron que la inteligencia artificial generativa podría fortalecer la formulación de decisiones gubernamentales sustentadas en evidencia científica y análisis automatizados de información ecológica. Finalmente, la educación y sensibilización ambiental representaron un aporte complementario orientado a promover una mayor conciencia social sobre sostenibilidad y conservación de la biodiversidad.
En conjunto, los resultados obtenidos evidenciaron que la inteligencia artificial generativa se ha consolidado como una herramienta tecnológica emergente con aplicaciones relevantes en biología y gestión ambiental. Las investigaciones revisadas demostraron que su incorporación favorece el procesamiento eficiente de información ecológica, fortalece la toma de decisiones ambientales y contribuye al diseño de estrategias orientadas a la conservación sostenible de los ecosistemas. No obstante, también se identificaron desafíos técnicos, éticos y estructurales que requieren atención para garantizar una implementación responsable y equilibrada de estas tecnologías.
De manera general, la revisión documental reflejó que el desarrollo de sistemas inteligentes aplicados a las ciencias ambientales representa una oportunidad significativa para fortalecer la sostenibilidad ecológica y la protección de la biodiversidad. La integración de inteligencia artificial generativa en programas de conservación podría contribuir a mejorar la capacidad de respuesta frente a problemáticas ambientales complejas, siempre que su utilización se acompañe de criterios científicos, éticos y sostenibles orientados al bienestar ambiental y social.

DISCUSIÓN

Los resultados obtenidos evidenciaron que la inteligencia artificial generativa ha comenzado a ocupar un papel cada vez más relevante dentro de los procesos científicos vinculados con la biología y la gestión ambiental, especialmente en actividades relacionadas con monitoreo ecológico, análisis de biodiversidad y conservación sostenible (Abrahms et al., 2025; Wang et al., 2024). La literatura revisada permitió identificar una tendencia creciente hacia la incorporación de tecnologías inteligentes como herramientas de apoyo para el procesamiento de información ambiental compleja y la formulación de estrategias orientadas a la protección de los ecosistemas (Brown et al., 2022; Tuia et al., 2026).

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Estos hallazgos coinciden con la evolución reciente de las ciencias ambientales, las cuales han experimentado importantes transformaciones a partir de la integración de sistemas digitales capaces de automatizar procesos analíticos y optimizar la toma de decisiones basada en evidencia científica (Feuerriegel et al., 2023; Anderson et al., 2021).

La predominancia del monitoreo ambiental como principal área de aplicación reflejó la necesidad de fortalecer los mecanismos de vigilancia ecológica frente a las crecientes amenazas ambientales. El uso de modelos inteligentes en el seguimiento de ecosistemas permitió mejorar la detección temprana de alteraciones ambientales, facilitando respuestas más oportunas ante fenómenos asociados al cambio climático, la deforestación y la degradación de hábitats naturales (Ahmed et al., 2023; Silva et al., 2024). Esto demuestra que la inteligencia artificial no solo constituye una herramienta orientada a automatizar tareas, sino también un recurso estratégico para fortalecer la gestión preventiva de los recursos naturales y disminuir los impactos derivados de las actividades humanas sobre el ambiente (Peterson et al., 2025; Ramírez et al., 2022).
Los hallazgos relacionados con el análisis de biodiversidad evidenciaron que los sistemas generativos poseen un importante potencial para transformar la investigación biológica contemporánea. La automatización de procesos de clasificación de especies y reconocimiento de patrones ecológicos representa un avance significativo en términos de eficiencia científica, especialmente en contextos donde el volumen de información biológica supera las capacidades tradicionales de procesamiento manual (Kumar et al., 2025; Johnson et al., 2023). Este aspecto adquiere especial relevancia en regiones con alta diversidad ecológica, donde la conservación depende de información precisa y actualizada sobre las condiciones de los ecosistemas. En consecuencia, la inteligencia artificial generativa podría consolidarse como una herramienta fundamental para fortalecer programas de monitoreo biológico y conservación de la biodiversidad a escala global (Silva et al., 2024; Kong et al., 2025).

Los resultados también mostraron que el modelado predictivo constituye una de las aplicaciones más relevantes de la inteligencia artificial generativa dentro de la gestión ambiental. La posibilidad de simular escenarios ecológicos futuros y anticipar riesgos asociados a fenómenos climáticos representa una contribución significativa para la planificación sostenible y la formulación de políticas ambientales (Patel et al., 2025; Silva et al., 2024). Estas capacidades predictivas permiten desarrollar estrategias preventivas sustentadas en datos científicos, favoreciendo una gestión ambiental más eficiente y orientada a minimizar impactos ecológicos antes de que se produzcan daños irreversibles (Chen et al., 2024; Peterson et al., 2025). Desde esta perspectiva, la inteligencia artificial generativa amplía las capacidades analíticas de las ciencias ambientales y fortalece la capacidad institucional para enfrentar problemáticas ecológicas complejas mediante enfoques anticipatorios.
Otro aspecto relevante identificado en la investigación correspondió a los beneficios asociados con la optimización del procesamiento de datos ecológicos. La capacidad de analizar grandes volúmenes de información en tiempos reducidos representa una ventaja importante frente a los métodos tradicionales de investigación ambiental, los cuales suelen requerir extensos periodos de análisis y elevados recursos humanos (Li et al., 2022; Hernández et al., 2023). Los resultados indicaron que las herramientas inteligentes favorecieron la automatización de tareas repetitivas y mejoraron la precisión en la interpretación de datos ambientales. Esto resulta especialmente importante en investigaciones relacionadas con imágenes satelitales, sensores remotos y monitoreo automatizado de variables ecológicas, donde la rapidez y exactitud del procesamiento influyen directamente en la calidad de los resultados científicos obtenidos (Ahmed et al., 2023; Wang et al., 2024).

A pesar de las contribuciones identificadas, la investigación también permitió reconocer diversos desafíos asociados a la implementación de inteligencia artificial generativa en contextos ambientales y biológicos. Entre ellos, la calidad y confiabilidad de los datos utilizados por los modelos inteligentes constituyó una de las principales preocupaciones señaladas en la literatura científica (Lee et al., 2024; Félix et al., 2026). Los sistemas generativos dependen significativamente de la información empleada durante su entrenamiento, por lo que la existencia de datos incompletos, desactualizados o sesgados puede afectar la precisión de las predicciones y generar interpretaciones erróneas de la realidad ecológica.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Esta situación pone de manifiesto la necesidad de fortalecer mecanismos de validación científica y control de calidad en el desarrollo de tecnologías aplicadas a la conservación ambiental (Guerrero-Casado et al., 2026; Johnson et al., 2023).

Los sesgos algorítmicos identificados en algunos estudios reflejan igualmente la importancia de analizar críticamente las implicaciones éticas derivadas del uso de inteligencia artificial en la gestión de ecosistemas. La automatización de procesos científicos no garantiza por sí sola objetividad absoluta, ya que los modelos pueden reproducir limitaciones presentes en los datos de origen o en los criterios establecidos durante su programación (Lee et al., 2024). Por esta razón, resulta indispensable promover enfoques interdisciplinarios que integren conocimientos tecnológicos, ambientales y éticos para asegurar que la implementación de inteligencia artificial responda a principios de transparencia, responsabilidad y sostenibilidad (Martínez et al., 2025; Félix et al., 2026).

Las limitaciones tecnológicas y las brechas de acceso digital también representaron factores relevantes dentro de la discusión de resultados. Aunque las herramientas de inteligencia artificial ofrecen ventajas importantes para la investigación ambiental, su implementación continúa dependiendo de infraestructura especializada, disponibilidad de recursos computacionales y acceso a bases de datos de alta calidad (Islam et al., 2026; Vuilliomenet et al., 2026). Esta situación genera desigualdades entre instituciones científicas y regiones con distintos niveles de desarrollo tecnológico, limitando la posibilidad de aplicar sistemas inteligentes en contextos donde podrían resultar especialmente necesarios para la conservación de ecosistemas vulnerables. En consecuencia, la democratización del acceso a tecnologías emergentes constituye un desafío fundamental para garantizar que los beneficios de la inteligencia artificial puedan extenderse de manera equitativa dentro del ámbito ambiental.

Las contribuciones identificadas para la sostenibilidad ecológica demostraron que la inteligencia artificial generativa posee un importante potencial para fortalecer estrategias orientadas a la protección de la biodiversidad y la gestión sostenible de recursos naturales (Rodríguez et al., 2026; Anderson et al., 2021). La capacidad de integrar información ambiental diversa, generar simulaciones predictivas y automatizar procesos de monitoreo permite desarrollar modelos de gestión más dinámicos y adaptativos frente a los desafíos ecológicos contemporáneos (Chen et al., 2024; Patel et al., 2025). Además, la incorporación de sistemas inteligentes podría favorecer una mayor articulación entre investigación científica, políticas públicas y programas de conservación, facilitando decisiones fundamentadas en análisis técnicos y evidencia empírica (Brown et al., 2022; Reuters, 2026).

La discusión de los hallazgos también permite reflexionar sobre la necesidad de establecer marcos regulatorios y lineamientos éticos que orienten el uso responsable de inteligencia artificial generativa en contextos ambientales. La creciente dependencia de sistemas automatizados dentro de procesos científicos exige garantizar transparencia en el manejo de datos, protección de información ecológica sensible y supervisión humana en la interpretación de resultados (Lee et al., 2024; Martínez et al., 2025). Del mismo modo, resulta necesario promover políticas de formación especializada que permitan fortalecer las competencias digitales de investigadores y profesionales vinculados con las ciencias ambientales y biológicas.

Desde una perspectiva científica, la investigación evidenció que la integración de inteligencia artificial generativa en biología y gestión ambiental constituye una línea de estudio en constante expansión, caracterizada por un elevado potencial interdisciplinario (Tuia et al., 2026; Feuerriegel et al., 2023). La convergencia entre innovación tecnológica y sostenibilidad ecológica abre nuevas posibilidades para desarrollar herramientas capaces de enfrentar problemáticas ambientales complejas mediante enfoques más precisos, predictivos y automatizados. No obstante, el aprovechamiento efectivo de estas tecnologías dependerá de la capacidad de las instituciones científicas y ambientales para implementar modelos responsables que equilibren eficiencia tecnológica, rigor científico y compromiso ético con la conservación de los ecosistemas.

En términos generales, los resultados y su discusión permitieron comprender que la inteligencia artificial generativa representa una oportunidad significativa para transformar los procesos de investigación y gestión ambiental en el contexto contemporáneo. Su aplicación adecuada podría contribuir al fortalecimiento de programas de conservación sostenible, optimización de recursos ecológicos y protección de la biodiversidad frente a los desafíos derivados del cambio climático y las actividades humanas (Rodríguez et al., 2026; Kong et al., 2026).

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Sin embargo, también quedó evidenciado que el desarrollo de estas tecnologías debe acompañarse de una visión crítica y responsable que garantice su utilización orientada al bienestar ambiental, social y científico a largo plazo.
Entre las principales limitaciones de la investigación se reconoce el carácter documental del estudio, ya que los hallazgos dependen exclusivamente de la literatura científica revisada y no de experiencias experimentales o estudios de campo. Asimismo, la rápida evolución de las tecnologías basadas en inteligencia artificial generativa podría generar cambios acelerados en las aplicaciones y tendencias identificadas, por lo que futuros estudios empíricos permitirían ampliar y validar los resultados obtenidos.

CONCLUSIONES

La presente investigación permitió analizar la aplicación de la inteligencia artificial generativa en biología y gestión ambiental, evidenciando que estas tecnologías poseen un importante potencial para fortalecer los procesos de conservación sostenible. La revisión documental demostró que los sistemas inteligentes favorecen el monitoreo ecológico, el análisis de biodiversidad, el modelado predictivo y la gestión de recursos naturales mediante el procesamiento eficiente de información ambiental.

Los hallazgos permitieron identificar que la inteligencia artificial generativa contribuye a optimizar el análisis de grandes volúmenes de datos ecológicos, facilitando la detección de patrones y la generación de predicciones útiles para la toma de decisiones ambientales. Asimismo, se constató que las aplicaciones más frecuentes se relacionan con monitoreo automatizado de ecosistemas, identificación de especies y simulación de escenarios asociados al cambio climático y la conservación de la biodiversidad.
No obstante, el estudio también evidenció desafíos importantes vinculados con la calidad de los datos, los sesgos algorítmicos, las limitaciones tecnológicas y las brechas de acceso digital. Estas situaciones reflejan la necesidad de fortalecer mecanismos de validación científica, supervisión ética y regulación responsable en la implementación de inteligencia artificial dentro de las ciencias ambientales y biológicas.
La investigación permitió comprender que la inteligencia artificial generativa no debe considerarse un sustituto del trabajo científico humano, sino una herramienta complementaria orientada a fortalecer las capacidades analíticas y operativas de investigadores y organizaciones ambientales. Su aprovechamiento efectivo dependerá de la integración equilibrada entre innovación tecnológica, rigor científico y sostenibilidad ecológica.
En términos generales, se concluye que la incorporación responsable de inteligencia artificial generativa puede contribuir significativamente al fortalecimiento de estrategias de conservación sostenible y protección de los ecosistemas frente a los desafíos ambientales contemporáneos. Finalmente, se recomienda promover investigaciones interdisciplinarias, formación especializada y políticas públicas que garanticen un uso ético, inclusivo y sostenible de estas tecnologías en beneficio del medio ambiente y la sociedad.

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MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

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Monitoreo de depredación de modelos artificiales de ranas (*Dendrobates auratus*) en bosque secundario utilizando cámaras trampa

Monitoring predation on artificial models of frogs (*Dendrobates auratus*) in a secondary forest using camera traps.

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INFORMACIÓN SOBRE EL ARTÍCULO

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ABSTRACT: In a secondary forest in Playa El Sol, Bahía Honda, Veraguas, Panama, the survival of artificial models of the poison dart frog *Dendrobates auratus*, a species classified as vulnerable under national regulations, was studied. The aim was to understand whether predation and forest canopy cover could influence the survival rates of *D. auratus* in tropical ecosystems. One hundred artificial models were made of non-toxic clay, painted with Raven Black acrylic to simulate aposematism, and distributed in a zigzag pattern along 10 linear transects in July 2025. Forest canopy cover was measured using a concave densiometer to assess its influence on predation. Twenty camera traps were deployed to complement predator identification. Over seven days, 26 attacks on the models were recorded, attributed to mammals, birds, crabs, and unidentified predators, as evidenced by markings on the models and camera traps. An attack by a bird (*Aramides cajaneus*), previously unrecorded as a potential predator of this frog, was reported. Analysis showed that canopy cover does not affect the survival of *D. auratus*. Statistical analyses were performed in R 4.3.2 and figures were visualized with ggplot2 3.3.2. This study reaffirms the ecological importance of amphibians and provides information on the potential predator-prey interaction in fragmented ecosystems, such as secondary forests in the tropics.

KEYWORDS: Aposematism, artificial models, camera traps, canopy cover, *Dendrobates auratus*, predation, secondary forest.

Rodríguez, J. *et al*.,
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RESUMEN: En un bosque secundario de “Playa El Sol” en Bahía Honda, Veraguas, Panamá, se estudió la supervivencia de modelos artificiales de la rana venenosa *Dendrobates auratus*, especie clasificada como vulnerable por las normativas nacionales. Se buscó entender si la depredación y la cobertura del dosel forestal podrían influir en las tasas de sobrevivencia de *D. auratus* en ecosistemas tropicales. Se fabricaron 100 modelos artificiales de arcilla no tóxica, pintados con acrílico Raven Black para simular su aposematismo, y se distribuyeron en un bloque con un arreglo en zigzag a lo largo de 10 transectos lineales en julio de 2025. Se midió la cobertura del dosel forestal con densiómetro cóncavo para evaluar su influencia en la depredación. Se desplegaron 20 cámaras trampa para complementar la identificación de depredadores. Durante siete días, se registraron 26 ataques a los modelos, atribuidos a mamíferos, aves, cangrejos y depredadores no identificados, evidenciados mediante marcas en los modelos y cámaras trampa. Se reportó el ataque de un ave (*Aramides cajaneus*) sin registros previos como potencial depredador de esta rana. El análisis mostró que la cobertura del dosel no afecta la supervivencia de *D. auratus*. Los análisis estadísticos se realizaron en R 4.3.2 y la visualización de figuras con “ggplot2” 3.3.2. Este estudio reafirma la importancia ecológica de los anfibios y aporta información sobre la potencial interacción depredadores-presa en un entorno de ecosistemas fragmentados, como los bosques secundarios en los trópicos.

Palabras Clave: Aposematismo, bosque secundario, cámaras trampa, cobertura del dosel, *Dendrobates auratus*, depredación, modelos artificiales.

INTRODUCCIÓN

La presente nota corta trata depredación es una interacción ecológica clave que regula la dinámica poblacional y las redes tróficas en los ecosistemas (Begon, Townsend & Harper, 2006). En particular, las ranas dardo verdinegras (*Dendrobates auratus*) representan un modelo valioso para estudiar cómo la presión de depredación influye en la divergencia fenotípica, un proceso fundamental en la evolución del aposematismo (Willink *et al*., 2014). Las curvas de supervivencia, como las de Kaplan-Meier, permiten evaluar la probabilidad de supervivencia a lo largo del tiempo y estimar el riesgo de mortalidad por depredación (Bewick, Cheek & Ball, 2004).

En Panamá, aproximadamente un 25% de las especies de anfibios están catalogadas como amenazadas, mientras que para 26 especies aún no existe información suficiente para evaluar su estado de conservación (ANAM, 2011).La especie *D. auratus* se considera vulnerable a nivel nacional según la Resolución No. AG-0051-2008, lo que subraya la urgencia de implementar estrategias de conservación específicas. Los experimentos con modelos artificiales de arcilla han demostrado ser una herramienta eficaz y no invasiva para evaluar la presión de depredación natural en anfibios, al permitir la identificación de marcas de ataque y, complementariamente, el uso de cámaras trampa para reconocer depredadores en condiciones de campo (Paluh *et al*., 2014; Bateman *et al*., 2017).

La fragmentación y alteración de los bosques secundarios costeros de Panamá incrementan la vulnerabilidad de las especies que los habitan, pero existe escasez de datos empíricos sobre las presiones de depredación que afectan a *D. auratus* en estos ecosistemas. En este contexto, el presente estudio tuvo como objetivo evaluar la supervivencia de modelos artificiales de *D. auratus* en relación con la depredación y la cobertura del dosel forestal en bosques secundarios costeros de Bahía Honda, Veraguas. Se planteó la hipótesis de que una mayor cobertura del dosel reduciría la tasa de depredación. Este enfoque aporta evidencia empírica sobre las interacciones depredador-presa y contribuye al diseño de estrategias de conservación más precisas para anfibios, organismos que desempeñan un papel crucial como controladores biológicos en los ecosistemas tropicales.

MATERIALES Y MÉTODOS

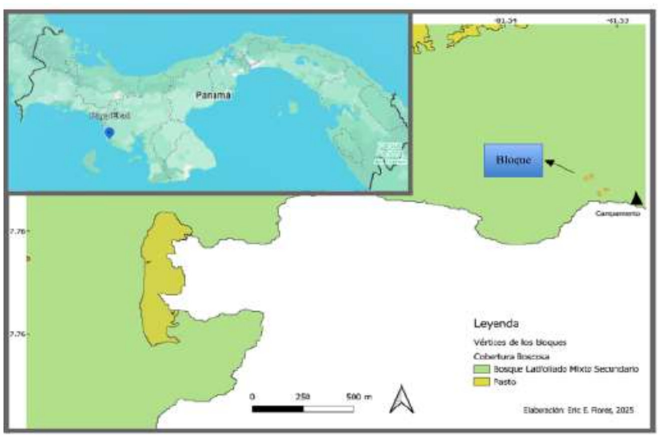
La investigación se desarrolló conforme a protocolos estandarizados para estudios experimentales de depredación. Se emplearon modelos artificiales de *Dendrobates auratus* elaborados en arcilla no tóxica, fijados sobre hojas de banana (*Musa sp.*). Se instalaron cámaras trampa Reconyx HyperFire 2, georreferenciación GPS y herramientas de medición bajo el Permiso de Acceso ARB-100-2024.

Área de estudio

Ubicada en bosque tropical secundario en Playa El Sol, Bahía Honda, Veraguas (7º 46' 00.1" N, 81º 31' 44.1" W; 41 msnm). Son bosques secundarios influenciados por la cercanía al mar, alta humedad y matriz heterogénea, hábitats adecuados para *D. auratus*, aunque expuestos a depredación debido a fragmentación (Ibáñez *et al*., 1999; Donnelly, 1991).

Figura 1.

Ubicación del área de estudio en Playa El Sol, Bahía Honda, Veraguas.



Fuente: Eric E. Flores, 2025.

Fabricación de modelos artificiales

Se elaboraron moldes de resina simulando un individuo adulto de 30 mm de longitud hocico-cloaca, con impresora 3D. Se usó arcilla Sculpey III y Fimo (mezclando color verde, negro, rojo, blanco y azul) pintados con acrílico Raven Black simulando el aposematismo local (Flores *et al.*, 2015).

Marcación de transectos

Se seleccionó un bloque en bosque secundario con diseño de bloque randomizado. Se marcaron en zigzag 10 transectos lineales, en los cuales se distribuyeron 100 modelos artificiales (10 en cada uno), registrando las coordenadas en un GPS (Garmin) con precisión 3 m.

Medición de dosel forestal

Se estimó la cobertura mediante densiómetro cóncavo (SUGRA ART) a 1,30 m del suelo. Se sumaron y dividieron lecturas de los puntos cardinales, aplicando un factor de corrección de 1,04 para obtener el porcentaje de cobertura (Matuz-Cruz, 2020).

Colocación de modelos

Se desplegaron 100 modelos en julio de 2025. Se monitorearon diariamente a la misma hora durante 7 días, se registró la depredación mediante marcas directas y a través de las cámaras trampa (Willink *et al*., 2014; Flores *et al*., 2015).

Cámaras trampa

Se colocaron 20 cámaras Hyperfire 2 de manera aleatoria en los transectos, camufladas y con pantimedias sobre el lente infrarrojo para camuflarlas de los posibles depredadores. Se configuraron en 10 s de video y 2 fotos por activación del sensor de movimiento en su periodo de mayor actividad desde el amanecer hasta las 14:00 h (Graves, 1999).

Análisis de datos

Los datos se codificaron sistemáticamente (1= depredado, 0= intacto, NA= desaparecido) en Excel y se importaron al software estadístico R 4.3.2 (R Core Team, 2023). Los gráficos se elaboraron con ggplot2 3.3.2.

RESULTADOS

Supervivencia de modelos artificiales

Durante el periodo de muestreo, se registraron 26 ataques o depredaciones a los modelos artificiales, lo que representa un 26 % de depredación y una supervivencia del 74 % para los modelos en los 10 transectos. Además, se estimó la probabilidad de supervivencia mediante la curva de Kaplan-Meier. La cual evidenció una disminución progresiva en el tiempo, con una tendencia estable entre los días 2 y 4, lo que indica que la tasa de depredación no fue constante durante todo el monitoreo.

Identificación de depredadores por transectos con ayuda de cámaras trampa

Los ataques registrados se atribuyeron principalmente a cuatro grupos de depredadores: mamíferos, aves, cangrejos y depredadores no identificados. Los mamíferos fueron el grupo dominante, responsable del 57,6 % de los ataques, seguidos de las aves con el 26 %, los cangrejos con el 15,3 % y un 7,6 % correspondiente a depredadores no identificados. Las cámaras capturaron imágenes y videos de mamíferos pequeños cerca de los modelos, y demuestra una distribución amplia de estos depredadores por todos los transectos. Se identificó un ataque del ave *Aramides cajaneus*, un registro inédito para esta especie en relación con la depredación de *D. auratus*, confirmado por imágenes de las cámaras trampa y marcas características en los modelos.

Relación entre supervivencia y cobertura del dosel forestal

Los resultados se clasificaron en cuatro intervalos equidistantes (A, B, C y D), que representan desde baja hasta muy alta cobertura del dosel, a cubrir desde el 45 % hasta el 100 % de dosel, de acuerdo con los porcentajes observados en el bosque secundario estudiado. Los análisis revelaron que la mayoría de los ataques de depredación ocurrieron en zonas con cobertura media del dosel, mientras que las áreas con cobertura alta y muy alta registraron menor incidencia de ataques.

En base a estos resultados de cobertura de dosel forestal, se procedió a relacionar la cantidad de ataques con la supervivencia de los modelos en el transcurso de los días de muestreo, por medio de la curva de Kaplan-Meier.

Tabla 1.

Ataques por nivel de cobertura de dosel forestal

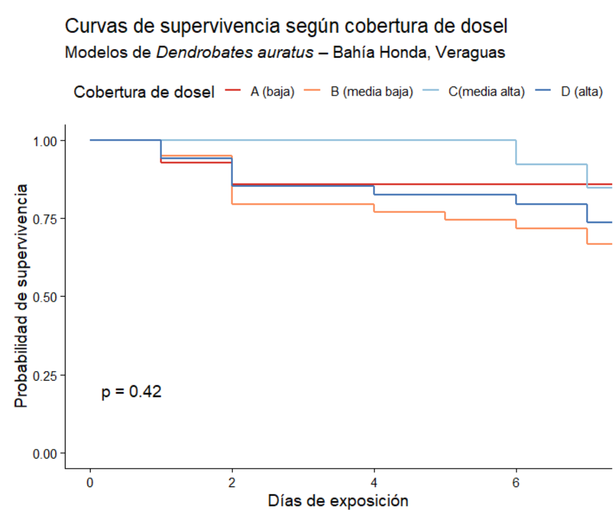
Cobertura	A	B	C	D
Ataques	1	14	2	9

Fuente: Rodríguez, J.

Nota: La tabla 5 muestra la distribución de ataques de depredadores en relación con la cobertura del dosel forestal. Se observa que la cobertura media (B) presenta la mayor incidencia de ataques (14), lo que sugiere que los modelos expuestos bajo coberturas intermedias fueron más vulnerables a la depredación. En contraste, las coberturas altas (C y D) registraron menor cantidad de ataques (2 y 9), lo que podría indicar que una mayor densidad del dosel ofrece mayor protección visual o física frente a los depredadores.

Figura 2.

Curva de probabilidad de supervivencia según la cobertura del dosel forestal.



Fuente: Rodríguez, J.

Nota: La figura 5 muestra las curvas de supervivencia de Kaplan–Meier de los modelos de Dendrobates auratus expuestos en función de cuatro niveles de cobertura de dosel (A = baja, B = media baja, C = media alta y D = alta).

Las curvas evidencian que, durante los primeros días de exposición, la probabilidad de supervivencia se *mantiene relativamente alta en todos los niveles; sin embargo, ocurre una disminución progresiva. Existe una tendencia a una mayor supervivencia en áreas con cobertura de dosel media-alta y alta (C y D), cuyas curvas presentan pendientes más suaves.*

La prueba de log-rank no detectó diferencias estadísticamente significativas entre las curvas de supervivencia (p = 0,42). La cobertura de dosel no explicó de manera concluyente las variaciones en el tiempo de depredación, pero el patrón observado sugiere un posible efecto modulador del dosel sobre la detectabilidad.

DISCUSIÓN

El análisis de supervivencia y los patrones de depredación permiten comprender la dinámica ecológica de *Dendrobates auratus* en bosques secundarios costeros. La supervivencia del 74 % de los modelos durante los siete días de exposición constituye un punto de partida para interpretar la intensidad de la depredación. Los modelos replican el patrón aposemático y permiten evaluar cómo los depredadores exploran elementos novedosos y cuán susceptibles podrían ser individuos juveniles (Saporito *et al*., 2009).

La curva de Kaplan–Meier mostró un descenso progresivo, notable los primeros dos días, seguido de una fase estable. Esto sugiere que los depredadores responden rápidamente a estímulos novedosos, estabilizando su actividad después. En transectos con estructura vegetal variable, las condiciones de visibilidad aumentaron, facilitando a depredadores oportunistas detectar los modelos.

Los mamíferos pequeños fueron el grupo con mayor incidencia (57,6% de ataques). Patrones coincidentes demuestran que roedores y pequeños marsupiales interactúan impulsados por comportamientos exploratorios (Costa *et al*. 2020; Nguyen *et al*., 2023). Las aves representaron el segundo grupo (26 %), sobresaliendo la confirmación de *Aramides cajaneus*. Este hallazgo amplía el espectro trófico de la especie, no documentada en depredación de ranas aposemáticas. Marcas en forma de U o V respaldan los ataques aviares (Willink *et al*., 2014).

La participación de cangrejos (15,3 %) complementa el patrón de depredación, ya que utilizan sus quelas para fragmentar tejidos blandos de anfibios incluso tóxicos (Wehrtmann *et al*., 2019). Eventos no identificados (7,6 %) evidencian la presencia de interacciones nocturnas o especies que no dejan marcas.

La mayor incidencia de ataques se registró en coberturas medias de dosel (58,75 % – 72,5 %), donde los depredadores tienen condiciones favorables de desplazamiento y detección (Stevens *et al*., 2008). En coberturas altas, la menor cantidad de ataques podría deberse a reducción de flujo luminoso. Aunque las diferencias de supervivencia no fueron estadísticamente significativas, el patrón sugiere que la fragmentación estructural del dosel puede incrementar la vulnerabilidad de la especie.

CONCLUSIONES

La identificación de depredadores evidenció que los mamíferos eran los depredadores principales, seguidos por las aves, cangrejos y grupo no identificados, lo que refleja la dinámica natural y la eficacia de los modelos de arcilla para analizar interacciones. El registro inédito de *Aramides cajaneus* depredando los modelos aporta información novedosa sobre la plasticidad trófica del ave en bosques secundarios.

La cobertura del dosel forestal influyó cualitativamente; los ataques se concentraron en coberturas intermedias favorables para la visibilidad, mientras que los doseles densos fungieron como refugios aparentes reduciendo ataques tempranos. En síntesis, la depredación sobre *D. auratus* es un proceso complejo dictado por diversidad de depredadores y estructura del hábitat, resaltando la relevancia de estas interacciones al diseñar estrategias de conservación y protección para esta especie vulnerable en ecosistemas panameños fragmentados.

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MESOAMERICANA
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NOTA CIENTÍFICA
Temática: Entomología

Prevalencia de coccidae (hemiptera) en cultivos de traspatio en Cerro Punta – Chiriquí, Panamá

Prevalence of coccidae (hemiptera) in backyard crops in Cerro Punta – Chiriquí, Panama

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INFORMACIÓN SOBRE EL ARTÍCULO

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Contribución del autor: El autor de este trabajo declara haber participado en la realización de este proyecto de investigación en todas sus etapas, trabajo de campo, la identificación, así como la discusión y el análisis de datos.

Editor: Dr. Alonso Santos Murgas

RESUMEN. La familia Coccidae (Hemiptera), comprende especies plaga polífagas y cosmopolitas, asociadas a diversas plantas. Cerro Punta es de las principales zonas productoras de hortalizas en Panamá, pero en los traspatios es frecuente encontrar especies frutales y ornamentales. El objetivo del estudio fue determinar la prevalencia Coccidae como plaga. Se escogieron al azar tres higueras, tres naranjos, un limonero mandarino, tres hibiscos y un abutilón. Se revisaron al azar cuatro brotes del tercio medio por planta. Según los resultados, se identificaron formas inmaduras de dos especies de Coccidae, *Coccus hesperidum* y *Saissetia coffeae*; las cuales prevalecieron en promedio en un 67% en las higueras, 83% en naranjos, 100% en limonero mandarino, 17% en hibiscos y 25% en abutilón. En conclusión, las especies de Coccidae identificadas prevalecen como plagas importantes en traspatios de Cerro Punta, por lo que se recomienda implementar manejo integrado de plagas.

PALABRAS CLAVES: *Coccus*, frutales, ornamentales, plaga, *Saissetia*.

ABSTRACT. Family Coccidae (Hemiptera) comprises polyphagous and cosmopolitan pest species associated with various plants. Cerro Punta is one of the main vegetable-producing areas in Panama, but fruit and ornamental plants are frequently found in backyards. The aim of this study was to determine the prevalence of Coccidae as pest. Three fig trees, three orange trees, one mandarin lemon tree, three hibiscus plants, and one abutilon plant were randomly selected. Four shoots from the middle third of each plant were randomly checked. According to the results, immature forms of two Coccidae species, *Coccus hesperidum* and *Saissetia coffeae*, were identified; these were prevalent on average at 67% in fig trees, 83% in orange trees, 100% in mandarin lemon trees, 17% in hibiscus plants, and 25% in abutilon plants. In conclusion, the identified Coccidae species are prevalent as major pests in backyards in Cerro Punta, therefore it is recommended to implement integrated pest management.

KEYWORDS: *Coccus*, fruit plants, ornamental plants, pest, *Saissetia*.

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La familia Coccidae (Hemiptera), comprende especies que han sido reportadas como plagas en diversos cultivos estratégicos para la seguridad alimentaria y nutricional, como son los cítricos (Atencio-Valdespino et al., 2023), el mango (Lanuza-Garay, 2014), el higo (Fuentes-Guardiola et al., 2024); además de afectar plantas ornamentales (El-Amir et al., 2023).

Cerro Punta, Distrito de Tierras Altas – Provincia de Chiriquí, Panamá, es de las principales zonas productoras de hortalizas en Panamá, siendo responsable de cubrir más del 80% de la demanda de dichos rubros en el país (Lindsay & Weinberg, 2019). Sin embargo, en los traspatios es frecuente encontrar frutales y ornamentales (Collantes y Jerkovic, 2020).

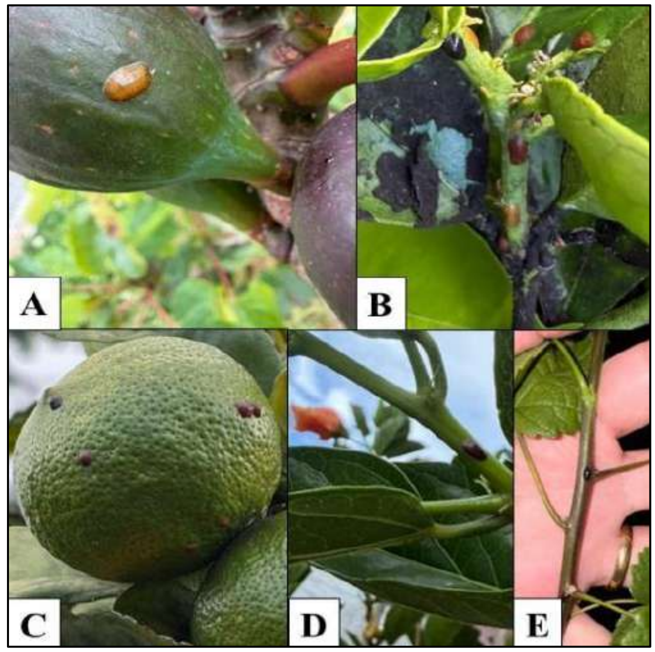
En recorridos de campo realizados recientemente en Cerro Punta (8°51’50” N 82°34’58,17” O, 1860 msnm) (Figura 1), se observaron especies frutales y ornamentales afectadas por Coccidae, por lo que el objetivo del estudio (de carácter conservacionista), fue identificar dichos insectos plaga y determinar su prevalencia en las plantas afectadas.

Figura 1.

Sitio de estudio en Cerro Punta, Tierras Altas – Chiriquí, Panamá (Mapa: Google Earth, 2026).

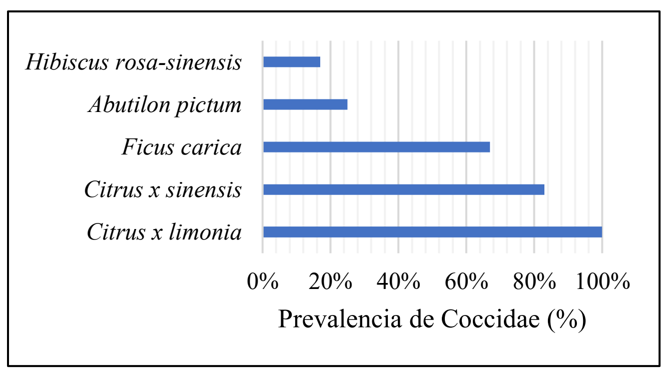
Se escogieron al azar 11 plantas: tres higueras, tres naranjos, un limonero mandarino, tres hibiscos y un abutilón. Se revisó un brote por cada punto cardinal, del tercio medio por planta (44 muestras en total). Se llevó un registro fotográfico, se confirmó con ayuda de un especialista la identificación de insectos y se consultó literatura especializada (Collantes & Jerkovic, 2020; El-Amir et al., 2023; Iowa State University, 2026).

Figura 2.
Coccidae en traspatio, Cerro Punta: A) Higo; B) Naranjo; C) Limón mandarino; D) Hibisco; E) Abutilón.



Según los resultados, el hábito observado de las formas inmaduras corresponde a *Coccus hesperidum* L., 1758 y *Saissetia coffeae* (Walker, 1852) (Coccidae); las cuales prevalecieron principalmente en cítricos (Figura 3).

Figura 3.
Prevalencia de Coccidae por especie vegetal, Cerro Punta.



Si bien se tienen reportes previos en Panamá, sobre Coccinellidae (Coleoptera) depredadores con potencial para el control biológico de Coccidae (Lanuza-Garay,

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

2014; Collantes & Jerkovic, 2020); además de parasitoides encontrados en otras latitudes (Fuentes-Guardiola et al., 2024), lo recomendable es apostar por el manejo integrado de plagas (MIP); siendo recomendable en pequeñas extensiones agrícolas el control biológico por conservación (Collantes, 2026). En conclusión, las especies de Coccidae identificadas prevalecen como plagas importantes en traspatios de Cerro Punta, recomendándose implementar el MIP.

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Conflicto de interés
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Population Dynamics, Somatic Growth, and Mortality Patterns of *Leukoma asperrima* (Bivalvia: Veneridae) in the Panamanian Pacific

Dinámica Poblacional, Crecimiento Somático y Patrones de Mortalidad de *Leukoma asperrima* (Bivalvia: Veneridae) en el Pacífico Panameño

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ABSTRACT

Sustainable management of commercial bivalves in the Eastern Tropical Pacific requires an in-depth understanding of their bionomics in response to seasonal oceanographic variability. This study evaluated the growth and mortality dynamics of *Leukoma asperrima* in the Gulf of Panama over an annual cycle (November 1995 – October 1996). The population exhibited a mean shell length of 25.99 mm and a total weight of 7.05 g, with significant fluctuations associated with the coastal upwelling regime. Results revealed non-uniform growth across cohorts; the highest longitudinal increment rate was recorded in intermediate-sized individuals (0.109 mm/month), whereas maximum weight gain (0.13 g/month) was observed in larger specimens, suggesting high efficiency in phytoplankton assimilation during the rainy season. Average monthly mortality was 11.3%, with critical peaks in October (21.5%) and January (19.42%) linked to post-reproductive stress and senescence. The detection of endoparasites in gonadal tissue is postulated as a determining factor in tissue disorganization and adult survival. These findings highlight the importance of environmental and pathological factors in regulating *L. asperrima* biomass, providing critical parameters for the implementation of fisheries exploitation models.

Keywords: coastal upwelling, bivalve bionomics, allometric growth, *Leukoma asperrima*, fisheries management, seasonal mortality, Eastern Tropical Pacific.

Resumen
La gestión sostenible de los bivalvos comerciales en el Pacífico Este Tropical requiere un conocimiento profundo de su bionomía en respuesta a la variabilidad oceanográfica estacional. Este estudio evaluó la dinámica de crecimiento y mortalidad de *Leukoma asperrima* en el Golfo de Panamá durante un ciclo anual (noviembre 1995 – octubre 1996). La población exhibió una talla media de 25.99 mm y un peso de 7.05 g, con fluctuaciones significativas asociadas al régimen de afloramiento costero. Los resultados revelaron que el crecimiento no es uniforme entre cohortes; la mayor tasa de incremento longitudinal se registró en individuos de talla intermedia (0.109 mm/mes), mientras que el crecimiento ponderal máximo (0.13 g/mes) se observó en ejemplares de mayor tamaño, sugiriendo una alta eficiencia en la asimilación de fitoplancton durante la temporada lluviosa. La mortalidad mensual promedio fue del 11.3%, con picos críticos en octubre (21.5%) y enero (19.42%), vinculados al estrés post-reproductivo y la senescencia. La presencia detectada de endoparásitos en el tejido gonadal se postula como un factor determinante en la desorganización tisular y la supervivencia de los adultos. Estos hallazgos subrayan la importancia de los factores ambientales y patológicos en la regulación de la biomasa de *L. asperrima*, proporcionando parámetros críticos para la implementación de modelos de explotación pesquera.

Palabras claves: afloramiento costero, bionomía de bivalvos, crecimiento alométrico, *Leukoma asperrima*, manejo pesquero, mortalidad estacional, Pacífico Este Tropical

INTRODUCTION

The white clam, *Leukoma asperrima* (Sowerby, 1835), constitutes one of the most ecologically relevant and economically promising benthic resources for coastal communities in the Central American Pacific. In the Gulf of Panama, the dynamics of these populations are intrinsically linked to seasonal environmental variability, particularly the coastal upwelling phenomenon occurring between January and April. This oceanographic event, characterized by the ascent of nutrient-rich deep waters, generates drastic fluctuations in temperature and salinity, which in turn regulate primary productivity and the availability of phytoplankton, the primary energy source for filter-feeding bivalves. Growth in bivalve mollusks is not a linear process but an adaptive response to exogenous factors such as water temperature and available food ration.

According to Bayne (1976), growth efficiency is a function of animal size and the nutritional value of the ingested food. In tropical systems, it has been postulated that growth rates may decrease upon reaching sexual maturity due to energy reallocation toward gametogenesis. However, research on the genus *Leukoma* suggests variable patterns where the energy required for reproduction may limit or delay somatic growth depending on the species' metabolic strategy.

Authors such as Ansell (1961) have emphasized that the relationship between growth and the reproductive cycle is highly specific and depends on the energy balance accumulated in storage tissues prior to the gonadal proliferation phase. Conversely, mortality in marine bivalves is a multifactorial phenomenon including predation, thermal stress, sedimentation, and parasitic pathologies. Kautsky (1982) notes that food shortages and reproductive metabolic stress can exacerbate mortality rates in natural populations.

In *L. asperrima*, the presence of endoparasites that disorganize gonadal tissue has been documented, representing a critical pathological factor for population survival. Broom (1982) contends that in intertidal bivalves, mortality due t

post-reproductive stress can account for up to 20% of annual population loss, which is consistent with observations along the Panamanian Pacific coast. The present study aims to evaluate variations in size, weight, and mortality of *L. asperrima* under the fluctuating conditions of the Panamanian Pacific, providing fundamental data for the biological management of the resource.

MATERIALS AND METHODS

Collection and Culture Area

Specimens were collected at Playa Bique (8° 53' 27" N, 79º 39' 44" W), a sandy-muddy shoreline in the Arraiján District. Subsequently, they were transferred to the Smithsonian Tropical Research Institute (S.T.R.I.) facilities at Isla Naos (8° 54' 55" N, 79° 31' 37" W). Organisms were placed in lantern nets with pearl net subdivisions at a density of 30 individuals per basket.

Biometric Analysis and Growth Rates

Total length (L) was determined for everyone using a digital caliper (±0.01 mm precision), and total wet weight (*W*) was measured with an analytical balance (±0.01 g). The population was categorized into five size classes for differential analysis (See Table 1). Monthly growth rates (TC) were calculated using the relationship:

$$TC = \frac{L_f - L_i}{\Delta t}$$

Table 1.
Size classification of L. asperrima based on shell height.

Size	Shell Height
1	17.0-21.0 mm
2	21.1-24.0 mm
3	24.1-27.0 mm
4	27.1-31.0 mm
5	31.1 mm-36.0 mm

Mortality Estimation and Statistical Analysis

Mortality was quantified monthly as the percentage of dead individuals (empty valves with remaining tissue or evidence of recent predation) relative to the total sample. Data normality was verified using the Shapiro-Wilk test. Due to the non-parametric nature of the mortality distribution, the Kruskal-Wallis test was applied to evaluate significant differences between months and size classes ($P < 0.05$).

RESULTS

Population Structure and Biometric Variation

The *Leukoma asperrima* population exhibited relative biometric stability, with an average annual size of 25.99 mm and a total weight of 7.05 g. A marginal increase in parameters was observed during the transition to the rainy season (May-October), where size rose to 26.14 mm and weight to 7.18 g, compared to the 25.77 mm and 6.88 g recorded at the start of the cycle.

Growth Rate Analysis

Longitudinal and ponderal growth exhibited allometric variations according to size class (Table 2). The highest longitudinal growth rate was quantified in Size Class 3 at 0.109 mm/month, while maximum weight gain was recorded in Size Class 5 with an increment of 0.13 g/month. The average population growth was 0.081 mm/month and 0.05 g/month.

Table 2.
Monthly growth dynamics by size range in L. aspérrima

Size Class	Length Growth (mm/month)	Weight Growth (g/month)
Talla 1-2	0.049	0.05
Talla 3	0.109	0.05
Talla 4	0.084	0.04
Talla 5	0.083	0.13

Mortality Patterns
The average annual mortality stood at 11.3%. Statistical analysis (Kruskal-Wallis) confirmed significant differences between months ($P < 0.05$). The lowest mortality levels were reported in March (3.3%), while critical peaks occurred in October (21.5%) and January (19.42%). By category, Size Class 4 exhibited the greatest vulnerability, with a cumulative mortality of 12.4%.

DISCUSSION

The growth patterns observed in *L. asperrima* during the annual cycle in the Panamanian Pacific reflect phenotypic plasticity adapted to high environmental variability regimes. The reported mean size (25.99 mm) and weight (7.05 g) are consistent with descriptions by Palacios (1985) for populations in the Gulf of Nicoya, suggesting a stable bionomic structure for the species in the Eastern Tropical Pacific.

A critical finding was the acceleration of the longitudinal growth rate during the juvenile-adult stage (Size Class 3: 0.109 mm/month) and the maximum weight increment in the largest specimens (Size Class 5: 0.13 g/month). This phenomenon contradicts the classic model of declining post-maturity growth in tropical bivalves, suggesting that *L. asperrima* possesses high metabolic efficiency to capitalize on phytoplankton peaks during the rainy season and upwelling periods. Ansell (1961) postulates that somatic growth in venerids is contingent upon the balance between food ration and the energy cost of reproduction; in this study, the weight gain in Size Class 5 indicates substantial reserve accumulation prior to spawning events.

Mortality dynamics (11.3% average) showed marked seasonality. The peak recorded in October (21.5%) coincides with maximum reproductive effort and the end of the rainy season, suggesting post-spawning physiological weakening. Conversely, the high mortality in January (19.42%) may be linked to the initial thermal stress of upwelling or the senescence of individuals reaching their biological limit following the massive end-of-year spawning. The identification of endoparasites in gonadal tissue reinforces the hypothesis that local pathologies act as limiting factors for survival, disorganizing tissue architecture and compromising population resilience to environmental fluctuations.

CONCLUSIONS

The *L. asperrima* population in the Gulf of Panama exhibits a stable biometric structure, with an average annual size of 25.99 mm and a weight of 7.05 g, reflecting successful adaptation to the region's seasonal regimes.

Somatic growth in this species does not follow a linear post-maturity decline; instead, larger specimens (Size Class 5) show the highest weight increment rate (0.13 g/month), indicating high metabolic efficiency in energy assimilation during periods of high phytoplankton productivity.

Mortality exhibits marked seasonality with a monthly average of 11.3%, reaching critical peaks exceeding 20% in October—a phenomenon closely linked to physiological stress from massive reproductive effort and the potential incidence of gonadal endoparasites.

It is concluded that the population dynamics of *L. asperrima* are regulated by a complex interaction between exogenous factors (food availability and temperature) and endogenous factors (reproductive cost), which must be considered when formulating closed seasons and minimum catch sizes to ensure resource resilience.

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Reporte del éxito reproductivo de una pareja de *Ara severus* (Linnaeus, 1758) utilizando un árbol muerto de cuipo (*Cavanillesia platanifolia*) en Darién, Panamá

Report of the reproductive success of a pair of *Ara severus* (Linnaeus, 1758) using a dead cuipo tree (*Cavanillesia platanifolia*) in Darién, Panamá

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RESUMEN. Debido a que hay poca información de esta ave en el medio silvestre, presentamos una serie de observaciones de un nido exitoso en la provincia del Darién, Panamá (8.4348286N, -77.93783877W), durante un poco más de 80 días de observaciones, utilizando un árbol muerto de *Cavanillesia platanifolia* (Cuipo), la Guacamaya Frenticastaña (*Ara severus*) realizó una incubación que duró unos 30 días, el polluelo permaneció en el nido durante un mínimo de 9 semanas y un año después los tres individuos se observan juntos. Estos reportes contribuyen a actualizar y conocer la dinámica reproductiva de la especie para el país, ya que sus observaciones son poco comunes o poco documentadas hasta el momento.

PALABRAS CLAVE: *Ara severus*, provincia de Darién, éxito reproductivo.

ABSTRACT. Because there is little information on this bird in the wild, we present a series of observations of a successful nest in the Darién Province, Panama (8.4348286N, -77.93783877W). Over a period of just over 80 days, using a dead *Cavanillesia platanifolia* (Cuipo) tree, the Chestnut-fronted Macaw (*Ara severus*) incubated for about 30 days. The chick remained in the nest for a minimum of 9 weeks, and a year later, all three individuals were observed together. These reports contribute to updating and understanding the reproductive dynamics of the species in the country, as these observations are uncommon or poorly documented to date.

KEYWORDS. Chestnut-fronted Macaw, Darién province, reproductive success.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

INTRODUCCION

La Guacamaya Frenticastaña (Ara severus) es un ave de la familia de los loros (Psittacidae), natural de América. Su distribución se extiende desde las selvas del Darién en Panamá y Colombia hasta la cuenca del Amazonas, el este de Perú, llegando al centro de Bolivia hacia el este de Venezuela y el centro de Brasil, figura #1.

Figura 1.
Distribución geográfica de la Guacamaya Frenticastaña Ara severus en América según eBird 2026, el punto rojo indica donde registramos nuestras observaciones.

Esta especie ha sido registrada en distintos tipos de hábitat, como bosques inundados estacionalmente, bosques de galería, zonas pantanosas, bosques de segundo crecimiento y ocasionalmente, bosques húmedos de tierras bajas de tierra firme. A menudo se le observa volando sobre selva continua, entra a los llanos a través de bosques de galería. Se le documenta desde el nivel del mar hasta los 800 msnm. Angehr & Dean. 2010, indican que es común en Darién hasta los 600 msnm.

No tiene dimorfismo sexual. Principalmente verde con la coronilla azul, en el frente tiene una banda estrecha y poco visible de color castaño, su cola larga, aguda y verde teñida de rojizo. Su pico negro grisáceo, la piel facial y la garganta se encuentra desnuda de color blanquecino, las plumas de las alas son azules por encima, el interior de las alas es rojo opaco.

Tiene por lo menos la mitad del tamaño de las Guacamayas grandes. Su nombre Ara es una onomatopeya tupí utilizada para referirse a las guacamayas y severus deriva del latín y significa cruel (Wikiaves Icesi. 2023).

Su dieta es muy variable e incluye las semillas, la pulpa y las flores de varios tipos de plantas, principalmente semillas de *Hura crepitans* (Tronador). A diferencia de muchas otras especies de loros y guacamayos, las poblaciones de *Ara severus* parecen ser estables. Aunque en Panamá se encuentra en la categoría CR: Críticamente Amenazada junto a otras 27 especies a nivel nacional según el Comité de Registros de la Sociedad Audubon de Panamá (2025).

Se cree que la temporada reproductiva en el país es entre marzo y mayo. Generalmente anida en cavidades de árboles muertos o palmas muertas. La nidada consiste de 2 a 3 huevos.

Esta nota científica busca aportar datos actualizados de observaciones paso a paso de una pareja en vida silvestre cuyo nido y polluelo tuvieron éxito.

Materiales y Métodos

Nuestras observaciones surgen en una finca privada (sin nombre), dedicada a cultivos de maíz y otros vegetales ubicada en la Provincia del Darién, Panamá (8.4348286N, -77.93783877W), figura #2.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Figura 2.
Mapa de la República de Panamá donde mostramos en punto rojo la ubicación de la finca donde fue observado el nido de Ara severus, según https://ebird.org/checklist/S221493522

Durante un recorrido de observación de aves el pasado 13 de marzo 2025, observamos un individuo de Guacamaya Frenticastaña (*Ara severus*), posiblemente una hembra que se asomaba al hueco ubicado en un árbol de Cuipo (*Cavanillesia platanifolia*), figura #3.

Figura 3.
Ara severus observando desde el hueco del nido en árbol muerto de Cuipo (*Cavanillesia platanifolia*).

Todas nuestras observaciones fueron realizadas utilizando binoculares Vortex 10x42 y Zeiss 10x42, los datos fueron registrados en la aplicación de ciencia ciudadana eBird, las fotografías de paisajes fueron tomadas con celular Honor 7b y las fotos de las guacamayas con cámara Canon R7 y lente telefoto de Canon 800mm.

RESULTADOS / OBSERVACIONES

Conociendo la dinámica de forrajeo de la pareja de guacamayas dispusimos que las observaciones serían en las mañanas entre las 06:30 am y por espacio de 2 a 3 horas observábamos que un adulto sobrevolaba alrededor del nido, ahuyentaba a otras aves como carpinteros e inclusos loros, luego se posaba sobre uno de los árboles cercanos mientras que el otro adulto en el nido asomaba su cabeza, cuando el área era segura este salía del nido, figura #4, perchaba al lado del otro adulto para ser alimentada, posteriormente se acicalaban por unos segundos, incluso se apareaban, algunas veces ambos volaban por unos minutos lejos del nido, minutos después uno de los adultos regresaba y entraba al nido.

Desde el 13 de marzo y hasta finales del mes, 31 de marzo, la hembra poco ha salido del nido, sólo por algunos breves minutos para ser alimentada por el macho en horas de la mañana o en las tardes, hasta aquí han pasado 19 días desde que los notamos en el hueco del Cuipo.

Figura 4.
Ara severus saliendo desde el hueco del nido en árbol muerto de Cuipo (*Cavanillesia platanifolia*).

Foto: Jorge Moisés Herrera R.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Entre el 01 y 30 de abril realizamos observaciones en la mañana y en las tardes, conociendo ya el movimiento de los adultos nos dispusimos a llegar al árbol nido alrededor de las 4:00 y hasta las 6:30 pm, la dinámica es similar a la observada en las mañanas, un adulto suele volar y sobrevolar peleando con otras aves como carpinteros lineados (*Dryocopus lineatus*), una vez despejada el área de otras aves, el adulto dentro del nido sale y se percha al lado del otro adulto para ser alimentada por espacio de 5 a 10 minutos, luego ambos se desplazan a otro árbol cercano al nido, permanecen juntos poco menos de 3 minutos cuando uno de ellos vuela al nido entra y permanece asomado con la cabeza en el hueco hasta que el otro adulto se retira del área, este mes de abril, ya notamos más tiempo fuera del nido al segundo adulto, sin embargo, ya entra comida al nido, al menos dos veces en este mes observamos a ambos entrar al nido al caer la noche. Para el 25 de abril y luego de realizar la misma dinámica, siendo las 6:30pm la hembra entra al nido y escuchamos sonidos de pichones reclamando ser alimentados, luego a las 6:35 pm salió la hembra y entro el macho, según nuestros registros la incubación duró unos 30 días.

Luego de confirmar la presencia de pichones en el nido notamos que la dinámica de alimentación varia un poco, ya que los adultos llegan juntos, se perchan, se acicalan, más tarde la hembra ingresa al nido, sale y entra el macho, al parecer se turnan para alimentar a los pichones, mientras un adulto se mantiene afuera vigilante, sale la hembra, ambos se van, minutos después ambos regresan y nuevamente, uno ingresa con alimentos, otro vigila y luego cambian los roles. En las tardes luego de alimentarse mutuamente, la hembra ingresa al nido y se queda ahí mientras que el macho permanece perchado algunos minutos antes de irse.

Iniciamos mayo con la misma dinámica observada en abril, los adultos llegan en la mañana, sabemos que al menos uno duerme en el nido, salen muy temprano en busca de comida. Han pasado 59 días desde que notamos el cortejo entre los adultos, se nota una cabecita de polluelo asomarse a la entrada del nido, era notable las líneas blancas de su cara, figura #5.

Figura 5.

Polluelo de Ara severus en sus primeros días explorando desde el nido.

Foto: Ada Barría.

Hasta este momento tenemos claro que hay dos periodos de alimentación intensos y cortos en la mañana entre las 06:10 a 07: 40am y en la tarde entre las 05:00 y 06:30pm.

Para el 22 de mayo (día 71) logramos ver un poco mejor al polluelo, ya presenta un pico bastante negro, muy marcado el verde en su plumaje, sin plumas aún en el pecho, escuchamos cierta vocalización cuando llegan los padres. Para el día 79 de observaciones notamos que el pichón está como escalando en la entrada del nido, los adultos están perchados muy cerca al nido, el macho alimenta a la hembra mientras están atentos a su pichón.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Iniciamos junio, día 80 de observaciones, los adultos están perchados en un árbol cerca del nido y el polluelo asomado en el nido muy atento a los sobrevuelos que hacen sus padres dando vueltas alrededor del nido, en el pichón ya se notan plumas de adulto las típicas plumas rojas y azules en sus alas son muy claras y notorias, el juvenil responde al llamado de los adultos, una llamada muy áspera y escandalosa.

Al día 88 de las observaciones (9 de junio), los llamados de *Aras severus* llegan hasta la casa de quien había monitoreado el nido por casi tres meses, la pareja de guacamaya y su juvenil estaban a 5 metros de su casa, perchados, un adulto, suponemos la madre, acicala al juvenil, limpia sus alas por más de 20 minutos, se mantiene al lado de él mientras que el otro adulto permanece cerca en el mismo árbol, después de este tiempo los adultos se mueven, regresan pasado unos 15 minutos y repiten el patrón, el polluelo permanece en el mismo árbol, regresan los adultos con su llamado característico, el polluelo sólo se movió en la misma rama, para luego cerca del medio día los tres emprenden vuelo, creemos que al árbol nido, donde efectivamente los veríamos en horas de la tarde, figura #6.

Figura 6.

Polluelo de Ara severus en sus primeros días fuera del nido.

Foto: Ada Barría.

DISCUSIONES

Según Collar *et al*., 2020, *Ara severus* en Panamá, inicia su reproducción en febrero, nuestras observaciones inician un 13 de marzo y dado que hay poca información sobre reproducción y comportamiento durante la misma decidimos realizar observaciones todos los días desde que observamos a esta pareja aparearse y utilizar el hueco de este árbol muerto como nido.

Nuestras observaciones sugieren que la incubación se dio alrededor de 30 días, Collar *et al*., 2020 indica que la especie reporta incubación de 28 días en cautiverio, nuestro registro es de aves en vida silvestre, lo que aporta resultados interesantes para la especie.

Por otro lado, nuestras observaciones concuerdan con las reportadas por Collar *et al.*, 2020 que el periodo de pichón no va más de nueve semanas, sin embargo, a un año de estas observaciones seguimos observando a los tres individuos juntos, no hemos encontrado reportes de cuánto tiempo permanecen los jóvenes junto a sus padres adultos antes de dispersarse del territorio donde nacieron, sin embargo, algunos registros de guacamayas en cautiverio sugieren que una guacamaya juvenil alcanza la madurez entre 3 y 6 años después de la eclosión y luego encuentra un compañero. Estas aves tropicales viven entre 30 y 35 años en la naturaleza y algunas viven hasta 50 años en cautiverio.

Debido a que gran parte de la información del ciclo reproductivo se tiene de aves en cautiverio, consideramos que esta nota y sus observaciones contribuyen a entender un poco más nuestras aves en su entorno silvestre.

CONCLUSIONES

Nuestras observaciones sugieren que la incubación de *Ara severus* en vida silvestre puede tomar un poco más de 28 días, nuestro nido tomó 30 días, la salida del polluelo del nido tardó unas nueve semanas y un año después el juvenil sigue volando junto a sus padres, lo que es posible ya que en general las guacamayas pueden alcanzar la madurez entre los 3 y 6 años después de la eclosión.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

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MESOAMERICANA
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NOTA CIENTÍFICO
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Primer registro del leucismo en el Chorlo de Wilson *Anarhynchus wilsonia* (charadiiformes: charadiidae) en Panamá

Frist record of leucism in the Wilsons´s Plover *Anarhynchus wilsonia* (charadiiformes: charadiidae) in Panama

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Editor: Dr. Alonso Santos Murgas

RESUMEN. Se documenta el primer registro de leucismo en el Chorlo de Wilson, *Anarhynchus wilsonia*, en Panamá. El individuo fue observado el 28 de febrero de 2026 durante un monitoreo de aves playeras en Playa El Agallito, Chitré, provincia de Herrera. El ejemplar presentó extensas áreas blancas en el dorso, escapulares, cobertoras alares y parte de la región cefálica, mientras que el pico, las patas y los ojos conservaron la coloración característica de la especie, lo que corresponde con leucismo parcial. El ave se encontraba asociada a miles de individuos con plumaje típico y no mostró alteraciones conductuales evidentes durante el periodo de observación. El registro fue documentado mediante observación directa y evidencia fotográfica. Este hallazgo amplía el conocimiento sobre aberraciones cromáticas en aves playeras de la región y constituye el primer caso documentado para la especie en Panamá.

PALABRAS CLAVES. Leucismo, aberraciones cromáticas, aves playeras, chorlos.

ABSTRACT. The first record of leucism in the Wilson's Plover, *Anarhynchus wilsonia*, in Panama is documented. The individual was observed on 28 February 2026 during a shorebird monitoring survey at Playa El Agallito, Chitré, Herrera Province. The specimen showed extensive white areas on the back, scapulars, wing coverts, and part of the head region, while the bill, legs, and eyes retained the characteristic coloration of the species, consistent with partial leucism. The bird was associated with thousands of individuals showing typical plumage and did not exhibit evident behavioral alterations during the observation period. The record was documented through direct observation and photographic evidence. This finding expands the knowledge of chromatic aberrations in shorebirds in the region and constitutes the first documented case for this species in Panama.

KEYWORDS: leucism, chromatic aberrations, shorebirds, plovers.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

INTRODUCCIÓN

Las aberraciones cromáticas en aves incluyen albinismo, leucismo, melanismo y otras variaciones en la pigmentación (van Grouw 2006, 2013). El leucismo se produce por una alteración en la migración o diferenciación de los melanocitos durante el desarrollo embrionario, lo que genera una pérdida parcial o total de pigmentación en el plumaje, mientras que los ojos y otras partes blandas conservan su coloración normal (van Grouw 2013).
Esta condición ha sido documentada en numerosos órdenes de aves alrededor del mundo (Jehl 1985; Guay *et al.* 2012), incluyendo especies acuáticas y costeras (Gross 1965; Ayala-Pérez *et al.* 2013, 2014). En aves playeras (Charadriiformes), los registros son relativamente escasos y, por lo general, corresponden a observaciones aisladas (Ayala-Pérez *et al.* 2013).
El Chorlo de Wilson (*Anarhynchus wilsonia*) es una especie ampliamente distribuida en ambientes costeros arenosos del continente americano. En Panamá está presente en ambas vertientes, con mayor abundancia en el Pacífico, donde utiliza albinas, playas y planicies intermareales. A la fecha, no existen registros publicados de aberraciones cromáticas en esta especie para el país.

OBSERVACIÓN

El 28 de febrero de 2026, a las 14:30 h, durante un monitoreo rutinario de aves playeras en Playa El Agallito, Chitré (8.002222° N, 80.401891° W), se observó un individuo adulto de *A. wilsonia* con plumaje anómalo. El ave se encontraba descansando en la zona intermareal junto a varios miles de individuos, de la misma especie, con plumaje típico.
El ejemplar presentó extensas áreas blancas en el dorso, escapulares y algunas cobertoras alares, así como en parte de la región cefálica. Algunas zonas de la corona, plumas de vuelo primarias conservaron la pigmentación normal. El pico, las patas y los ojos mostraron la coloración característica de la especie, lo que permitió descartar albinismo y confirmar leucismo parcial, de acuerdo con los criterios diagnósticos establecidos por van Grouw (2013). No se observaron alteraciones conductuales evidentes. El individuo mostró comportamiento normal de forrajeo y respuesta ante disturbios. Se obtuvo documentación fotográfica que respalda el registro (Fig. 1).

Figura 1.
Individuo adulto de Anarhynchus wilsonia con leucismo parcial observado en Playa El Agallito, Chitré, provincia de Herrera, Panamá.

DISCUSIÓN

El leucismo ha sido reportado en diversas especies de aves acuáticas y costeras (Jehl 1985; Ayala-Pérez *et al.* 2014; Ramírez-Albores *et al*. 2020), aunque su frecuencia en poblaciones naturales generalmente se considera baja (Guay *et al.* 2012; van Grouw 2013). En aves playeras del orden Charadriiformes, la mayoría de los registros disponibles corresponden a observaciones aisladas en diferentes regiones del continente americano, particularmente en México y Sudamérica (Aráoz *et al*. 2012; Ayala-Pérez *et al.* 2013), lo que sugiere que estas anomalías cromáticas pueden pasar desapercibidas o ser poco documentadas en campo.

El presente registro constituye el primer caso documentado de leucismo en *Anarhynchus wilsonia* para Panamá y amplía el conocimiento sobre aberraciones cromáticas en aves playeras de la región mesoamericana. Aunque las causas del leucismo pueden estar asociadas a factores genéticos, ambientales o a procesos estocásticos durante el desarrollo (van Grouw 2013), la información disponible para poblaciones naturales sigue siendo limitada. En este sentido, el monitoreo continuo de aves costeras podría contribuir a detectar nuevos casos y mejorar la comprensión de la frecuencia y distribución de estas anomalías en poblaciones silvestres.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

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Distribución de los escorpiones (arachnida: scorpiones) según las observaciones de inaturalist en Panamá

Distribution of scorpions (arachnida: scorpiones) according to inaturalist observations in Panama

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ABSTRACT: Scorpions are an important component of Panama's biodiversity, yet their distribution remains poorly documented. This study analyzed their spatial distribution using 384 research-grade records obtained from iNaturalist between 2020 and 2025. A total of 15 species belonging to three families and five genera were identified. *Centruroides bicolor* was the most frequently recorded species, while the provinces of Panamá, Coclé, and Veraguas showed the highest species richness and number of observations. The results highlight the potential of iNaturalist as a complementary tool for studying distribution patterns, identifying knowledge gaps, and guiding future research on Panama's scorpion fauna.

KEYWORDS: Distribution; iNaturalist; Panama; Scorpions.

RESUMEN: Los escorpiones constituyen un grupo importante de la biodiversidad panameña, aunque su distribución aún es poco conocida. Este estudio analizó su distribución espacial en Panamá utilizando 384 registros con grado de investigación obtenidos de iNaturalist entre 2020 y 2025. Se identificaron 15 especies pertenecientes a tres familias y cinco géneros. *Centruroides bicolor* fue la especie más registrada, mientras que Panamá, Coclé y Veraguas concentraron la mayor riqueza y número de observaciones. Los resultados destacan el potencial de iNaturalist como herramienta complementaria para estudiar patrones de distribución, identificar vacíos de información y orientar futuras investigaciones sobre la escorpiofauna panameña.

Palabras Clave: Distribución; Escorpiones; iNaturalist; Panamá.

INTRODUCCIÓN

A nivel global, la diversidad conocida de escorpiones asciende a aproximadamente 2 872 especies (Rein, 2025), distribuidas en 19 familias reconocidas dentro del orden Scorpiones (Santibáñez-López *et al*., 2019). En este contexto, Panamá ha documentado 14 especies, ubicadas en tres familias (Teruel & Cozijn, 2011); sin embargo, este número ha ido incrementándose paulatinamente debido a la descripción de nuevas especies y nuevos registros para el país. Por ejemplo, la descripción de *Centruroides panamensis* por Quintero y Esposito (2014). Pese a estos avances, no existe aún un inventario exhaustivo y actualizado que integre todas las especies descritas o confirmadas después de 2011, lo que subraya la necesidad de una revisión moderna y completa de la escorpiofauna panameña.

iNaturalist es una organización independiente sin fines de lucro fundada en 2008 (Seltzer 2019). La flexibilidad de esta plataforma permite la recopilación y conservación de información científica, tanto como resultado de la conexión entre las personas y la naturaleza, como a través de oportunidades más formales o estructuradas facilitadas por los proyectos de iNaturalist o las anotaciones de observaciones (Mason *et al.*, 2025). Por ende, el presente estudio tiene como objetivo analizar la distribución espacial de las especies de escorpiones registradas en Panamá a partir de las observaciones disponibles en la plataforma iNaturalist. e identificar los patrones de distribución de las especies a nivel nacional, con énfasis en regiones con mayor concentración de observaciones.

MATERIALES Y MÉTODOS

Evaluación de Datos

A partir de la plataforma iNaturalist, se llevó a cabo una búsqueda sistemática de las observaciones de escorpiones registradas en la República de Panamá. Para garantizar la calidad de los datos, únicamente se seleccionaron aquellas observaciones que alcanzaban la categoría de grado de investigación (Research Grade).

Se consideraron los registros comprendidos entre el 1 de enero de 2020 y el 31 de diciembre de 2025. Posteriormente, la información validada, incluyendo especie, coordenadas geográficas y provincia de procedencia, fue organizada en una base de datos estructurada en Microsoft Excel para su posterior análisis espacial.

Análisis de Datos

Los análisis fueron realizados en R (4.4.2v), utilizando los paquetes *dplyr*, *ggplot2*, *sf*, *rnaturalearth* y *rnaturalearthdata*. Se cuantificó el número total de registros, especies, familias y localidades, así como la abundancia relativa de cada especie mediante el porcentaje de observaciones respecto al total. Además, se estimó el número de especies y registros por provincia.

La distribución geográfica de las especies fue representada mediante mapas separados por familia. Finalmente, se evaluó la tendencia temporal de los registros mediante una regresión lineal simple, utilizando el año como variable predictora y el número anual de observaciones como variable respuesta.

RESULTADOS

En los últimos 6 años se registraron 384 observaciones, correspondientes a tres familias, cinco géneros y 15 especies distribuidas en 10 provincias y dos comarcas de la República de Panamá. *Centruroides bicolor* fue la especie más reportada, con 97 registros (25.26%), seguida de *Opisthacanthus elatus* con 64 observaciones (16.67%) y *Centruroides granosus* con 55 registros (14.32%). *Tityus jaimei* aportó 36 observaciones (9.38%), mientras que *Centruroides limbatus* y *Centruroides edwardsii* registraron 30 individuos cada uno (7.81%). *Centruroides gracilis* representó 24 registros (6.25%), y *Tityus cerroazul* alcanzó 20 registros (5.21%). Las especies menos frecuentes fueron *Tityus championi* con 6 registros (1.56%), *Tityus ocelote* 6 registros (1.56%), *Tityus tayrona*, *Chactas exsul* y *Tityus festae* presentaron 4 registros cada una (1.04%), *Ananteris platnicki*, con 3 registros (0.78%) y finalmente *Centruroides margaritatus* un registro (0.26%).

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación
Youngs-Mitre *et al*.,
Vol. 28, No.2, septiembre 2026-febrero 2027, pp.54-59

Tabla 1.

Especies de escorpiones presentes en cada provincia de Panamá.

Provincia	Especie	Observación
Chiriquí	*Centruroides bicolor, Centruroides edwardsii, Centruroides gracilis, Centruroides limbatus, Opisthacanthus elatus, Tityus championi, Tityus tayrona*	82
Veraguas	*Ananteris platnicki, Centruroides bicolor, Centruroides edwardsii, Centruroides gracilis, Centruroides granosus, Centruroides margaritatus, Chactas exsul, Opisthacanthus elatus, Tityus cerroazul, Tityus jaimei, Tityus ocelote*	63
Panamá	*Ananteris platnicki, Centruroides bicolor, Centruroides edwardsii, Centruroides gracilis, Centruroides granosus, Centruroides limbatus, Opisthacanthus elatus, Tityus cerroazul, Tityus festae, Tityus jaimei, Tityus tayrona*	47
Coclé	*Ananteris platnicki, Centruroides edwardsii, Centruroides gracilis, Centruroides granosus, Chactas exsul, Opisthacanthus elatus, Tityus cerroazul, Tityus jaimei, Tityus tayrona*	38
Los Santos	*Centruroides bicolor, Centruroides edwardsii, Centruroides gracilis, Centruroides granosus, Opisthacanthus elatus*	38
Bocas del Toro	*Centruroides limbatus, Opisthacanthus elatus, Tityus jaimei*	30
Colón	*Centruroides bicolor, Centruroides gracilis, Chactas exsul, Opisthacanthus elatus, Tityus cerroazul, Tityus festae, Tityus jaimei, Tityus ocelote*	30
Panamá Oeste	*Centruroides bicolor, Centruroides edwardsii, Centruroides gracilis, Centruroides granosus, Opisthacanthus elatus, Tityus cerroazul, Tityus jaimei, Tityus ocelote*	26
Darién	*Opisthacanthus elatus, Tityus cerroazul, Tityus jaimei*	13
Herrera	*Centruroides bicolor, Centruroides gracilis, Centruroides granosus, Opisthacanthus elatus*	11
Kuna Yala	*Opisthacanthus elatus, Tityus festae*	3
Ngöbe Buglé	*Centruroides bicolor*	3

La distribución geográfica de los escorpiones en Panamá mostró diferencias entre las familias registradas (Figura 1). La familia Buthidae presentó la mayor riqueza específica y la distribución más extensa, con registros distribuidos a lo largo de gran parte del territorio nacional. Dentro de esta familia, las especies del género *Centruroides* concentraron una gran proporción de los registros y estuvieron presentes en múltiples localidades, mientras que varias especies de *Tityus* mostraron distribuciones más restringidas.

Por otra parte, Chactidae estuvo representada únicamente por *Chactas exsul*, cuyos registros se limitaron a pocas localidades, evidenciando una distribución geográfica reducida. De manera similar, Hormuridae estuvo representada exclusivamente por *Opisthacanthus elatus*; sin embargo, esta especie presentó una distribución más amplia que la observada para Chactidae, con registros en diversas regiones del país. En conjunto, los resultados evidencian diferencias en la riqueza específica y amplitud de distribución entre las familias de escorpiones presentes en Panamá.

MESOAMERICANA
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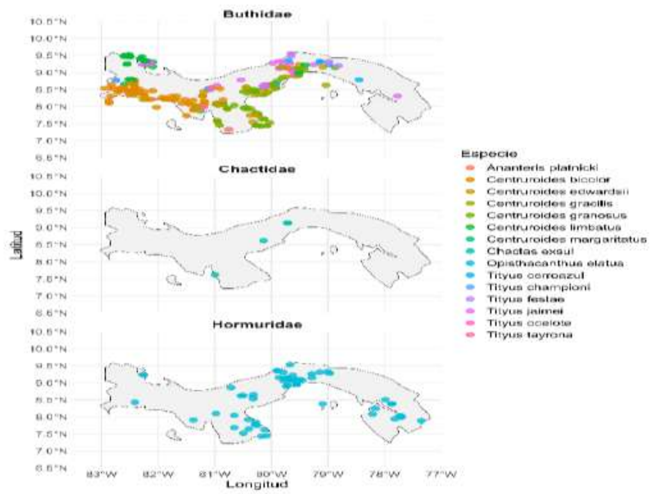
Figura 1.

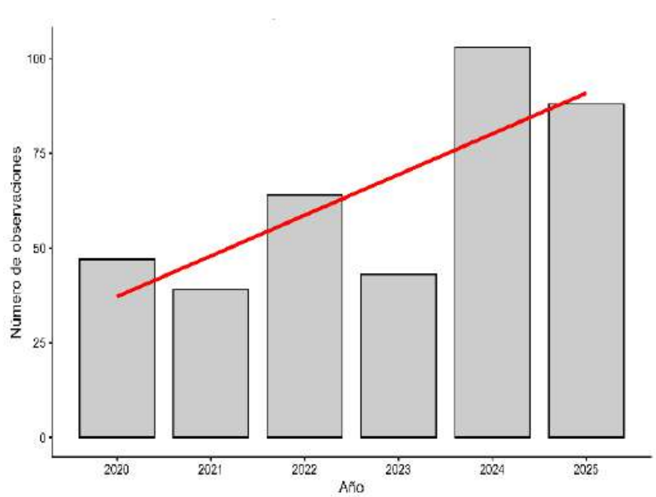
Distribución de escorpiones en Panamá.



El número de observaciones de escorpiones presentó una tendencia creciente a lo largo del período de estudio. El análisis de regresión lineal estimó un incremento promedio de 10.74 registros por año (β = 10.743), explicando el 58.5 % de la variación observada en los datos (R^2 = 0.585). Aunque la relación entre el año y el número de observaciones no alcanzó el umbral convencional de significancia estadística ($F_{1,4}$ = 5.64, p = 0.076), la pendiente positiva sugiere un aumento sostenido en la cantidad de registros a través del tiempo.

Figura 2.

Tendencia temporal de los registros de escorpiones en Panamá.



DISCUSIÓN

La ciencia ciudadana ha emergido como una herramienta valiosa para el monitoreo de la biodiversidad a escalas espaciales y temporales que serían difíciles de alcanzar mediante métodos de muestreo convencionales (Jacobs & Zipf, 2017). Los patrones de distribución observados en este estudio muestran una concentración notable de registros de escorpiones en las provincias del centro de Panamá, particularmente Panamá, Coclé y Veraguas. Este resultado coincide con Youngs-Mitre *et al.* (2025), donde señalan que algunas de las especies del género *Centruroides* y *Tityus* muestran alta plasticidad ante los ambientes urbanos y periurbanos. El predominio de *C. bicolor* y *C. granosus* en los registros es consistente con estudios previos, que indican que estas especies presentan distribuciones amplias y tolerancia a hábitats abiertos y modificados (Quintero & Esposito, 2014).

La concentración de especies en el núcleo central del país también puede estar influenciada por la heterogeneidad ambiental y la presencia de mosaicos de hábitats que combinan áreas urbanas, fragmentos de bosque y zonas agrícolas. Este tipo de paisajes favorece la coexistencia de especies generalistas y especialistas, y ha sido señalado como un factor clave en la persistencia de escorpiones de importancia médica en ambientes modificados (Lourenço & Cloudsley-Thompson, 2012). En particular, la capacidad de algunas especies de *Centruroides* y *Tityus* para tolerar perturbaciones antrópicas podría explicar su amplia distribución y alta frecuencia en los registros analizados.

El menor número de especies registradas en provincias como Guna Yala, Ngöbe Buglé, Darién y Bocas del Toro probablemente no refleja una baja diversidad real de escorpiones, sino más bien un sesgo asociado al esfuerzo de muestreo y a la distribución espacial de los observadores. Estudios previos han demostrado que los datos provenientes de plataformas de ciencia ciudadana tienden a concentrarse en áreas urbanas, periurbanas o con mayor accesibilidad, mientras que regiones remotas o con menor densidad poblacional suelen estar subrepresentadas (Boakes *et al.,* 2010; Isaac *et al.,* 2014; Chandler *et al.,* 2017). En Panamá, estas provincias coinciden con zonas de difícil acceso, menor infraestructura vial y menor número de usuarios activos en iNaturalist, lo que limita la probabilidad de detección y registro de escorpiones, independientemente de su presencia real.

A pesar de sus limitaciones, los datos de iNaturalist representan una herramienta valiosa para generar hipótesis biogeográficas, identificar vacíos de información y orientar futuros muestreos sistemáticos. Diversos estudios han demostrado que, cuando se filtran adecuadamente por calidad taxonómica, los registros de ciencia ciudadana pueden complementar de manera efectiva los inventarios tradicionales y contribuir a la comprensión de patrones espaciales a escalas regionales (Chandler *et al.,* 2017; Callaghan *et al.,* 2021). En el caso de los escorpiones de Panamá, el uso de iNaturalist permite visualizar tendencias preliminares de distribución y resaltar regiones prioritarias para estudios de campo, especialmente aquellas con baja representación en la plataforma.

CONCLUSIÓN

El presente estudio demuestra que los registros de ciencia ciudadana disponibles en la plataforma iNaturalist constituyen una herramienta valiosa para caracterizar preliminarmente la distribución de los escorpiones en Panamá. A partir de 384 observaciones con grado de investigación se documentó la presencia de 15 especies pertenecientes a tres familias, evidenciándose una mayor riqueza y concentración de registros en las provincias centrales del país. Las especies del género *Centruroides*, particularmente *C. bicolor*, *C. gracilis* y *C. granosus*, presentaron una distribución amplia y una alta frecuencia de observaciones, lo que sugiere una mayor capacidad para persistir en ambientes intervenidos y una elevada detectabilidad en zonas urbanas y periurbanas.

La menor representación de registros en provincias como Guna Yala, Ngöbe Buglé, Darién y Bocas del Toro probablemente refleja diferencias en el esfuerzo de muestreo y en la distribución de los observadores, más que una menor diversidad real de escorpiones. Este resultado resalta la necesidad de fortalecer los inventarios biológicos y los muestreos sistemáticos en regiones poco exploradas, con el fin de obtener un conocimiento más completo de la escorpiofauna panameña.

En conjunto, los resultados evidencian el potencial de iNaturalist como una fuente de información complementaria para el monitoreo de la biodiversidad, la identificación de vacíos de información y la generación de hipótesis sobre los patrones de distribución de las especies. La integración de registros de ciencia ciudadana con estudios de campo, revisiones taxonómicas y colecciones biológicas permitirá construir un inventario más robusto y actualizado de los escorpiones de Panamá, proporcionando información de utilidad para futuras investigaciones ecológicas, biogeográficas, taxonómicas y de importancia médica.

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MESOAMERICANA
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Voices of the sea: community perspectives on indigenous languages, ecological knowledge, and mangrove conservation education

Voces del mar: perspectivas comunitarias sobre las lenguas indígenas, el conocimiento ecológico y la educación para la conservación de los manglares

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Contribución del autor: Los autores de este trabajo declaran haber participado en la realización de este proyecto de investigación en todas sus etapas, trabajo de campo, la identificación, así como la discusión y el análisis de datos.

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ABSTRACT. This paper explores how community-authored multilingual ethnotestimonials serve as both cultural documentation and pedagogical intervention in the context of mangrove conservation education. Drawing from eight seafaring cultures, including Wayuu, Yucatec Maya, Mopán Maya, Q'eqchi' Maya, Garifuna, Miskitu, Ulwa, Burmese, Bahasa and Belizean Kriol, I analyze a series of reflective Introductions to conservation textbooks written in Indigenous languages and translated into either English or Spanish. These ethnotestimonials reveal how language, place, and ecological knowledge are intertwined in the lived experiences of coastal communities, and how these connections can inform more inclusive and effective conservation education. I propose that these ethnotestimonials are not only vehicles of memory and identity but also instruments for hybridizing ecological knowledge systems and operationalizing decolonial science education. This work supports the foundation for the first author's previously published frameworks on the *Ethnotranslation Model* and the *Hybridization Hypothesis of Ecological Knowledge Systems*, and informed the development of a related Maya-language master's thesis project, which found that culturally resonant, mother-tongue instruction improved both science learning and cultural identity among students.

KEYWORDS: Mangrove conservation; Indigenous knowledge; Multilingual education; Environmental education; Science education; Language revitalization; Biocultural education; Ethnotranslation; STEM.

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RESUMEN. Este artículo explora la función de los etnotestimonios multilingües, creados por las propias comunidades, como herramientas de registro cultural y como estrategias pedagógicas enfocadas en la enseñanza de la preservación de los manglares. A partir de ocho culturas marineras, incluyendo wayuu, maya yucateco, maya mopán, maya q'eqchi', garífuna, miskitu, ulwa, birmano, bahasa y criollo beliceño, analizo una serie de introducciones reflexivas a libros de texto sobre conservación, escritas en lenguas indígenas y traducidas al inglés o al español. Estos etnotestimonios revelan cómo la lengua, el lugar y el conocimiento ecológico se entrelazan en las experiencias de las comunidades costeras, y cómo estas conexiones pueden fundamentar una educación para la conservación más inclusiva y eficaz. Propongo que estos etnotestimonios no son solo vehículos de memoria e identidad, sino también instrumentos para hibridar los sistemas de conocimiento ecológico y para poner en práctica la educación científica descolonial. Este trabajo refuerza los marcos teóricos previamente establecidos por el autor primero sobre el *Modelo de Etnotraducción* y la *Hipótesis de la Hibridación de los Sistemas de Conocimiento Ecológico*. De igual manera, contribuyó a un proyecto de maestría en lengua maya, donde se halló que enseñar en la lengua materna, adaptándose a la cultura local, mejora positivamente la adquisición de conocimientos científicos y la identidad de los estudiantes.

PALABRAS CLAVES: Conservación de manglares; Conocimiento indígena; Educación multilingüe; Educación ambiental; Educación científica; Revitalización lingüística; Educación biocultural; Etnotraducción; STEM.

Introduction

For millennia, Indigenous and Creole communities have maintained reciprocal relationships with the environments they inhabit, viewing landscapes and ecosystems not only as ecological resources but also as cultural and spiritual homelands (Berkes, 2018; Cajete, 2000; Kimmerer, 2013). Yet the dual forces of environmental degradation and linguistic marginalization now threaten these relationships. Formal education systems, often delivered in dominant languages, contribute to cultural disorientation[1] and the erosion of ecological knowledge systems by disrupting the intergenerational transmission of language, identity, and place-based knowledge systems (Aikenhead & Jegede, 1999; Battiste, 2013; Harmon & Maffi, 2002; Maffi, 2005). This paper centers multilingual, community-authored ethnotestimonials that were written as Introductions to mangrove conservation textbooks in nine languages. Rather than being centrally curated, each contribution emerged from an open-ended prompt: "What would you like to say about this book and this project?[2]" In each case, the book referred to the newly created mangrove conservation text written in the contributor's home language. The project encompassed a broader Marine Conservation without Borders (MCB) led initiative to advance ocean literacy and ecosystem conservation through multilingual, biocultural education. These books were first mentioned in Thigpen (2025).

Hilario Poot Cahun's master's thesis later served as a key conceptual bridge between this mangrove prototype phase and the development of the Maya-language STEM Plus textbooks. While his research is not the focus of this paper, his classroom trials provided empirical validation for several design principles first tested through the ethnotestimonials and the mangrove prototypes, demonstrating how insights from this phase could be translated into sustained, culturally grounded science education for Indigenous primary schools in the same ecoregion.

From Regional Prototypes to Maya Classrooms

An often-overlooked aspect of the Maya STEM Plus project is that the educational content evaluated during the pilot was not originally developed for Maya-speaking students in Quintana Roo. Rather, the materials emerged from a much longer process of experimentation involving conservation practitioners, scientists, Indigenous educators, fishers, and community collaborators throughout the greater Caribbean Basin and Mesoamerica. The project's multinational and multilingual developmental history has at times been obscured when viewed primarily through the lens of a single educational setting, language community, or disciplinary framework.

[1] In this paper, *Cultural Disorientation* is defined as the loss or weakening of the cultural, linguistic, and ecological reference points through which individuals and communities understand their place in the world. It often accompanies language shift, environmental degradation, and educational systems that marginalize local knowledge traditions, resulting in the erosion of biocultural identity and ecological stewardship. Unlike earlier uses of the term, which primarily describe difficulties associated with cross-cultural encounters, the present definition conceptualizes cultural disorientation as a consequence of language shift, environmental degradation, and the marginalization of local knowledge systems.

[2] The prompt was intentionally broad. Rather than soliciting responses about predefined themes, contributors were invited to determine the content and direction of their own testimonials. This approach is consistent with *Relational Learning* (Thigpen, 2026) and Indigenous dialogic traditions such as *Tsikbal* (Castillo Cocom et al., 2015) which emphasize participant agency and reciprocal knowledge exchange rather than researcher-directed extraction. (Poot Cahun, 2025)

Discussions concerning a second phase of development began during October and November 2019. During this period, prototype mangrove conservation materials were shared directly with linguistic and community stakeholders in Belize, México, Guatemala, Honduras, and Panamá. These face-to-face meetings provided opportunities to distribute materials in their respective languages, discuss future adaptations, and explore potential classroom pilots and community-based implementation strategies. The long-term vision already included expansion into Indigenous and Creole linguistic communities throughout the region, including Maya-speaking communities in México. At the time, however, Belize and Honduras appeared to be the most likely locations for the next phase of implementation due to the strength of existing partnerships and the coastal focus of the mangrove, fisheries, and marine conservation materials. Although discussions were underway in multiple countries, it was anticipated that Phase 2 would likely begin in one of these two nations.

These plans were interrupted by the emergence of the COVID-19 pandemic in early 2020, which brought border closures, travel restrictions, and delays to community-based educational initiatives throughout the region. As the pandemic unfolded, opportunities for in-person educational implementation became increasingly limited. During this period, the project temporarily expanded beyond conservation education to include multilingual COVID-19 community health materials. Working with Indigenous, Creole, and minority-language communities representing approximately fifteen languages, the first author developed culturally and linguistically adapted community health materials that provided an additional environment in which emerging *Ethnotranslation* methods continued to evolve.

Many of the multilingual conservation education and community health materials developed during this period, together with related educational resources produced through the Marine Conservation without Borders (MCB) research program, have since been archived in the Marine Conservation without Borders Collection at the Archive of the Indigenous Languages of Latin America (AILLA) (Archive of the Indigenous Languages of Latin America, n.d.), where they are freely available for download by educators, researchers, students, and community members.

As opportunities for implementation gradually re-emerged, collaborations with Maya educators, Indigenous primary schools, the *Universidad Intercultural Maya de Quintana Roo* (UIMQROO), and the *Secretaría de Educación de Quintana Roo* (SEQ) created an unexpected beginning for the next phase of the project. Rather than commencing in Belize or Honduras as originally anticipated, large-scale implementation first emerged in Maya-speaking communities of Quintana Roo. Although the starting point differed from earlier expectations, the broader trajectory remained unchanged: the development of multilingual, biocultural educational materials capable of supporting language revitalization, ecological literacy, and conservation across diverse linguistic communities.

Consequently, the Maya project became the first large-scale educational implementation of a framework that had already undergone years of conceptual development, multilingual experimentation, and iterative refinement across multiple countries and linguistic communities.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

This history is important because it demonstrates that the materials evaluated by Poot Cahun (2025) were not locally produced content created specifically for a single educational context. Instead, they represented a synthesis of scientific knowledge, conservation experiences, linguistic innovations, and pedagogical strategies originating from diverse ecological, cultural and epistemic settings. Chapters authored by taxonomists, fisheries scientists, primatologists, ornithologists, marine conservationists, and Indigenous educators were adapted (ethnotranslated) into a common Maya-language epistemological framework. In many cases, the species, examples, and narratives were modified substantially during this process. Some chapters were rewritten around species more relevant to Maya students, while others were linguistically and culturally recontextualized through the *Ethnotranslation Model* and community review. (Thigpen, 2025, Thigpen, 2026)

Viewed in this light, the significance of the Maya pilot extends beyond the evaluation of individual educational materials. The project effectively tested whether scientific knowledge developed across multiple countries, disciplines, ecosystems, and cultural contexts could be successfully integrated into a coherent Indigenous-language educational system. The positive outcomes reported by Poot Cahun (2025) therefore suggest not merely the effectiveness of particular lessons, but the viability of an educational framework capable of interoperating across diverse knowledge traditions, scientific disciplines, and regional contexts.

While Poot Cahun's (2025) research is not the focus of this paper, his classroom trials provided empirical validation for several design principles first tested through the ethnotestimonials and mangrove prototypes, demonstrating how insights from this phase could be translated into sustained, culturally grounded science education for Indigenous primary schools in the same ecoregion.

Each mangrove prototype examined in this study was developed under the editorial and scientific direction of the first author and further developed in Tegucigalpa, Honduras with Grazzia Matomoros Erazo and José Antonio Romero Durón, and ethnotranslated by a respected knowledge keeper and cultural protector from the corresponding linguistic community. These Indigenous and Creole ethnotranslators were recognized on the cover as coauthors and were also cited as coauthors in academic references to the texts, granting full credit for their linguistic and ecological expertise (Thigpen, 2026). The Indigenous and Creole coauthors, linguistic communities, and community affiliations represented in this phase of the project are summarized in **Table 5.**

One guiding instruction given to each local coauthor [ethnotranslator] was to forget conventional translation methods and to simply "make it work", to render scientific ideas in ways that resonated with local knowledge systems, cultural values, and, where appropriate, community cosmologies. This liberated the process from the constraints of Western translation methodologies, especially those ill-suited for converting biological concepts into historically oral languages. Additionally, this gave the first author the opportunity to observe how each collaborator would interpret the instruction to ignore convention and just make it work. Each contributor approached the task differently, some created neologisms, others used transliteration for scientific terms, and all applied their deep community-specific insight. This diversity of approaches became a valuable source of learning. The first author was able to identify what worked best by listening to and learning from their Indigenous and Creole coauthors and collaborators.

These early experiments directly informed the next stage of curriculum development for the Maya project. The development of the early Maya-language textbooks followed an intentionally iterative design process in which multiple pedagogical, linguistic, and curricular strategies were treated as working hypotheses and evaluated through practice. Some approaches proved effective and were retained, while others were modified or abandoned as new observations accumulated. The textbooks that ultimately emerged therefore reflect not a predetermined model, but a process of continual experimentation, assessment, and refinement.

To preserve the integrity of concurrent classroom-based evaluation (Poot Cahun, 2025), these design decisions were not disclosed during the active research phase. This allowed for independent assessment of how students and teachers engaged with the materials, free from influence by ongoing methodological refinement. While early versions of the textbooks functioned as effective prototypes of biocultural education, subsequent iterations led to a more streamlined and replicable set of design principles grounded in community insight and pedagogical performance.

These two Maya-language textbooks served both as a formal data source for Hilario Poot Cahun's master's thesis and as a testbed for integrating and stress-testing methods derived from these earlier multilingual mangrove prototypes (Thigpen and Poot Cahun 2022, Poot Cahun and Thigpen 2023) derived from these earlier multilingual mangrove prototypes. The first author conducted informal, unstructured conversations with Maya university research assistants and professors at *la Universidad Intercultural Maya de Quintana Roo* (UIMQROO), teachers from the *Departamento de Educación Indígena de los Servicios Educativos de Quintana Roo* (SEQ), and the family members of Indigenous primary school students throughout the two-year trial. These discussions revealed how the materials were received and which elements resonated or did not. However, to protect the thesis's integrity, many of these reflections were not shared with Hilario or other participants during the active research phase. The aim was to quietly observe how well previously successful techniques such as ethnobiological metaphors, community-driven translation, and visual-linguistic alignment performed when brought together into a single, structured classroom setting.

The multilingual adaptations presented here highlight multiple, layered processes. *Ecological Translanguaging* appears as a pedagogical strategy within texts that blend local and dominant languages for clarity or rhetorical effect. *Ethnotranslation* refers more broadly to the act of re-articulating scientific content through culturally grounded narrative forms. These processes often give rise to hybridized texts where distinct ecological knowledge systems remain visible but interdependent. Together, they contribute to a pluriversal approach to science education, in which no single worldview is privileged, and multiple epistemologies are permitted to coexist in generative tension. (Thigpen, 2025; Thigpen, 2026)

These texts offer a rare polyphonic reflection on conservation, language, and education. Written by elders, teachers, and community leaders, they ground the mangrove prototypes in the lived experience and moral authority of each community. I argue that the ethnotestimonials and methods learned here are more than introductory texts: they represent an emergent methodology for re-centering voice, place, and language in science education.

While related to traditions of testimonial literature and participatory narrative, ethnotestimonials differ in that they are embedded within scientific and educational materials and function simultaneously as narrative, data, and methodological intervention. Unlike conventional testimonials, which are often retrospective accounts of lived experience, ethnotestimonials are forward-facing and actively shape how knowledge is structured, taught, and transmitted within multilingual educational contexts.

This paper asks: What are the pedagogical and epistemological implications of allowing Indigenous and Creole communities to author their own multilingual environmental science materials? How do these ethnolinguistic adaptations reshape not only language but the structure and purpose of science education?"

As this paper will show, each version of the mangrove prototype is not merely a translation, but a cultural re-articulation of ecological education. The adaptations from poetic testimony in the Wayuu edition to the ecological translanguaging of the Belizean Kriol version demonstrate how multilingual, community-led co-authorship can shape not just the language of science education, but its structure, tone, and pedagogical function.

This re-articulation of science education through community-led, multilingual design laid the groundwork for two subsequent manuscripts: the *Hybridization Hypothesis of Ecological Knowledge Systems* (Thigpen 2025), and *Ethnotranslation and Biocultural Education: Bridging Indigenous Knowledge and STEM Curricula (Thigpen, 2026)*. These subsequent works formalize concepts and methods that emerged inductively from the empirical and collaborative processes documented in this study. The *Hybridization Framework* emerged from early insights documented here regarding how culturally distinct ecological knowledge systems, Indigenous or Creole ecological epistemologies and Western ecological science can coexist without subsumption in educational materials. Likewise, the *Ethnotranslation Model* formalizes the methodological processes first developed during the creation of the multilingual mangrove prototypes presented here, offering a replicable approach to preserving linguistic and cultural integrity while maintaining scientific coherence. Together, these works build directly upon the field practices and collaborative strategies initiated during the mangrove prototype phase of the STEM Plus project.

The polylingual mangrove prototypes documented here served as the empirical foundation for the subsequent development of the *Ethnotranslation Model* (Thigpen, 2026) and contributed to the observations that later informed the *Hybridization Hypothesis of Ecological Knowledge Systems* (Thigpen, 2025). These methods were subsequently applied in the development and pilot testing of MCB's Maya-language STEM Plus curricula in Quintana Roo, Mexico, where Poot Cahun (2025) documented positive outcomes related to linguistic and cultural identity, environmental learning, and community engagement. Together, these works represent successive stages in the evolution of a broader biocultural educational framework, progressing from multilingual prototype development, to methodological formalization, to theoretical articulation, and

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

finally to classroom-based evaluation.

Contribution Statement

This paper makes three primary contributions. First, it introduces *ethnotestimonials* as a distinct form of community-authored scientific discourse that integrates narrative, ecological knowledge, and linguistic expression. Second, it demonstrates how these texts function as sites of epistemological production, where Indigenous and Creole knowledge systems are not merely represented but actively shape the structure and meaning of ecological education. Third, it establishes that multilingual, community-authored curriculum development can serve as a generative methodological space, producing insights that informed the subsequent development of the *Ethnotranslation Model* and the *Hybridization Hypothesis of Ecological Knowledge Systems*. In this sense, the present study represents the empirical and narrative foundation from which these later theoretical frameworks emerged.

Throughout this paper, the term multilingual is used to describe the educational materials and collaborations under discussion. However, the processes documented here extend beyond the production of educational materials in multiple languages. Knowledge moved among linguistic communities through iterative cycles of co-development, ethnotranslation, validation, adaptation, and reuse. In this sense, the project may be more accurately understood as an emerging example of a *Polylingual Education*[3] *Model*, in which knowledge is co-developed, translated, validated, adapted, and transmitted across multiple linguistic communities, with each linguistic community and its language serving not merely as a vehicle of instruction but also as a site of knowledge generation (Thigpen 2026).

Methods

This study employs qualitative discourse analysis on a corpus of multilingual Introductions to prototype mangrove conservation texts produced through a participatory curriculum development process led by Marine Conservation without Borders. Contributions were collected from speakers of Wayuu (Colombia/Venezuela), Maya Yucatec (Belize, México), Maya Mopán, and Q'eqchi' Maya (Belize / Guatemala), Kriol (Belize), Miskitu and Ulwa (Nicaragua / Honduras), Garifuna (Belize / Guatemala / Honduras / St. Vincent Nicaragua), Burmese (Myanmar) and Bahasa (Indonesia). The linguistic communities, geographic origins, and developmental lineage of these prototype adaptations are summarized in **Table 1**, while the Indigenous and Creole coauthors who participated in their development are identified in **Table 5**.

Relational learning as methodological foundation

In addition to qualitative discourse analysis, this study is grounded in a *Relational Learning* orientation as articulated within the *Ethnotranslation Model* (Thigpen, 2026). *Relational Learning* refers to methodological insight generated through sustained, trust-based engagement with a core group of Indigenous and Creole collaborators during the early mangrove prototype phase, including Belizean Kriol, Maya, Garifuna, and Mestizo fisher folk whose livelihoods are directly embedded in mangrove and littoral ecosystems. These long-term interactions

[3] *Polylingual Education* refers to educational systems in which knowledge is co-developed, ethnotranslated, validated, adapted, and transmitted across multiple linguistic communities, with each linguistic community and its language serving not merely as a vehicle of instruction but also as a site of knowledge generation.

informed transferable design principles related to narrative structure, metaphor use, visual / linguistic alignment; and epistemological and pedagogical framing.

Following this foundational phase, additional linguistic groups were invited to ethnotranslate the mangrove prototypes using methods derived from earlier *Relational Learning*. While extended engagement with these later collaborators was intended, funding constraints limited the depth of interaction. Nonetheless, the relationally derived methods proved effective across diverse ecoregions, species ranges, and coexisting linguistic communities, demonstrating the methodological portability of the *Ethnotranslation Model* (Thigpen, 2026) and aligning with the cross-contextual dynamics described in the *Hybridization Hypothesis of Ecological Knowledge Systems* (Thigpen, 2025).

The analysis followed an inductive thematic approach, whereby codes and themes were developed iteratively from the data rather than being imposed a priori. *Ethnotestimonials* were treated as units of analysis and examined for recurring patterns in narrative structure, metaphor use, expressions of ecological relationships, and positioning of language within knowledge generation and transmission. Cross-linguistic comparison focused on identifying both convergent themes and culturally specific divergences across the nine linguistic communities. Particular attention was given to how ecological concepts were framed, how authority was constructed within the text, and how relationships between humans and mangrove ecosystems were articulated. These patterns were then interpreted in relation to broader questions of epistemology, pedagogy, and multilingual curriculum design.

While the Belizean Kriol edition did not contain an Introduction in the style of the other prototypes, it included a Dedication that reflected the voice and intent of its community coauthors. Although structurally different, this Dedication conveyed cultural, ecological, and pedagogical perspectives consistent with the goals of the project. For the purposes of this study, we examined and compared the content of this Kriol mangrove prototype Dedication alongside the Introductions and content from the other editions, noting both its unique form and its thematic resonance with the broader corpus.

In addition to the qualitative discourse analysis and *Relational Learning* presented here (Thigpen, 2026), this study is further grounded by the complementary research of Hilario Poot Cahun (2025), whose master's thesis incorporated both quantitative and ethnographic methods.

Poot Cahun's fieldwork was conducted within a broader collaborative research program established through a tripartite partnership among Marine Conservation without Borders (MCB), the *Universidad Intercultural Maya de Quintana Roo* (UIMQROO), and the *Departamento de Educación Indígena of Servicios Educativos de Quintana Roo* (SEQ) (MCB & UIMQROO, 2024; MCB & SEQ, 2022). The research operated within a formal institutional governance framework established through separate research agreements between MCB and UIMQROO and between MCB and SEQ. Together, these agreements defined the governance structure, institutional responsibilities, and procedures governing project implementation. The SEQ–MCB agreement was executed on behalf of SEQ by Mtra. Ana Isabel Vázquez Jiménez, Director General of SEQ, and Dra. Luz María Abuxapqui González, *Coordinadora General de Educación Básica*.

As the governmental educational authority, SEQ authorized research activities in the participating Indigenous primary schools, while project implementation and site access were coordinated through MCB as the designated implementing entity in accordance with the SEQ–MCB agreement (MCB & SEQ, 2022; MCB & UIMQROO, 2022).

Under the direction of Robert C. Thigpen III as project leader (Poot Cahun, 2025; SEQ, 2022), MCB served as the coordinating and implementing organization responsible for curriculum development, project coordination, implementation management, and oversight of the broader research environment, while UIMQROO and SEQ provided academic, institutional, and educational support. In addition to reviewing the educational materials, SEQ required that proposed Maya-language terminology and neologisms be evaluated by its Maya Commission, composed of Indigenous educators, school administrators, supervisors, and pedagogical advisors affiliated with the Department of Indigenous Education, prior to classroom implementation. Both the pilot and final versions of the educational materials were subject to this review process (MCB & SEQ, 2022), providing an additional layer of linguistic, cultural, and educational validation beyond the curriculum development team itself. The broader partnership framework and implementation structure are also documented in Poot Cahun's (2025) thesis, which describes the collaboration among the partner organizations; MCB, UIMQROO, and SEQ throughout the development and pilot testing of the Maya-language STEM Plus materials.

The MCB implementation framework was intentionally designed to support multiple downstream research projects, student researchers, institutional collaborations, and educational initiatives operating within a common governance and implementation environment.

School selection was carried out by SEQ following the establishment of the tripartite research framework. As project leader, Robert C. Thigpen III established a limited set of project requirements to guide school selection, including minimum and maximum student enrollment thresholds necessary to support meaningful statistical analyses and project logistics, together with the inclusion of both inland and coastal communities. SEQ retained responsibility for the final selection of participating schools. During project planning, the possibility of selecting schools with exceptionally strong Maya-language literacy was considered; however, the project leader recommended against this approach in favor of a more heterogeneous sample. The objective was to approximate, as closely as practical within the constraints of an applied educational intervention, a sample that reflected the diversity of Indigenous primary schools rather than one intentionally biased toward the strongest Maya-language settings.

Beyond the general selection parameters established during project planning, the specific weighting of factors used by SEQ in selecting participating schools was not disclosed to the project leader. Nevertheless, the resulting sample included schools that differed substantially in geographic location, community characteristics, student enrollment, and levels of Maya-language use. Although several communities within the Maya Zone are recognized for substantially stronger Maya-language vitality than some of the participating schools, the final sample was not restricted to those settings. This indicates that maximizing Maya-language use was not the sole consideration in school selection and resulted in a more

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

heterogeneous sample than would have been obtained through purposive selection of only the strongest Maya-speaking communities. Consequently, the educational materials were evaluated across a broader range of sociolinguistic and educational contexts, improving the representativeness of the pilot and increasing the potential applicability of the findings to Indigenous primary schools throughout the region.

While this paper offers an accessible read, it performs significant conceptual and methodological groundwork. It addresses a series of interrelated hypotheses concerning knowledge portability, ecological interoperability, linguistic knowledge generation, multilingual curriculum design, and community coauthorship. Together, these ideas contributed to the expansion of the project's curricular framework, enabling the development of multilingual educational materials that integrate aquatic, marine, and terrestrial ecological knowledge systems across international, cultural, linguistic, and disciplinary boundaries.

H-1. Community-authored, multilingual ethnotestimonials function as one mechanism through which the *Hybridization of Ecological Knowledge Systems* occurs, integrating place-based ecological knowledge, cultural memory, and scientific understandings of mangrove ecosystems within a shared educational framework, while structural and stylistic divergences serve as expressions of curriculum sovereignty, cultural relevance, ecological continuity, and methodological portability.

H-2. Ecological Curriculum Portability Hypothesis: Ecological and conservation knowledge organized around a shared ecological curriculum core can be successfully rearticulated through ethnotranslation across multiple linguistic communities that share ecological systems, species assemblages, ecological processes, and conservation challenges, without requiring the development of entirely separate ecological curricula for each language group.

Research Questions:

1. **Cultural, Epistemic and Pedagogical Function:**
   How do community-authored, multilingual ethnotestimonials function simultaneously as cultural documentation, pedagogical tools, and epistemic resources in mangrove conservation education?
2. **Language, Place, and Ecological Knowledge:**
   What insights do these ethnotestimonials offer into the relationships among language, place, and ecological knowledge in seafaring Indigenous and Creole communities?
3. **Hybridization and Decolonial Education:**
   In what ways can these multilingual ethnotestimonials contribute to the *Hybridization of Ecological Knowledge Systems* and support decolonial frameworks in science education?
4. **Ethnotranslation as Methodological Reframing:**
   How does the *Ethnotranslation Model*, as practiced by Indigenous and Creole coauthors, challenge and reframe conventional approaches to translation in science curricula?
5. **Linguistic and Cultural Divergence Across Editions:**
   What structural, linguistic, and cultural distinctions emerge across the localized editions of mangrove conservation texts, and how do these affect their pedagogical function?
6. **Scalability, Portability and Curriculum Design:**

How can the insights gained from these ethnotestimonials and prototype texts inform the development of scalable, portable, culturally resonant, and linguistically inclusive STEM Plus curricula?

Belize, Panamá, Guyana, and Suriname may represent ideal proof-of-concept environments because each contains a relatively small number of major linguistic communities distributed across shared ecological systems. In principle, a common ecological curriculum could be adapted through the *Ethnotranslation Model* for every major linguistic group within a country, allowing researchers to evaluate whether multilingual conservation education can achieve national-scale coverage without requiring the development of entirely separate ecological curricula for each language community.

Each Introductions contributor was asked by their community's ethnotranslator to reflect on the role of language, the importance of mangroves, and the goals of multilingual education. They were to share exactly what they thought of their book and the project. Translations into English and / or Spanish accompanied the originals. Themes were identified inductively, with attention to metaphors, affective language, and conceptual linkages among land, sea, and language.

The multilingual mangrove prototypes developed for this project were designed not as final products, but as pedagogical and methodological learning tools, as were MCB's 4th and 5th grade Maya-language STEM Plus prototypes (Thigpen & Poot Cahun 2022; Poot Cahun, & Thigpen 2023) later used in Poot Cahun's (2025) master's thesis. Each prototype enabled the project leader to experiment with how ecological concepts, narrative tone, visual structure, and linguistic adaptation functioned across distinct cultural and linguistic contexts. The goal was to determine not only what scientific and ecological concepts should be communicated, but also how they could be communicated most effectively within different communities and knowledge traditions.

The broader goal the first author was not simply to create multilingual conservation education materials, but to create educational experiences that "*speak to the heart and teach the mind*." Recent scholarship has likewise emphasized that language revitalization efforts should strengthen not only Indigenous languages themselves but also the social prestige and educational opportunities of their speakers (Sima Lozano et al., 2014). The prototypes were therefore designed to communicate scientific concepts in ways that remained culturally meaningful, emotionally resonant, and relevant to contemporary environmental challenges (Thigpen, 2026). This approach reflects an effort to develop educational materials capable of engaging both the intellectual and emotional dimensions of learning while connecting language, identity, culture, and ecology. In this sense, the project sought not only to transmit information, but also to cultivate stewardship, strengthen linguistic and cultural continuity, and create pathways through which communities could carry both their knowledge and their languages into the future. Ultimately, the goal was to help ensure that Indigenous and local languages remained not only languages of memory and heritage, but also languages of learning, problem-solving, innovation, and hope (Cru, 2016).

Insights gained through these early experiments informed the development of the 4th and 5th grade STEM Plus textbooks, co-developed for Indigenous primary schools in the Maya Zone of Quintana Roo, México,

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

and later used in three university classrooms in México and Belize.

These Maya-language prototype textbooks served not as endpoints, but as a second-generation testbed where lessons derived from the multilingual mangrove prototypes could be combined, refined, and intentionally stress-tested within formal educational settings. Later evaluated in situ through Poot Cahun's (2025) master's thesis research, these materials provided an opportunity to assess which approaches remained effective when integrated into a structured classroom environment. Together, the mangrove prototypes, the COVID-19 community health materials, and the Maya STEM Plus textbooks laid the empirical and methodological foundation for the concepts and approaches later formalized in the *Hybridization Hypothesis of Ecological Knowledge Systems* (Thigpen, 2025) and the *Ethnotranslation Model* (Thigpen, 2026).

The scientific content used in both the 4th and 5th grade books was developed under the author's editorial supervision by biologists primarily from the Global South as part of the *Ethnotranslation Process* which was still being developed (Thigpen & Poot Cahun 2022; & Poot Cahun & Thigpen 2023). Each contributor worked with aquatic, marine or terrestrial species they actively studied in their home countries, ensuring ecological and taxonomic accuracy from the perspective of practicing conservation scientists who worked with and respected Creole and Indigenous communities. These collaborators were not from the Yucatán Peninsula or from Maya communities. They did not attempt to frame their material through Maya cultural lenses. Instead, their role was to provide clear and accessible scientific foundations described in the *Ethnotranslation Frameworks* and emphasizing *biocultural constants* (Thigpen, 2025; Thigpen, 2026). The final steps of ethnotranslation, adapting these materials linguistically, epistemologically and pedagogically for Maya primary school students were carried out by Hilario Poot Cahun, a maya educator, whose expertise ensured that each chapter became not only comprehensible in Yucatec Maya but resonant with local epistemologies and classroom realities.

Knowledge Provenance and Chapter Origins

The Maya-language STEM Plus textbooks were not developed from a single research project, institution, disciplinary tradition, or geographic region. Rather, they assembled scientific content contributed by researchers, conservation practitioners, Indigenous educators, and community knowledge keepers working within the same ecoregions or species ranges. The geographic, disciplinary, and linguistic provenance of these materials is summarized in Table 4. Importantly, none of the content was originally developed for Maya-speaking students in Quintana Roo. At the time these materials were being created, the next phase of implementation was expected to begin in either Belize or Honduras, where many of the original Indigenous, Kriol and governmental partnerships had been established and where the coastal focus of the mangrove and fisheries materials was most immediately applicable. Expansion into Maya-speaking communities was always part of the broader regional vision, but the COVID-19[4] pandemic altered the project's developmental pathway. As opportunities for

[4] Concerns about introducing COVID-19 into partner communities influenced implementation timelines. The author participated in the AstraZeneca COVID-19 vaccine trial and was assigned to the treatment group prior to resuming field-based activities.

implementation re-emerged, collaborations with Maya educators, Indigenous primary schools, UIMQROO, and SEQ created an unexpected beginning for the next phase of the project, resulting in the first large-scale implementation occurring in Maya-language schools in Quintana Roo.

The resulting textbooks therefore represent a convergence of multiple knowledge networks whose original audiences often differed substantially from the Maya primary school students who later participated in the pilot. The 4th grade volume incorporated contributions from researchers working on mangroves, primates, sea turtles, manatees, invasive species, birds, wetlands, and coastal ecosystems. The scientific contributors, knowledge origins, and conservation contexts represented in the 4th-grade textbook are summarized in **Table 2**. The 5th grade volume expanded this network further by incorporating content derived from systematic biology, fisheries science, invasive species management, ornithology, coral reef conservation, and Maya language education. The geographic origins, conservation contexts, and linguistic pathways associated with the 5th-grade textbook are summarized in Table 3.

Contributors included scientists from institutions such as the Smithsonian National Museum of Natural History, Sirenian International, The Gulf and Caribbean Fisheries Institute, ECOSUR, the University of Panamá, the Belize Fisheries Department, *Stichting Nationale Parken* Bonaire, Belize Bird Rescue, *Universidad Autónoma Metropolitana*, UIMQROO, SEQ, and numerous conservation organizations throughout the Caribbean and Abiayala.

Many chapters originated from ongoing conservation programs and scientific investigations located far from the Yucatán Peninsula. The primate materials, for example, emerged from broader Panamanian primate conservation efforts and were subsequently ethnotranslated to focus on species more relevant to Maya students. The invasive lionfish materials were originally associated with Belizean fisheries and conservation initiatives. Coral and reef chapters reflected expertise developed through work on Raja Ampat coral reefs, sea turtles, fisheries, and coastal ecosystems. During adaptation, species selections, examples, illustrations, and linguistic framing were modified to increase cultural relevance for Maya students while preserving scientific rigor.

Visual representation emerged as an important consideration throughout both the multilingual mangrove prototype phase and the subsequent Maya-language STEM Plus curriculum. While efforts were made to incorporate locally relevant photographs, illustrations, species, landscapes, and cultural references, the degree of visual localization varied among editions. Much of the project's photography, artwork, scientific expertise, design work, and editorial labor were donated, and financial constraints limited the ability to commission extensive community-specific visual materials for every linguistic group and educational context.

At the same time, not all imagery was intended to be locally specific. The project sought to balance place-based relevance with broader ecological literacy by including images that illustrated species, ecological processes, conservation challenges, and environmental relationships extending beyond individual communities and national boundaries. This approach reflected the project's broader emphasis on ecological connectivity, knowledge portability, and shared stewardship across ecoregions.

Future iterations would benefit from greater investment in community-generated visual archives, locally commissioned artwork, and regionally specific photography. Such additions would further strengthen cultural representation while maintaining the broader ecological perspective that underlies the STEM Plus framework.

The significance of this process extends beyond curriculum development. It demonstrates that scientific knowledge generated within distinct institutional, disciplinary, and geographic contexts can be reorganized through ethnotranslation into a coherent educational framework capable of functioning in a new linguistic and cultural environment. To further illustrate these pathways of knowledge movement and adaptation, Table 4 synthesizes the geographic, disciplinary, and linguistic provenance of the major STEM Plus themes incorporated into the Maya pilot. The Maya pilot therefore evaluated not only educational materials but also the interoperability of culturally significant scientific knowledge originating across multiple ecological, cultural, disciplinary, and social settings.

Importantly, the contributors represented in Tables 2–5 were not merely content providers; they were also stakeholders in the broader success of the multilingual mangrove prototypes and the Maya STEM Plus project. Tables 2–4 summarize the scientific and educational contributors whose work informed the curriculum, while Table 5 identifies the Indigenous and Creole coauthors whose linguistic, cultural, and ecological expertise shaped the multilingual prototype series from which many of these methods emerged. These stakeholders included conservation scientists, Indigenous and Creole educators, ethnotranslators, language activists, community knowledge keepers, conservation practitioners, and a wider network of photographers, illustrators, designers, and other collaborators who donated their time, expertise, images, artwork, and creative skills in support of the project's educational and conservation goals. Although they worked in different countries, institutions, disciplines, and linguistic communities, many were engaged with conservation challenges affecting the same ecoregions, migratory species, fisheries, forests, and coastal ecosystems represented within the curriculum. Sea turtles move across the Caribbean Basin, mangrove ecosystems span national boundaries, invasive species spread through interconnected watersheds, and many terrestrial species occupy ranges extending across multiple countries. Consequently, the successful adaptation of these materials within Maya-speaking communities provided an opportunity to evaluate whether scientific and ecological knowledge developed in one cultural, linguistic, geographic, or institutional context could be effectively communicated, understood, and applied in another.

Many contributors were also committed to broader goals of conservation education, community engagement, language revitalization, and linguistic inclusion. Notably, many of these stakeholders were not trained linguists, language scholars, or specialists in Indigenous language revitalization. Rather, they were biologists, ecologists, fisheries scientists, conservation practitioners, wildlife rehabilitators, educators, and community leaders whose primary professional interests centered on biodiversity conservation and environmental stewardship. For these stakeholders, the Maya pilot represented not simply a local educational intervention; it served as a test of whether community-authored, multilingual educational materials could successfully bridge scientific research, Indigenous and

Creole knowledge systems, and local ecological stewardship. In this sense, the project's outcomes carried implications not only for Maya-speaking students in Quintana Roo, but also for conservation practitioners, educators, language activists, artists, communicators, and researchers working throughout the greater Caribbean Basin and Abiayala who face similar challenges of communicating ecological knowledge across linguistic, cultural, and political boundaries. In this respect, the Maya pilot served as a shared proof-of-concept for a diverse network of stakeholders whose conservation, educational, and linguistic goals extended far beyond Quintana Roo.

Additionally, attention was paid to how curriculum design itself evolved across linguistic groups. The prototype template originally developed in Honduras using content derived from "*Lilian di Labsta*", the first authors first attempt to create biocultural materials in Belize (Thigpen, 2025), was adapted in distinctive ways, some versions emphasized spiritual framing, others conversational tone, and still others rigorous terminological consensus. These divergences are central to understanding the *Ethnotranslation Model* not only as a linguistic method, but as a vehicle for curricular transformation.

Throughout this paper, I refer to ethnotranslation as the process of adapting ecological content into local languages in ways that reflect culturally specific epistemologies, worldviews, and narrative forms. This stands in contrast to conventional translation, which often assumes linguistic equivalence without regard for epistemic or pedagogical difference. (Thigpen, 2026) Likewise, the *Hybridization Hypothesis* describes the coexistence of distinct ecological knowledge systems, as Indigenous cosmologies and Western ecological science within a shared curricular frame, **without** requiring assimilation or synthesis into a Western framework (Thigpen, 2025).

Results

The analysis of multilingual ethnotestimonials and classroom implementations revealed consistent patterns across linguistic and cultural contexts. These patterns extend beyond individual narratives, pointing to shared mechanisms through which language, ecological knowledge, and epistemologies interact. Three primary themes emerged: (1) the alignment of local ecological knowledge with scientific concepts, (2) the role of language in shaping student engagement and identity, and (3) the emergence of shared ecological understandings across geographically and linguistically distinct communities [biocultural constants]. Together, these findings demonstrate that multilingual, community-authored materials do not merely translate scientific content but restructure how ecological knowledge is recognized, organized, and transmitted.

a. Language as Ecological Memory

Many contributors describe their mother tongues as the primary means by which ecological knowledge is transmitted. References to moon phases, bird calls and fishing practices appear as culturally embedded knowledge (Thigpen, 2026). Language is portrayed not merely as a tool, but as the medium through which people come to know their local ecosystems (Thigpen, 2025).

b. Educational Alienation and Cultural Loss

These *Ethnotestimonials* frequently critique national education systems for ignoring Indigenous languages and environmental realities. When schooling displaces local cosmologies, children become linguistically

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

and ecologically disoriented. This concern is echoed across all communities represented.

c. Curriculum as Cultural Revitalization
Several authors express hope that the mangrove textbooks can serve as bridges between traditional knowledge and formal education. By including Indigenous language and worldview in science education, these materials help affirm identity and empower youth as stewards of their territories (Poot Cahun, 2025; Thigpen, 2025).

These aspirations are also consistent with broader Indigenous scholarship on Maya language revitalization. Cru (2016), drawing on the reflections of young Maya scholars and language activists, describes an evolution from viewing language revitalization primarily in terms of linguistic purity toward a more functional understanding of Maya. As Yazmin Novelo observes, *jach Maya* is ultimately "that which is understood, which allows communication." Although developed independently, MCB's *STEM Plus Framework* reflects a complementary perspective by seeking to demonstrate that Indigenous languages are capable not only of communication, but also of supporting scientific inquiry, environmental stewardship, higher education, and knowledge generation. Together, these perspectives suggest that the long-term vitality of Indigenous languages depends not only on their preservation as repositories of cultural heritage, but also on their continued use in addressing contemporary educational, environmental, and societal challenges.

This perspective is also consistent with Sima Lozano, Perales Escudero, and Be Ramírez (2013), who argue that language policies should seek to increase not only the prestige of the Maya language itself but also the prestige of its speakers. In many respects, the community-authored educational model presented here contributes to that objective by recognizing Indigenous educators, students, community knowledge keepers, and language specialists as coauthors, ethnotranslators, researchers, and knowledge generators. By positioning Maya as a language of scientific inquiry, environmental stewardship, higher education, and community leadership, the project seeks to strengthen the status and legitimacy of both the language and its speakers while recognizing Indigenous languages as active sites of knowledge generation as well as knowledge transmission (Thigpen, 2026).

These findings also emerged through structural divergence across editions. In some languages, lessons are highly formalized, while in others they take the form of storytelling or metaphor. Even though the ecological realities remained constant, the means of engagement and emotional texture varied dramatically. These variations reflect the linguistic, epistemic and pedagogical traditions of each community and demonstrate the centrality of cultural form in determining educational impact.

These divergences extended beyond narrative tone and pedagogical framing into the technical realities of multilingual publishing itself. While some editions emphasized storytelling, spiritual reflection, or ecological translanguaging, others introduced challenges associated with entirely different orthographic systems. The Burmese edition, for example, required substantial adaptation to accommodate non-Latin script formatting, rendering behavior, and localized typographic conventions. Community collaborators, including Ne Nan Nandar Nwe of Myanmar, became essential not only as ethnotranslators but also as technical and publishing mediators who helped ensure that the educational materials functioned coherently within local linguistic infrastructures.

These experiences demonstrated that multilingual conservation education requires not only linguistic and ecological adaptation, but also technological flexibility capable of supporting diverse writing systems and modes of textual organization.

Polyphonic Reflections

These quotations from the Introductions illustrate the diversity and convergence of perspectives:

- **Wayuu:** "*My reading was nothing but the song of birds, the tracks of animals in the sand, the morning revelation of night dreams*." ~Maria Josefa Epieyuu (Thigpen etal. 2018)

- **Yucatec Maya:** "*This project provides Maya students an opportunity to learn in their own language, through which they better understand and appreciate science, and affirm their cultural identity*." ~Felicita Cantun (Thigpen and Poot Cahun; 2018)

- **Mopán Maya:** "*This mangrove book in our Mopán language will promote appreciation of both language and the deep meaning of mangroves to our coastal ecosystems*." ~Midonio Cal (Thigpen etal., 2021)

- **Q'eqchi' Maya:** "*Indigenous wisdom is the foundation for teaching the importance of protecting Mother Nature and the Caribbean Sea*." ~Edgar Fernando Pop Tiul (Thigpen and Pop Tuil; 2020)

- **Garifuna:** "*The sea is the heritage of many peoples. It is our responsibility to protect it for our children's children*." ~Cheryl L. Noralez (Thigpen and Bermudez; 2018)

- **Miskitu:** "*Our ancestors used natural resources wisely and sustainably. We must return to those ways*." ~Scott Wood Ronas (Thigpen and Ronas; 2019)

- **Ulwa:** *Our mother tongue is what identifies us as a united people moving toward a better future*. ~Leonzo Knight Julian (Thigpen and Julian; 2021)

- **Bahasa:** "*My Earth, Your Earth, His Earth is Our Earth*." ~M. Irham Saputra (Thigpen etal., 2020)

- **Burmese**: "*These books are designed to blend local fishers' knowledge and their local languages with the language and concepts of science so they are better equipped to discuss these issues in the languages they use*." ~Ne Nan Nandar Nwe (Thigpen and Nwe, in press.)

These reflections are poetic, affective, and epistemological. They connect the act of speaking with the act of knowing and caring for place. Their inclusion in the textbooks marks a rebalancing of authorship and authority.

Although many participants were from either Indigenous or Creole communities, these educational interventions also sparked interest among dominant-language speakers in adjacent communities. These findings point to the value of localized, bioregional science education that transcends ethnolinguistic lines and international borders; and reinforces shared environmental responsibilities. Remarkably, this may represent the first documented instance in which dominant-language speakers openly acknowledged that educational materials developed for Indigenous and Creole communities were superior to those used in their own classrooms.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Linguistic and Cultural Distinctions Across Prototypes

Although all nine prototypes are based on a shared ecological curriculum, each one bears the imprint of its respective linguistic, cultural, and interpretive context. The Garifuna edition is rooted in maritime communalism and intergenerational responsibility, while the Q'eqchi' Maya version presents mangroves as sacred ancestral landscapes, blending spiritual and ecological metaphors. The Miskitu edition echoes a didactic tone, grounded in oral traditions of sustainability. The Ulwa book places emphasis on language reclamation and the emotional weight of remembering ancestors.

Meanwhile, the Wayuu prototype stands out for its poetic, metaphor-rich expression and inclusion of a photo of the contributor, Maria Josefa Epieyuu, visually reaffirming the personal voice of the testimony. The Yucatec Maya version reflects academic collaboration, where university translation workshops at UIMQROO and consensus lexicons enabled structured neologism creation. The Mopán edition was highly integrated with school partnerships, reinforcing its role in language preservation and curriculum testing. Finally, the Belizean Kriol book featured the most adaptive ethnotranslation, utilizing ecological translanguaging, neologisms, and ecological transknowledging to reach students in their home linguistic register.

These distinctions underscore that there is no singular cultural or linguistic instantiation of Indigenous ecological knowledge translation. The methodological portability observed across ecoregions and species ranges was made possible by *Relational Learning* grounded in long-term engagement with Belizean Kriol, Maya, Garifuna, and Mestizo fisher folk, whose everyday interactions with mangrove and coastal ecosystems informed design choices that remained effective when later applied across diverse linguistic and ecological contexts. Rather than producing uniform outputs, each testimony reflects a distinct form of curriculum sovereignty rooted in local cosmologies, pedagogical traditions, and sociolinguistic landscapes.

At the same time, the *Ethnotranslation Model* outlines a replicable, phased methodology in which the first phase establishes the relational, ethical, and epistemic conditions necessary for ecological content to be rearticulated. It is this initial phase grounded in *Relational Learning* that creates the environment enabling content to be rearticulated in diverse languages and cultural registers while preserving a consistent scientific framework (Thigpen, 2026). Together, these localized adaptations form a pluriversal archive of how science education can be reimagined from the ground up, demonstrating both structural flexibility and epistemic integrity within the STEM Plus model.

Linguistic and Curricular Distinctions Across Prototypes

While all prototypes share a common ecological foundation rooted in mangrove ecology and conservation biology, each localized edition diverges meaningfully in how that content is translated, framed, and delivered. These divergences are not superficial. They reflect deep commitments to community-defined values, linguistic integrity, and epistemic relevance.

The original Spanish/English prototype, co-developed in Honduras by Grazzia Matamoros Erazo, José Antonio Romero Durón, and the project leader, served as the foundational template for the series. It established the dual-language modular

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

structure and visual-textual pairing. This template was first applied in the Belizean Kriol prototype, which quickly demonstrated the adaptability of the original model.

Each subsequent edition adapted and sometimes fundamentally reimagined the English / Spanish mangrove prototype to suit local epistemologies, linguistic registers, and pedagogical expectations while maintaining a recognizable ecological curriculum core grounded in shared biocultural constants.

English / Spanish: Serving as the foundational source text for many subsequent adaptations, the bilingual English-Spanish edition was designed to bridge scientific terminology and conservation concepts across linguistic communities throughout the greater Caribbean Basin. Drawing upon both marine biology and social scientific approaches, it explicitly sought to integrate local fishers' ecological knowledge with the language and concepts of science. The edition introduced many of the pedagogical structures, ecological themes, and neologism-development challenges that would later be adapted and expanded through subsequent ethnotranslations. Rather than functioning solely as a translation, it served as a foundational reference point from which later Indigenous and Creole language editions diverged while maintaining a shared ecological foundation (Thigpen, etal 2018).

Although all editions shared a common ecological architecture rooted in mangrove ecology, fisheries connectivity, and community stewardship, each community adapted the material according to its own linguistic conventions, cultural priorities, educational traditions, and knowledge systems.

Belizean Kriol: This edition uses ecological translanguaging[5] (Thigpen, 2025), neologisms, borrowed words written using the phonetic structure of Belizean Kriol and ecological translanguaging to mirror students' home speech. Its tone is intimate, rhythmic, and conversational intentionally designed to sound as if it *belongs* around a kitchen table in Pickstock or on the Caye. This aligns with García and Kleyn's (2016) observation that translanguaging can amplify student engagement when instructional language reflects authentic communicative practice. (Thigpen etal 2017)

Wayuu: Opened by an oral-style testimony from an elder woman who never learned to read or write. This version critiques disruptive effects of dominant language literacy on Indigenous knowledge transmission. It invokes memory, metaphor, and intergenerational knowledge in place of formal instruction. (Thigpen etal. 2018)

Garifuna: Developed in collaboration with Garifuna educators, language activists, and cultural organizations in Belize, Honduras, Guatemala, and the United States, this edition explicitly links mangrove conservation to Garifuna cultural survival, food security, and maritime heritage. Rather than treating conservation as a purely scientific subject, it frames the sea as both an ecological and cultural inheritance. The edition combines

[5] Thigpen (2025) defines Ecological Translanguaging as the intentional use of multiple languages in biology education to support ecological understanding across linguistic, cultural, and epistemological boundaries. Drawing on the tradition of translanguaging as both a sociolinguistic and ecological practice (Fine, Caitlin G.2018; García & Kleyn, 2016; Lewis, Jones, & Baker, 2012; Li Wei, 2018), and informed by language ecology theory (Haugen, 1972). The term here describes how multilingual learners mobilize their full linguistic repertoire to engage with both Indigenous or Creole and Western ecological knowledge systems.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

newly created scientific terminology, community language planning, and reflections on intergenerational stewardship, while emphasizing the preservation of both ecosystems and the Garifuna language itself. The translation process relied heavily on Garifuna linguistic expertise and became an early demonstration of how conservation education could simultaneously support language revitalization and ecological literacy. (Thigpen & Bermúdez, 2018)

Yucatec Maya: This version emerged from translation workshops at UIMQROO and consensus-building among Maya educators and researchers. It uses carefully structured neologisms and became a laboratory for later STEM Plus iterations. (Thigpen and Poot Cahun; 2018)

Miskitu: Written in a more didactic tone, this edition reflects oral teaching traditions and ancestral stewardship practices. Coauthored with educators from the *Centro de Educación Bilingüe Intercultural de la Mosquitia Hondureña* it blends formal instruction with narrative cadence. (Thigpen and Ronas; 2019)

Q'eqchi' Maya: Framed in ancestral spirituality, this edition presents mangroves as sacred landscapes. It combines moral teachings with cosmological references and critiques of extractive logics. (Thigpen and Pop Tuil; 2020)

Ulwa: Developed with Karawala's language committee, the Ulwa edition emphasizes linguistic reclamation and emotional connection to the land. It reflects a community emerging from cultural trauma with renewed purpose. (Thigpen and Julian; 2021)

Bahasa/Burmese (Indonesia/Myanmar): These Southeast Asian prototypes represented the most geographically distant adaptations within the mangrove curriculum lineage. The Indonesian edition contextualized mangrove conservation through regional fauna, marine biodiversity associated with Alor Island, and mangrove regeneration, demonstrating that the ecological framework could be successfully transferred beyond the Caribbean Basin while retaining its core conservation concepts (Thigpen et al., 2020). The Burmese edition further expanded this experiment by demonstrating how multilingual conservation curricula must adapt not only to different languages but also to entirely different writing systems, textual organizations, and technological infrastructures. The Burmese ethnotestimonial emphasized the integration of local fishers' ecological knowledge with scientific language to strengthen community participation in marine conservation. Community collaborators, including Ne Nan Nandar Nwe, became essential not only as ethnotranslators but also as technical mediators capable of adapting the curriculum to function coherently within local typographic systems. Together, these Southeast Asian editions expanded the concept of ethnotranslation beyond language itself, demonstrating that multilingual curriculum sovereignty also depends upon technological accessibility, script inclusivity, and the successful transfer of ecological concepts across distinct biogeographic regions (Thigpen et al., 2020; Thigpen & Nwe, in press).

These distinctions do more than localize vocabulary; they reframe what counts as knowledge, who counts as an author, and how conservation is taught. As such, each book constitutes an act of curricular sovereignty and a contribution to a pluriversal archive of Indigenous, Creole and coastal ecological education.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Table 1. Developmental Lineage of the Multilingual Mangrove Prototype Series and Related STEM Plus Adaptations

Linguistic Community	*Country / Region*	*Developmental Significance*
Belizean Kriol	Belize	Rooted in lessons learned from *Lillian the Lobster* and early multilingual conservation education efforts; foundational influence on later STEM Plus development.
English	Belize	Early conservation education adaptations that facilitated broader regional dissemination.
Spanish	Honduras and wider Mesoamerica	First major cross-linguistic adaptation pathway and foundation for later Indigenous-language adaptations.
Garifuna	Belize / Honduras Guatemala / Nicaragua	Early heritage-language adaptation that helped test community-based ethnotranslation approaches.
Wayuu	Colombia / Venezuela	Early Indigenous-language adaptation demonstrating transferability beyond the Mesoamerican context.
Yucatec Maya	Mexico / Belize	First large-scale classroom implementation and formal evaluation of STEM Plus materials.
Mopán Maya	Belize / Guatemala	Extension of the model into additional Maya-speaking communities.
Q'eqchi' Maya	Belize / Guatemala	Further Indigenous-language adaptation and testing.
Ulwa	Karawala, Nicaragua	Expansion into a distinct linguistic family and cultural tradition.
Miskitu	Nicaragua / Honduras	Adaptation within another Indigenous linguistic and ecological context.
Bahasa Indonesia	Indonesia	Demonstrated transferability beyond the Caribbean Basin and Mesoamerica.
Burmese	Myanmar	Demonstrated applicability across major geographic, cultural, and linguistic boundaries.

Table 1. Developmental Lineage of the Multilingual Mangrove Prototype Series and Related STEM Plus Adaptations. This table summarizes the major linguistic adaptations that contributed to the evolution of the STEM Plus project. Rather than representing simple translations of a common text, each adaptation involved varying degrees of ecological interpretation, cultural contextualization, neologism development, and pedagogical innovation. Collectively, these adaptations provided the experimental foundation from which the Ethnotranslation Model and later Maya-language STEM Plus curriculum emerged.

Table 2. Provenance of Scientific Content in the 4th-Grade Maya STEM Plus Textbook

Chapter	*Author(s)*	*Knowledge Origin*	*Original Context*	*Languages Used Prior to or Alongside Maya*
Scientific Names and Taxonomy	Anna J. Phillips	USA	Smithsonian taxonomy and systematics	English, Spanish, Maya
Maya Orthography	Hilario Poot Cahun	Quintana Roo	Maya language education	Maya
Mangroves	Matamoros, Romero Durón, Thigpen	Honduras / Belize	Mangrove prototype	English, Spanish, Kriol, Maya, Mopán, Garifuna, Q'eqchi'
Sea Turtles	Contuchio, Moreno Munar, Thigpen	Caribbean Basin	Marine conservation education	English, Spanish, Maya
Primates	Gutiérrez, Méndez-Carvajal	Panamá	Primate conservation	Spanish, English, Maya
Manatees	Corona, Castelblanco-Martínez, Brady, Thigpen	Guatemala/ Colombia / USA / Belize	Aquatic mammal conservation	English, Spanish, Maya
Scarlet Macaws	Joyner	Honduras	Community conservation education	English, Spanish, Maya
Invasive Catfish	Schmitter-Soto, Quintana et al.	Belize / Quintana Roo	Belize Fisheries Dept. invasive species management	English, Kriol, Spanish, Maya
Sargassum	Bartlett	UK / Caribbean	Coastal management	English, Spanish, Maya

Table 2. Scientific Contributors, Knowledge

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Origins, and Conservation Contexts Represented in the Maya STEM Plus Textbooks. *This table identifies the principal scientific contributors whose work informed the 4th and 5th grade Maya STEM Plus textbooks. The chapters originated from diverse conservation, research, and educational contexts throughout the Caribbean and Mesoamerica and were subsequently adapted through the Ethnotranslation Model for use in Maya-language primary school classrooms.* (Thigpen & Poot Cahun 2022; & Poot Cahun & Thigpen. 2023)

Table 3. Provenance of Scientific Content in the 5th-Grade Maya STEM Plus Textbook

Chapter	*Author(s)*	*Knowledge Origin*	*Original Context*	*Languages Used Prior to or Alongside Maya*
Scientific Names and Taxonomy	Anna J. Phillips	USA	Smithsonian parasitic taxonomy and systematics	English, Spanish, Maya
Maya Orthography	Hilario Poot Cahun	Quintana Roo	Maya language education	Maya
Lionfish	R. Leroy Creswell	Caribbean Basin	Invasive species management	English, Spanish, Maya
Queen Conch	Monique Grol	Bonaire	Fisheries and conservation	English, Dutch, Papiamentu, Spanish, Maya
Coral Reefs	Phil Dustan	Raja Ampat	Coral reef ecology	English, Spanish, Maya
Amazona Parrots	Nikki Buxton	Belize	Wildlife rehabilitation	English, Spanish, Maya
Spider Monkey	Braulio Pinacho Guendulain,	Tabasco, Mexico	Biodiversity and primate conservation	Spanish, Maya

Table 3. Geographic and Linguistic Pathways Through Which Scientific Knowledge Entered the Maya STEM Plus Curriculum. *This table traces the geographic origins, original conservation contexts, and linguistic adaptation pathways associated with major themes incorporated into the Maya STEM Plus textbooks. The table illustrates how knowledge developed across multiple countries, disciplines, and linguistic traditions was adapted and integrated into a common Maya-language educational framework.*

Table 4. Geographic and Linguistic Provenance of Major STEM Plus Themes Incorporated into the Maya Pilot

Chapter / Theme	*Primary Contributor(s)*	*Knowledge Origin*	*Original Context*	*Linguistic Pathways and Adaptations*
Scientific Taxonomy	Anna J. Phillips	United States	Systematics and biological classification	All Mangrove Prototype Languages
Maya Orthography	Hilario Poot Cahun	Quintana Roo, Mexico	Maya language revitalization and literacy	Maya → Spanish → English →
Mangroves	Grazzia Matamoros, José A. Romero Durón, Robby Thigpen	Honduras / Belize	Original mangrove prototype and coastal conservation education	English → Spanish → Kriol → Maya → additional adaptations
Sea Turtles	Jenna Contuchio, Alvaro Andrés Moreno Munar, Robby Thigpen	Global	Marine conservation and environmental education	English → Spanish → Maya
Primates	Karol Gutiérrez, Pedro G. Méndez-Carvajal	Panamá	Neotropical primate conservation	Spanish → Maya
Manatees	Fabiola Corona, Nataly Castelblanco-Martínez, Beth Brady	Guatemala / Colombia / Belize / United States	Aquatic mammal conservation and environmental education	English → Spanish → Maya
Scarlet Macaws	LoraKim Joyner	Honduras	Community-based parrot conservation	Spanish → Maya

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

Invasive Catfish (*Pterygoplichthys* spp.)	Juan J. Schmitter-Soto et al.	Belize / Quintana Roo	Fisheries science and invasive species management	English / Kriol → Spanish → Maya
Sargassum	Debbie Bartlett	United Kingdom / Caribbean Basin	Coastal and marine environmental management	English → Spanish → Maya
Lionfish (*Pterois volitans*, *P. miles*)	R. Leroy Creswell	Wider Caribbean	Invasive species management and fisheries education	English → Spanish → Maya
Queen Conch (*Lobatus gigas*)	Monique Grol	Bonaire / Caribbean Basin	Fisheries management and marine conservation	English / Dutch / Papiamentu → Spanish → Maya
Coral Reefs	Phil Dustan	Raja Ampat, Indonesia	Coral reef ecology and conservation science	English → Spanish → Maya
Amazona Parrots (*Amazona* spp.)	Nikki Buxton	Belize	Wildlife rehabilitation and conservation education	English → Kriol → Spanish → Maya
Spider Monkey (*Ateles geoffroyi*)	Braulio Pinacho Guendulain,	México	University level primate ecology	Spanish → Maya

Table 4 illustrates that the scientific content incorporated into the Maya pilot originated from multiple countries, conservation programs, and disciplinary traditions. In most cases, these materials were developed for audiences other than Maya-speaking students and subsequently adapted through the Ethnotranslation Model and STEM Plus framework. The table demonstrates that scientific knowledge generated across diverse ecological and linguistic contexts can be reorganized into a coherent educational system without requiring a common geographic origin, disciplinary background, or language of initial development.

Table 5. Indigenous and Creole Ethnotranslators, Community Coauthors, and Linguistic Communities Represented in the Multilingual Mangrove Prototype Series

Language / Community	*Coauthor(s)*	*Community / Affiliation*	*Country / Region*	*Role in Project*
Belizean Kriol	Yaricel Castillo, Celeste Castillo, Zaida Castillo	Belizean Kriol fishing community	Belize	Ethnotranslators and community coauthors
Garifuna	Cheryl Noralez, & Elmer Mauricio Enríquez Bermúdez	Garifuna language and cultural organizations	Belize / Guatemala / USA	Ethnotranslation, terminology development, cultural framing
Q'eqchi' Maya	Edgar Fernando Pop Tiul	Q'eqchi' Maya educator and conservation advocate	Guatemala	Ethnotranslation and ecological interpretation
Mopán Maya	Midonio Cal, Richard Peck & Juan Ico	Mopán Maya educator	Belize	Ethnotranslation and educational adaptation
Yucatec Maya	Felicita Cantun & Hilario Poot Cahun	Maya educators	Mexico / Belize	Ethnotranslation and curriculum adaptation
Miskitu	Scott Wood Ronas	Intercultural bilingual education leader	Honduras	Ethnotranslation and educational adaptation
Ulwa	Leonzo Knight Julian	Ulwa Language Committee	Nicaragua	Ethnotranslation and language revitalization
Wayuu	Maria Josefa Epieyu & Aminta Peláez Guariyu	Wayuu elder and knowledge keeper	Colombia/Venezuela	Ethnotestimonial contributor
Bahasa Indonesia	M. Irham Saputra & Suriyono	Community conservation educator	Indonesia	Adaptation and contextualization
Burmese	Ne Nan Nandar Nwe	Marine conservation educator	Myanmar	Ethnotranslation and script adaptation

Table 5 identifies the Indigenous and Creole coauthors who contributed to the multilingual mangrove prototype series and the linguistic communities they represented. These collaborators served not merely as translators, but as ethnotranslators, community knowledge holders, educators, language activists, and cultural mediators whose

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

contributions shaped the linguistic, ecological, and pedagogical character of each edition. Their work informed the development of the Ethnotranslation Model, contributed to the observations that later informed the Hybridization Hypothesis of Ecological Knowledge Systems, and provided the community-authored foundation from which the Maya-language STEM Plus curriculum ultimately emerged. As stakeholders in the broader project, these coauthors helped demonstrate how conservation education can be adapted across diverse linguistic, cultural, and ecological contexts while maintaining both scientific rigor and local relevance .

Discussion and Framework Integration

The *Ethnotestimonials* analyzed here function as both curricular content and declarations of epistemic agency. They embody the principles of the *Ethnotranslation Model* developed in earlier research (Thigpen, 2025, 2026), treating language not as a neutral vessel for conveying information but as a living epistemology through which knowledge is produced, interpreted, and transmitted. Accordingly, ethnotranslation is understood not simply as linguistic transfer but as a process of ethical engagement, reciprocal recognition, and collaborative knowledge generation.

Although this work is informed by previous publications that formalized the *Hybridization Hypothesis of Ecological Knowledge Systems* and the *Ethnotranslation Model*, the educational prototypes examined here predate those theoretical frameworks. The theories were subsequently developed to explain patterns that had already emerged through the collaborative design, implementation, and evaluation of the educational materials. Thus, practice preceded theory, with the prototypes providing the empirical foundation from which the conceptual frameworks were derived. In fact, these community-authored reflections played a formative role in shaping both the *Ethnotranslation Model* and *Hybridization Hypothesis* frameworks. They served as foundational empirical touchpoints that informed and inspired the development of those subsequent models. The prototypes analyzed here thus serve as grounded examples of these frameworks in action, providing community-authored insight into how linguistic and ecological knowledge can be jointly revitalized through participatory curriculum design.

What emerged was a curriculum that braided three layers of expertise: Global South scientific authorship, editorial integration, and localized ethnotranslation (Thigpen & Poot Cahun, 2022; Poot Cahun & Thigpen 2023). The biologists provided regionally grounded ecological content often drawn from species and ecosystems far from the Yucatán Peninsula (Thigpen, 2025; Thigpen, 2026). These chapters, while scientifically rigorous and developed within culturally relevant conservation contexts, were not initially written with Maya students in mind. That act of Maya cultural alignment came later, through a careful process of the second phase of the *Ethnotranslation Model* and then finalized by Hilario Poot Cahun. This collaborative layering allowed the curriculum to maintain scientific rigor while also achieving local relevance, an approach that proved both effective and replicable. (Poot Cahun, 2025; Thigpen 2026)

The Southeast Asia adaptation further demonstrated that ethnotranslation operates not only at the conceptual and linguistic levels, but also within the technological infrastructures that enable polylingual publishing. The Burmese edition revealed that script rendering, typography, and digital formatting are themselves sites of inclusion or exclusion within global educational systems. In these contexts, community collaborators functioned simultaneously as translators, cultural interpreters, and technical mediators. This expanded the project's understanding of curriculum sovereignty by illustrating that linguistic

Vol.28, No.2, septiembre 2026-febrero 2027, pp.60-94

accessibility also depends upon the capacity of publishing systems to accommodate diverse orthographies, writing systems, and textual structures.

The Maya-language STEM Plus textbooks also provided important evidence for the portability of the methods that would later be formalized in the *Hybridization Hypothesis* and the *Ethnotranslation Model*. The fact that content written by biologists from the Global South, originally framed for entirely different countries and contexts, could be successfully integrated into a Maya-language curriculum underscores the robustness of the underlying approach. By emphasizing ecological specificity, layered authorship, and culturally grounded ethnotranslation, the methodology proved adaptable across linguistic, geographic, and educational boundaries. The 4th and 5th grade materials thus served as a proving ground for what would later become codified as a replicable, multilingual framework for biocultural education.

The Maya textbooks therefore became more than educational materials. They became a test of whether scientific knowledge generated by researchers working in entirely different ecological, linguistic, and institutional contexts could be reorganized through ethnotranslation into a coherent Indigenous-language curriculum. The positive outcomes reported by Poot Cahun (2025) suggest that such reorganization is not only possible, but can produce educational materials that are simultaneously scientifically rigorous, epistemically robust, culturally relevant, and linguistically accessible.

These findings also suggest that the primary unit of replication within this system is not language itself, but rather an underlying ecological curriculum core. Across the multilingual mangrove prototypes and subsequent Maya-language adaptations, linguistic forms, cultural examples, illustrations, narrative structures, pedagogical strategies, and epistemological perspectives varied substantially, while core ecological relationships, conservation concepts, and educational objectives remained recognizable and transferable across communities. The success of the Maya pilot therefore provides evidence that a shared ecological curriculum can be rearticulated through ethnotranslation into multiple linguistic and cultural contexts without requiring the creation of entirely new ecological frameworks for each community. Taken together, these findings suggest that the project is most accurately understood not as a stand-alone language revitalization initiative, conservation education program, or curriculum intervention, but as a *polylingual*[6], multi-stakeholder process in which scientific, cultural, and ecological knowledge was co-developed, adapted, and transmitted through the dynamic interaction of multiple linguistic communities.

An additional implication of this work has received relatively little attention. Belize serves as the first national-scale proof of concept for Thigpen's *Polylingual Education Model*. Within a single country, a shared ecological curriculum was successfully ethnotranslated across every major Indigenous and Creole linguistic community

[6] In the present study, the term *polylingual* refers not simply to the presence of multiple languages, but to an educational process in which knowledge is collaboratively generated, adapted, and circulated through the dynamic interaction of multiple linguistic communities. Unlike conventional multilingual approaches, which often treat languages as parallel or independent systems, a *polylingual* approach emphasizes the reciprocal movement of ideas, scientific concepts, and cultural knowledge across languages through collaborative educational practice.

MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

while maintaining scientific coherence and allowing each community to adapt the curriculum according to its own language, epistemology, and educational traditions. Collectively, the multilingual prototype series includes educational materials developed for Belizean Kriol, Yucatec Maya, Mopán Maya, Q'eqchi' Maya, and Garifuna, representing every major Indigenous and Creole linguistic community in Belize. To our knowledge, this may represent the first documented example of a multilingual nation in which every major Indigenous and Creole language community has access to at least one community-authored environmental science text in its own language. Although these materials were originally developed as conservation education prototypes rather than components of a coordinated national curriculum, they demonstrate that comprehensive multilingual science education across an entire nation's Indigenous and Creole language communities is technically achievable rather than merely aspirational.

The developmental history presented here also highlights a recurring challenge for *polylingual*, community-coauthored, and transdisciplinary initiatives. Projects that emerge simultaneously from conservation practice, Indigenous and Creole language collaboration, scientific communication, and curriculum development often resist easy classification within conventional academic categories. As a result, their broader developmental histories, stakeholder networks, and methodological contributions may be overlooked when interpreted primarily through the lens of a single discipline, institution, or educational framework. The *polylingual* mangrove prototypes examined here illustrate how knowledge can emerge through interactions among multiple linguistic communities, conservation practitioners, educators, and knowledge holders operating across diverse ecological and cultural contexts.

Viewed collectively, the multilingual mangrove prototypes, the Maya-language *STEM Plus* prototype textbooks, the *Ethnotranslation Model*, the *Hybridization Hypothesis of Ecological Knowledge Systems*, and the classroom findings reported by Poot Cahun (2025) should not be understood as independent projects. Rather, they represent successive stages within a single biocultural research ecosystem. The mangrove prototypes provided the initial experimental space in which multilingual curriculum design, community coauthorship, and ecological translanguaging were explored. These experiences informed the development of the *Ethnotranslation Model* and contributed to the observations that later informed the *Hybridization Hypothesis*. The resulting methods were subsequently applied within MCB's Maya-language *STEM Plus* project, where they were subjected to classroom-based evaluation in Indigenous primary schools. Together, these works illustrate an iterative process in which curriculum development, theory building, and educational practice informed one another through cycles of observation, adaptation, and refinement.

The decision to credit each Indigenous ethnotranslator as a coauthor on their book covers and in academic citations was central to ensuring local ownership of the materials. This practice acknowledges their expertise not only in language, but in ecological knowledge, epistemology, and cultural framing. It also affirms curriculum sovereignty by grounding the materials in relationships of mutual authorship and respect. In doing so, the mangrove prototypes became tools of both education and empowerment rooted in community voice and formally recognized as such.

The reciprocal nature of these collaborations was recognized early in the Maya Project's development. After reviewing materials associated with the multilingual mangrove prototypes, Glen Aikenhead Ph.D, a pioneering scholar of Indigenous and cross-cultural science education, observed: "You also played the role of a teacher who learns from his students – *tuakana* as the Māori would say." (Personal communication, August 5, 2020). Although made prior to the formal articulation of *Relational Learning* (Thigpen, 2026), the *Ethnotranslation Model* (Thigpen, 2026), and the *Hybridization Hypothesis of Ecological Knowledge Systems* (Thigpen, 2025), this observation anticipated a central feature of the project: the understanding that meaningful curriculum development emerges through dialogue, reciprocity, and mutual learning among scientists, educators, community knowledge holders, and linguistic experts. In many respects, this process parallels the Maya concept of *Tsikbal* (Castillo Cocom et al., 2015) in which knowledge is generated and refined through conversation, dialogue, and collective reflection rather than transmitted unidirectionally from expert to learner.

Hilario Poot Cahun's thesis represented not only an evaluation of MCB's Maya-language *STEM Plus* textbooks but also the first opportunity to apply, in a sustained classroom setting, many of the curricular strategies developed through the mangrove prototypes. In this sense, his work formed a critical link in the project's progression from experimental prototypes to validated, community-relevant educational tools.

The success of these curriculum strategies was later affirmed by Hilario Poot Cahun's master's thesis, which evaluated the impact of the 4th and 5th grade *STEM Plus* textbooks in Maya-language classrooms in Quintana Roo. His findings demonstrated that students not only retained more scientific content but also expressed a deeper sense of cultural identity and ecological responsibility when materials were delivered in their own language using culturally resonant metaphors. These results lend empirical support to the claim that ethnotestimonials and hybridized curriculum design can enhance both educational outcomes and community engagement. (Poot Cahun, 2025)

Moreover, this model affirms curriculum sovereignty: the right of communities to shape what counts as knowledge and how that knowledge is transmitted. The result is not a universal textbook, but a pluriversal one, grounded in multiple epistemologies that converge in their concern for ecological stewardship.

Operationalizing the Hybridization Hypothesis, Biocultural Constants and Ethnotranslation Models

The multilingual mangrove prototypes presented in this study function not only as curricular interventions but as empirical validation of three theoretical frameworks that would later emerge from this work: the *Hybridization Hypothesis of Ecological Knowledge Systems*, the concept of *Biocultural Constants* (Thigpen, 2025) and the *Ethnotranslation Model* (Thigpen, 2026). Each prototype served as a testbed for operationalizing the core principles of these models, revealing how scientific and Indigenous ecological knowledge systems can be ethically and effectively integrated through participatory design.

The *Hybridization Hypothesis* posits that sustainable science education must emerge from the productive convergence of distinct epistemologies, namely, Western ecological knowledge and place-based ecological worldviews. The mangrove prototypes embodied this hybrid approach through a layered authorship process. Scientific content was first developed by biologists from the Global South with field expertise, then edited centrally, and finally transformed through localized ethnotranslation by Indigenous and Creole coauthors. These ethnotranslators were instructed to disregard standard translation protocols and instead reframe ecological concepts using the linguistic, metaphorical, and pedagogical structures familiar to their communities. The result was not merely a translation of content but a cultural and epistemic re-articulation of conservation education.

This adaptive process generated nine distinct curricular expressions of the same scientific foundation. For example, the poetic and metaphor-rich Wayuu edition stands in sharp contrast to the didactic tone of the Miskitu version or the ecological translanguaging found in the Belizean Kriol edition. These structural, stylistic, and orthographic divergences were not ancillary, they were central to the hypotheses being tested. They confirmed that the *Hybridization Hypothesis*, when rooted in community authorship and curriculum sovereignty, produces not dilution but innovation. This echoes cognitive studies that show how cultural mental models of nature are shaped by local epistemologies (Bang, Medin, & Atran, 2007), reinforcing the viability of hybrid curricular forms.

The Burmese edition further demonstrated that hybridization can also occur through material and infrastructural adaptation, where script systems, typographic conventions, and localized publishing practices become part of the curriculum design process itself. In this context, multilingual curriculum development required not only epistemological negotiation, but also technological adaptation capable of supporting non-Latin orthographies and culturally specific textual organization.

Simultaneously, the prototypes illustrate the presence of *Biocultural Constants*, recurring ecological themes that transcend linguistic boundaries. Across all nine editions, language emerged as a vessel of ecological memory; mangroves were described not only as habitats but as kin, ancestors, and protectors; and contributors consistently framed ecological stewardship as both moral responsibility and cultural inheritance. These *biocultural constants* help explain how a shared ecological curriculum can remain recognizable across diverse linguistic and cultural contexts while allowing substantial variation in language, narrative structure, and epistemic approach.

In sum, the mangrove prototypes provided a proving ground for the *Hybridization Hypothesis* and the *Ethnotranslation Frameworks*. They transformed theoretical propositions into replicable practice and confirmed that polylingual, community co-authored science education can both preserve cultural knowledge and meet global conservation goals. Their iterative development and subsequent integration into the Maya STEM Plus textbooks affirmed that biocultural education is most impactful when it is co-created, culturally grounded, and structurally flexible.

Authorship and Contributions

This study was conducted through a collaborative process involving Indigenous and Creole ethnotranslators who served as coauthors of the original multilingual mangrove texts and contributed the ethnotestimonials analyzed in this paper. Their contributions include linguistic innovation, ecological interpretation, and narrative authorship grounded in community knowledge systems. These contributions shaped both the dataset and the analytical insights presented here. The corresponding author led the synthesis, analysis, and manuscript preparation, while all coauthors are recognized for their role in generating the foundational content upon which this study is based.

Data Availability

The multilingual educational materials referenced in this paper are archived in the Archive of the Indigenous Languages of Latin America (AILLA) as part of the Marine Conservation without Borders Collection and are publicly available for download. Additional information about the project is available through Marine Conservation without Borders. At the time of writing, the collection includes multilingual biocultural education and community health materials representing approximately thirty linguistic communities. To our knowledge, it constitutes one of the most linguistically and culturally diverse educational collections housed within AILLA. (Archive of the Indigenous Languages of Latin America, n.d.)

Conclusion

Community-authored multilingual ethnotestimonials and lessons learned from the mangrove prototypes are powerful tools for advancing marine conservation, Indigenous rights, and educational equity. The portability of these methods across species ranges and sociolinguistic contexts reflects their grounding in *Relational Learning* with coastal communities whose livelihoods are inseparable from the ecosystems the curriculum seeks to protect. As poetic declarations and curricular interventions, they make visible the ecological knowledge systems that standard education often renders invisible. The mangrove prototypes produced by Marine Conservation without Borders demonstrate how Indigenous and Creole communities can reclaim authorship over environmental narratives.

The differences between editions were not accidental, they were integral to the learning process. Each prototype tested the boundary between linguistic fidelity and cultural resonance. From the first Spanish / English version to the Ulwa, Wayuu, Miskitu, Kriol and Maya editions, the development process revealed that effective biocultural education must be structurally flexible, allowing form to follow worldview. The Burmese edition further revealed that this flexibility must extend beyond pedagogy and translation into the technological infrastructures of multilingual publishing itself, where script compatibility and orthographic accessibility become integral components of educational inclusion. These findings confirm that pluriversal design is not a theoretical aspiration, it is a pedagogical necessity (Thigpen 2025: Escobar, 2018).

Future research is already underway. In fact, the experiences described in this paper directly gave rise to two subsequent theoretical contributions: the *Hybridization Hypothesis of Ecological Knowledge Systems* and papers on *Ethnotranslation* and *Biocultural Education*. These frameworks were not conceived in abstraction, they were distilled from the practical challenges and insights encountered during the creation of the mangrove prototype.

The methodologies proposed in those papers were first developed and field-tested here. Later, they were combined and further refined during the development of the Maya 4th & 5th grade textbooks. Importantly, this author knew from the outset that not all of these strategies would work in combination. The process required identifying which methods were robust and which would fail under real-world conditions. That is why the initial Maya textbooks, though valuable as prototypes, were simply functioning as transitional materials by the time they were printed. The most effective approaches identified through this process now form the foundation for future multilingual curriculum development across diverse linguistic and cultural communities.

Though ultimately superseded by more refined models, the 4th and 5th grade Maya STEM Plus textbooks played a critical transitional role. They marked the first time that the mangrove prototype methods were integrated into a full curriculum for minority-language primary schools, translating emergent design principles into structured classroom practice. Even as the author anticipated their eventual refinement, the books delivered vital lessons: not just on what worked, but on what could be let go. These quiet discoveries are embedded in every subsequent step of the project

The success of the 4th & 5th grade materials also demonstrated the methodological portability that would later be described in the *Hybridization* and *Ethnotranslation* frameworks. These textbooks drew on scientific content from outside the Yucatán Peninsula, yet were rendered locally meaningful through careful, collaborative adaptation (ethnotranslation). This confirms that when scientific perspectives from the Global South are paired with culturally grounded translation processes, the resulting materials can serve diverse communities without compromising scientific or cultural integrity. This portability is key to future scaling. Together, these experiences suggest that future multilingual science education initiatives must be designed not only for linguistic portability, but also for infrastructural adaptability across diverse writing systems and publishing environments. As biocultural education continues to expand across languages and landscapes, these early prototypes remind us that inclusion, iteration, and community authorship are not luxuries, they are the foundations of educational transformation.
In effect, the Maya textbooks became a test of whether scientific knowledge generated by researchers working in entirely different ecological, linguistic, and institutional contexts could be reorganized through ethnotranslation into a coherent Indigenous-language curriculum. Their success demonstrated that scientific knowledge need not originate within a community to become meaningful there, provided that adaptation is guided by culturally grounded processes and local educational expertise. Importantly, the scientific content evaluated in the Maya pilot was originally developed for audiences outside Quintana Roo and outside of Maya-speaking communities, making the successful classroom outcomes reported by Poot Cahun (2025) an especially strong demonstration of educational interoperability.

A particularly noteworthy outcome emerged from the broader developmental pathway that began with the multilingual mangrove prototypes and culminated in the Maya-language STEM Plus pilot. As the project evolved, educators, university faculty, and other stakeholders whose primary language was Spanish or English increasingly engaged with materials originally developed for Indigenous and Creole communities. In several instances, these individuals suggested that the multilingual, biocultural STEM Plus materials were comparable or superior to educational resources available in their own classrooms. While the present study was not designed to systematically evaluate such perceptions, these observations challenge conventional assumptions regarding the direction of educational innovation. Rather than knowledge flowing exclusively from dominant-language institutions toward Indigenous and minority-language communities, the project suggests that community-authored, multilingual educational materials may generate innovations and pedagogical approaches that are recognized as valuable well beyond the communities for which they were originally developed.

These findings point not only to the transformative potential of polylingual science education, but also to a pathway for reshaping science curricula through linguistic and cultural sovereignty. As the STEM Plus model expands across additional bioregions, the lessons learned from these multilingual prototypes suggest that the future of conservation education lies not in translating science for communities, but in creating conditions through which communities become active participants in the creation, adaptation, validation, and transmission of scientific knowledge. In doing so, the model offers a scalable framework through which Indigenous and local communities can strengthen both biocultural resilience and scientific capacity while contributing to the global exchange of ecological knowledge.

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MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

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Reproductive ecology, gametogenic cycle, and spawning dynamics of *Leukoma asperrima* (Sowerby, 1835) in the Gulf of Panama

Ecología reproductiva, ciclo gametogénico y dinámica del desove de *Leukoma asperrima* (Sowerby, 1835) en el Golfo de Panamá

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ABSTRACT

Synchronization between bivalve reproductive cycles and primary productivity is fundamental for recruitment success in regions subject to seasonal upwelling. The gametogenic cycle of *Leukoma asperrima* was investigated using histometric indicators and physiological indices under the influence of thermal and salinity variability in the Panamanian Pacific. Analysis revealed a bimodal reproductive strategy, with a primary spawning period between October and February and a secondary event between April and June, coinciding with water cooling and increased phytoplankton density. The average annual Gonadosomatic Index (GSI) was 31.39, peaking in April (34.26). Histometrically, oocyte diameter ranged from 55.32 µm to 65.83 µm, reflecting intense vitellogenic activity prior to spawning peaks. The population was identified as dioecious, with a mean sex ratio of 1:1.2 (F:M) and no evidence of hermaphroditism. Sex determination was validated via gonadal smears, an essential technique given the absence of macroscopic chromatic dimorphism. It is concluded that temperature acts as the primary modulator of gonadal conditioning, while food availability regulates the rate of gamete maturation. This study provides novel data on the reproductive ecology of the species, essential for understanding its resilience to climate change and anthropogenic pressure.

Keywords: Bimodal, gametogenic cycle, dioecy, reproductive strategy, Gulf of Panama, oceanographic factors, gonadal smear, gonadosomatic index, vitellogenesis.

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MESOAMERICANA
Revista Oficial de la Sociedad Mesoamericana para la Biología y la Conservación

RESUMEN
La sincronización entre los ciclos reproductivos de los bivalvos y la productividad primaria es fundamental para el éxito del reclutamiento en regiones sometidas a afloramientos estacionales. Se investigó el ciclo gametogénico de *Leukoma asperrima* mediante indicadores histométricos e índices fisiológicos bajo la influencia de la variabilidad térmica y de salinidad del Pacífico panameño. El análisis reveló una estrategia reproductiva bimodal, con un periodo de desove máximo entre octubre y febrero, y un evento menor entre abril y junio, coincidiendo con el enfriamiento del agua y el aumento de la densidad fitoplanctónica. El Índice Gonadosomático (IG) promedio anual fue de 31.39, alcanzando su pico máximo en abril (34.26). Histométricamente, el diámetro de los ovocitos varió de 55.32 µm a 65.83 µm, reflejando una intensa actividad vitelogénica previa a los picos de desove. La población se identificó como dioica, con una proporción sexual promedio de 1:1.2 (H:M), sin evidencias de hermafroditismo. La determinación del sexo se validó mediante frotis gonadal, técnica esencial dada la ausencia de dimorfismo cromático macroscópico. Se concluye que la temperatura actúa como el principal modulador del acondicionamiento gonadal, mientras que la disponibilidad de alimento regula la tasa de maduración de los gametos. Este estudio aporta datos inéditos sobre la ecología reproductiva de la especie, esenciales para comprender su resiliencia ante el cambio climático y la presión antrópica.

Palabras claves: Bimodal, ciclo gametogénico, dioecia, estrategia reproductiva, golfo de Panamá, Factores oceanográficos, Frotis gonadal, gonadosomático, Índice, vitelogénesis

INTRODUCTION

Reproduction in marine filter-feeders is a physiologically demanding process requiring precise synchronization with environmental cycles to ensure recruitment success. Factors such as temperature, salinity, and phytoplankton density have been identified as the primary regulators of the gametogenic cycle in tropical bivalves. In the Gulf of Panama, the interaction between rainfall and seasonal upwelling creates an environmental gradient where salinity increases and temperature decreases during the dry season, a pattern that reverses during the rainy season. This inverse relationship (r = -0.69) is a determinant driver for the bioconversion of energy reserves into reproductive tissue.

Sastry (1975) postulates that these environmental cues act as physiological triggers initiating germ cell maturation. The reproductive cycle can be effectively monitored through indicators such as the Gonadosomatic Index (GSI) and oocyte histometric. Oocyte diameter is considered an excellent indicator of gonadal maturity, reflecting the increase in vitellogenesis prior to spawning. Previous studies on venerids have shown that nutrient accumulation before reproduction is reflected in significant variations in fresh meat weight, which is a more sensitive indicator of nutritional status and "fatness" than total animal weight. According to Giese & Pearse (1974), continuous reproductive cycles with seasonal peaks are common in low-latitude bivalves, where temperatures rarely drop below the metabolic arrest threshold.

Despite the importance of *Leukoma asperrima*, a knowledge gap exists regarding its specific reproductive strategies in Panamanian waters. While some authors suggest high temperatures induce spawning, others, such as Vélez & Epifanio (1981), have demonstrated that optimal gonadal development occurs under low-temperature conditions in other regional species. Furthermore, sex determination in this species represents a taxonomic challenge due to the lack of macroscopic chromatic dimorphism, necessitating gonadal smear techniques for accurate identification.

Researchers like Palacios (1985) and Pizarro & Cruz (1987) have highlighted that sex ratio and spawning synchrony are critical factors for mitigating larval dispersal effects. This work delves into the sexual maturity cycle, sex ratio, and the influence of oceanographic parameters on the reproductive effort of *L. asperrima*.

MATERIALS AND METHODS

Sample Processing and Environmental Parameters

A monthly subsample of 35 to 45 adult specimens was selected for reproductive analysis. Simultaneously, *in situ* physicochemical parameters—sea surface temperature (ºC) and salinity (psu)—were recorded, along with phytoplankton density using a standardized filtration method.

Physiological Indices and Gonadal Histometry

Nutritional condition was evaluated using the Gonadosomatic Index (GSI), calculated as:

$$IG = \left(\frac{\text{Peso de la gónada}}{\text{Peso total del tejido fresco}}\right) \times 100$$

This index allows for the normalization of gonadal weight variations relative to animal size. For histometric, the diameter of at least 50 oocytes per female was measured using an optical microscope equipped with a calibrated ocular micrometer, considering only oocytes with a visible nucleus to ensure precise equatorial measurement.

Sex Determination and Sex Ratio

Given the absence of chromatic dimorphism in *L. asperrima* gonads, sex identification was performed using the gonadal smear technique. Tissue was observed under a microscope at 40x; the presence of spherical, granular gametes identified females, while motile spermatozoa or fluid tissue identified males. The sex ratio was analyzed using the Chi-square (x^2) test to determine significant deviations from the theoretical 1:1 parity. Pearson correlation analysis was used to evaluate the relationship between oocyte diameter, GSI, and environmental variables ($P < 0.05$).

RESULTS

Sample Processing and Synchrony with Environmental Parameters

Analysis revealed that the reproductive physiology of *L. asperrima* is closely modulated by the Gulf of Panama's upwelling regime. A significant inverse correlation was observed between sea surface temperature and salinity ($r = -0.69$, $P < 0.05$), acting as the primary trigger for gonadal conditioning.

- **Upwelling Response:** The accelerated increase in GSI toward April (34.26) coincided with the 1996 upwelling period, characterized by minimum temperatures and high phytoplankton densities.
- **Gonadal Conditioning:** Gonadal development showed a direct response to food availability; high chlorophyll and nutrient concentrations during the dry season favored an increase in gonadal biomass prior to spawning.
- **Thermal Influence on Spawning:** Peak spawning periods (October–February) synchronized with water temperature decreases, suggesting that environmental cooling induces massive gamete release.

- **Condition Indicators:** Fresh meat weight and GSI proved to be more sensitive indicators of "fatness" and nutritional status than total animal weight.
- **Histometric Relationship:** Despite vitellogenic activity, no significant statistical correlation was detected between oocyte diameter and GSI, indicating that gonad weight variations depend on connective tissue proliferation and glycogen reserves rather than just germ cell size.
- **Seasonality Effect:** During the rainy season (May–October), rising temperatures and salinity stability allowed for progressive somatic recovery, preparing individuals for the second reproductive peak in October.

Gonadosomatic Index (GSI) Dynamics and Maturity

The average GSI for the total population was 31.39. Marked seasonal fluctuation was detected, with an accelerated increase toward April, reaching a maximum of 34.26, followed by a second peak in October (30.61). Individuals classified as "indeterminate" (post-spawning) showed a significantly lower GSI of 25.53 (Figure 1 and Table 1).

Figure 1.

Reproductive cycle and gonodosomatic index (GSI) for L. asperrima in the Gulf of Panama.

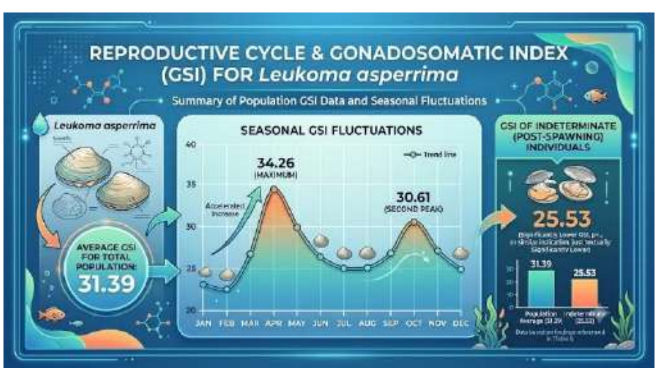

Table 1.

Reproductive and physiological indicators of L. asperrima

Parameter	Average Value / Range
Oocyte Diameter (Annual)	60.53 µm
Minimum Diameter (February)	55.32 µm
Maximum Diameter (October)	65.83 µm
IG Males	31.62
IG Females	31.23

Spawning Cycle and Environmental Variability

Two defined spawning periods were identified: a primary event from October to February and a secondary event from April to June. These periods coincided with decreasing surface temperatures and increased phytoplankton density during upwelling. No significant correlation was found between oocyte diameter and GSI ($P > 0.05$), suggesting that gonadal weight depends on factors beyond gamete size.

Sex and Sex Ratio

The species is dioecious and lacks macroscopic chromatic dimorphism; differentiation was achieved exclusively through gonadal smears (Table 2). The average sex ratio was 1:1.2 (F:M), showing no significant deviations from the 1:1 theoretical parity ($P > 0.05$), except for June and July. No hermaphroditic specimens were recorded.

Table 2.

Sexual structure of the analyzed sample (n=452)

Sex	Frequency (%)	Smear Characteristics
Males	51.99%	Fluid texture, without granules
Females	43.81%	Defined granular texture
Indeterminate	4.20%	Flaccid tissue (post-spawning)

DISCUSSION

The reproductive strategy of *L. asperrima* in the Gulf of Panama is defined as continuous with marked seasonal bimodality, adapted to synchronize with coastal upwelling. The identified spawning peaks (October–February and April–June) coincide with reports by Palacios et al. (1986c) and Pizarro & Cruz (1987), who associate gamete release with falling surface temperatures and rising primary productivity.

GSI fluctuations, peaking in April (34.26), evidence an immediate physiological response to the phytoplankton abundance characteristic of the upwelling period. However, the lack of significant correlation between GSI and oocyte diameter suggests that gonad weight gain depends not only on germ cell size but also on auxiliary cell proliferation and glycogen accumulation in the interfollicular connective tissue, as proposed by Gómez & Villalaz (1989). The population is strictly dioecious, with a sex ratio (1:1.2 F:M) that does not significantly diverge from parity for most of the cycle. This stability, along with the absence of hermaphroditism, positions *L. asperrima* as a robust reproductive system compared to other regional species like *Argopecten ventricosus*, which show hermaphroditic variations under environmental stress.

Finally, the use of gonadal smears proved to be the most efficient methodology for sex identification in tropical venerids, given the lack of chromatic dimorphism. The histometric and physiological results presented here confirm that temperature and food availability are the primary exogenous regulators of gametogenesis, where water cooling acts as the proximal stimulus for massive spawning.

CONCLUSIONS

L. asperrima is a functional dioecious species without macroscopic chromatic dimorphism, maintaining a sex ratio balance of 1:1.2, ensuring reproductive stability in the Panamanian littoral.

The reproductive strategy is continuous with a defined seasonal bimodality, featuring peak spawning between October and February and a secondary event between April and June.

GSI and fresh meat weight are robust indicators of condition and maturity, peaking during upwelling, confirming that water cooling is the main stimulus for gamete release.

The lack of significant correlation between GSI and oocyte diameter (annual average 60.53 µm) suggests that gonadal energy investment includes vitellogenesis as well as glycogen reserve accumulation and auxiliary tissue proliferation.

These findings establish a fundamental scientific basis for understanding how venerid bivalves optimize reproductive effort in response to oceanographic variability.

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