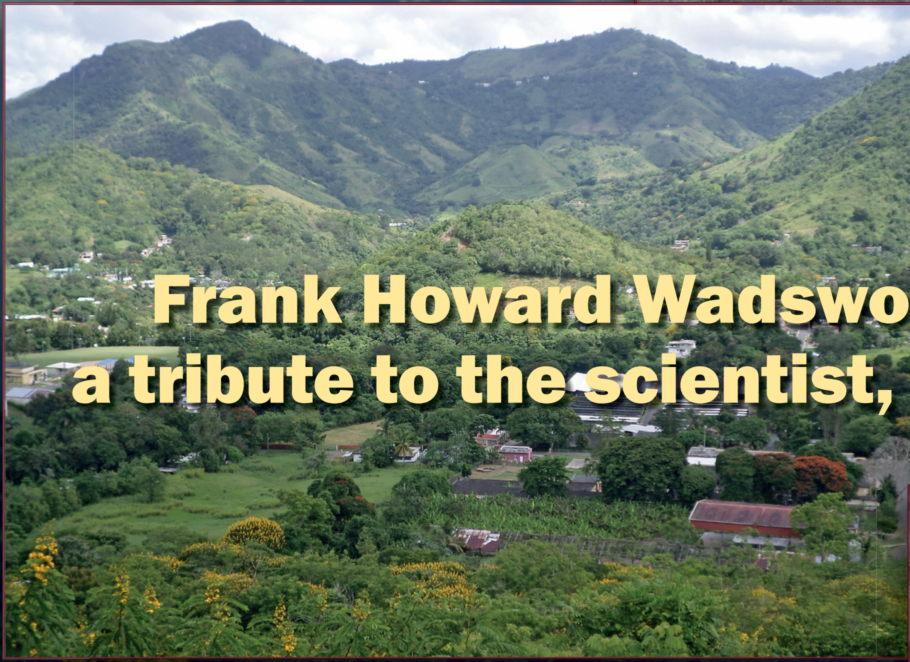
ACTA CIENTÍFICA
Una revista transdisciplinaria de Puerto Rico y el Caribe

EDICIÓN ESPECIAL

Frank Howard Wadsworth (1915-2022): un tributo al científico, mentor y amigo



SPECIAL EDITION

Frank Howard Wadsworth (1915-2022): a tribute to the scientist, mentor, and friend

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Portada

En esta portada se ilustra el paisaje, en blanco y negro, del sector La Plata en el pueblo de Aibonito, en la Cordillera Central de Puerto Rico, tal y como lucía en enero de 1938 (crédito: Rosskam, E., fotógrafo. 1938. “General view of La Plata project, Puerto Rico. Aibonito Municipality La Plata Puerto Rico, 1938.” Tomada de la Biblioteca del Congreso y disponible en https://www.loc.gov/item/2017764512/).

En 1938, esta área se utilizaba para el cultivo, casi exclusivo, del tabaco, y el paisaje se muestra tal cual, deforestado como casi igualmente estuvo el resto de Puerto Rico para entonces.

Le acompaña una vista del mismo paisaje, pero en octubre de 2016, donde se aprecia la cubierta forestal y de vegetación en general producto en gran parte de la sucesión secundaria (foto de Neftalí Ríos). En dos imágenes, la representación misma del doctor Frank Howard Wadsworth – en el hoy Instituto Internacional de Dasonomía Tropical, inclinado asistiendo a varios de los muchos estudiantes (provenientes de los Neotrópicos y el continente africano) en los cursos que organizó sobre dasonomía tropical (foto suministrada por Ariel E. Lugo).

Desde su llegada a Puerto Rico el 27 de enero de 1942, millones de árboles sembrados y nuevas reservas forestales, políticas públicas, agencias de gobierno, corredores naturales, adiestramientos en el ámbito internacional, manejo y conservación ejemplar para Puerto Rico, Latinoamérica y el mundo... en fin, un puertorriqueño por adopción y decisión, quien durante casi 80 años aportó enormemente al “milagro ecológico” con el que se refieren frecuentemente a Puerto Rico.

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EDITOR

Neftalí Ríos López
Universidad de Puerto Rico en Humacao
Call Box 860
Humacao, Puerto Rico 00792
neftali.rios@upr.edu

JUNTA EDITORIAL

Oscar J. Abelleira Martínez
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Recinto Universitario de
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Río Piedras, PR

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Universidad de Puerto Rico,
Recinto Universitario de
Río Piedras, PR

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Recinto Universitario de
Utuado, PR

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Editor en jefe: Neftalí Ríos López
Editor de producción: Pamela Navarro (pamelaapr@gmail.com)
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Revisores de artículos: Alberto R. Puente Rolón, Ariel E. Lugo, Elsie Rivera Ocasio, Neftalí Ríos López
Diseño y diagramación: Pascual Estrada (estrada.pascual@gmail.com)

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EDITORIAL

El volumen 33 de 2022 de *Acta Científica: Una revista transdisciplinaria de Puerto Rico y el Caribe* (*AC-PuR&C*) es especial ya que rinde honores, muy humildes, al legado e inspiración que un extraordinario gigante de nuestro entorno natural – doctor Frank Howard Wadsworth (26 de noviembre de 1915 – 5 de enero de 2022) – nos deja a inicios de este año. Un visionario, irradiante de rectitud, honestidad y entereza ante la adversidad (viniera de donde viniera), don Frank facilitó gran parte de la transfiguración de paisajes naturales en Puerto Rico que, desde mucho tiempo, estaban sujetos al uso y abuso irrestricto (aunque comprensible) y que de otra manera hubiese terminado en un desastre ecológico de grandes proporciones para un Puerto Rico agotado. No obstante, su contribución abonó significativamente al llamado "milagro ecológico" que representa Puerto Rico para el mundo entero y conspiró, muchas veces desde el anonimato, para la consecución de medidas trascendentales de conservación para Puerto Rico así como educación sin fronteras sobre silvicultura en particular y la biodiversidad en general. Con su partida, se nos hace imperioso recrear el "prohibido olvidar", por esto, este volumen 33 de *AC-PuR&C* cuenta con cuatro ensayos escritos por cinco autores que, aunque con diferentes trasfondos, convergen en letras, ideas y mensajes que destacan al científico, mentor y amigo, Frank Howard Wadsworth, en beneficio de las generaciones futuras y el entorno natural del que todos dependemos para nuestra subsistencia.

Se complementa este volumen 33 con siete trabajos de catorce colegas científicos y sobre temas variados como nuevos registros para la flora en Puerto Rico, respuesta social al recurso forestal ante fenómenos no humanos, acústica de cortejo de una especie de anfibio amenazada de Puerto Rico, inventario y cuantificación de composición de especies de plantas para estudios a largo plazo en una reserva natural en Puerto Rico, ecología fisiológica de un anfibio amenazado e implicaciones de conservación ante proyecciones de cambio climático, así como una nota corta que distingue la percepción de la realidad sobre la topografía de Puerto Rico en el contexto de su lecho marino y una opinión sobre estrategias de conservación para la diversidad global.

Finalmente, este volumen 33, con el que cerramos el año 2022, es posible gracias al servicio de nuestros colegas de Caracas, Venezuela, quienes proveen de la labor técnica y artística para la producción del mismo. La dirección, consejo, apoyo y contribución del Dr. Ariel Lugo a este volumen, así como del Servicio Forestal de los Estados Unidos de América, continúa manteniendo sobre ruedas el legado de *AC-PuR&C*, por lo que ratifico nuevamente mi más profundo agradecimiento.

Aprovecho para extender una cordial invitación a todos para que consideren a *AC-PuR&C* como un medio para publicar sus contribuciones y así, anuncio la disponibilidad de recibir sus manuscritos a la brevedad, de cara a la publicación del próximo volumen 34 en el 2023. Gracias por el continuo apoyo a *Acta Científica: Una revista transdisciplinaria de Puerto Rico y el Caribe* como foro de divulgación profesional. Los espero.

Neftalí Ríos López
Caguas, Puerto Rico

A TRIBUTE TO DOCTOR FRANK H. WADSWORTH: HIS VISION CONTINUES TO INSPIRE

Thrity Jal Vakil[1],*

[1] Director, Tropic Ventures Sustainable Forestry & Rainforest Enrichment Project, Las Casas de la Selva, Patillas, Puerto Rico.
* e-mail: 3tvakil@gmail.com

When I first arrived in Puerto Rico in 1999 and began living in the mountain forests of a project known as Las Casas de la Selva (LCS; www.eyeontherainforest.org), launched in the early 1980s by the Institute of Ecotechnics (IE; www.ecotechnics.edu), I had no notion of what sustainable forestry was or might be. I was not a forester, but I had recently returned from an intense three-year dive expedition aboard the Institute's Research Vessel Heraclitus (www.rvheraclitus.org). Onboard, as part of a small crew, I had been researching coral reefs – also known as the "rainforests of the sea" – all over the Red Sea and the Indian Ocean.

In the early 1980s, John Polk Allen (inventor and co-founder of *Biosphere 2*; see https://biosphere2.org/), John Druitt, and Harry Scott visited doctors Frank Wadsworth and Peter Weaver to discuss starting a forestry project in Puerto Rico. They had recently returned from an ethnobotanical mission up the Amazon River, where they had experienced firsthand the consequences of illegal logging and deforestation of primary rainforests (https://youtu.be/7Cp0SYUTCZk). They knew that Frank and many other members of the International Institute of Tropical Forestry (IITF, US Department of Agriculture) in Puerto Rico were interested in planting trees for timber and restoring the forests, almost completely devastated by the early 1900s, which had once covered most of the island.

With assistance from government programs offering tree seedlings, they pioneered planting 40,000 hardwood trees at the property they called *Las Casas de la Selva* after obtaining the land with assistance from Puerto Rico's Department of Natural and Environmental Resources. People were leaving the mountains for the cities or clearing the forest for cattle grazing and farming. Consequently, the Puerto Rican government wanted to encourage the return of tree growing and a local wood industry since the island imports 95% of the timber it uses. Las Casas de la Selva would be the Institute of Ecotechnics' rainforest biome demonstration project; no one had done anything like it before on the island.

Las Casas de la Selva has since developed into one of the most cutting-edge experiments in sustainable forestry and rainforest enrichment in Puerto Rico. It is situated in southeastern Puerto Rico in the Sierra de Cayey mountains. The 409-hectare forest at > 600 m above sea level (> 1,969 feet) receives 3,000 mm (over 118 inches) of rain annually. Despite being well forested, this area of Puerto Rico is prone to catastrophic erosion and landslides due to excessive rainfall, geology, and steep slopes. In addition, much of the land at LCS had been previously logged, cleared for short-term grazing, and planted with coffee trees, resulting in extreme soil erosion.

The tree planting program was carried out on 120 ha (~ 297 acres), about 30% of the property. The remaining 289 ha (~ 714 acres) near Patillas municipality were left as a control "wilderness" for the natural regeneration processes of a secondary forest. As a result, human uses are limited to restricted ecotourism, scientific research, and the conservation and protection of two critical watersheds, the Icaco and Hormiga valleys, vital as they drain into Lake Patillas (water reservoir). This reservoir supplies irrigation water, industry, and potable water to 40,000 residents.

Figure 1. At Frank's Home, San Juan, 2009. L-R: Thrity Vakil, Andrés Ruá, Dr. Frank H. Wadsworth, Dr. Mark Nelson, Enrique Santiago, Molly Robertson, and Bridget McNassar.

This program was designed to experimentally test forest enrichment through line planting, which is one of the methods for making secondary rainforest economically feasible. Planting valuable hardwood tree species along cleared lines allows them to develop under the protection of the existing forest, minimizing soil disturbance and fostering forest evolution.

My first forays into this subtropical wet forest, which neighbors the Carite State Forest in Patillas, were made with Sally Silverstone, then-director of LCS, and doctor Mark Nelson, the Chairman of the IE after they successfully wrote a research proposal to the "*Earthwatch Institute*" for the help of volunteer citizen scientists from all over the world. First, the research goals were to examine the influence of line-planting on tree and frog diversity, which is essential to ecosystem processes in these forests. Secondly, we wanted to assess how the planted trees fared since planting in the mid-1980s and following 1998's Hurricane George's direct strike on the forest, which also destroyed much of the project's infrastructure.

I studied as much as I could on the initial tree-planting project and began learning to recognize the trees in my immediate environment. Wherever I went, I carried my *bible*, "*Common Trees of Puerto Rico and the Virgin Islands*" by Elbert L. Little and Frank H. Wadsworth. For nearly a decade, with the help of volunteers from Earthwatch Institute, we measured trees on ten-day expeditions. We climbed

Figure 2. At IITF Library, San Juan, 2009. L-R: Edgardo González, Dr. Frank H. Wadsworth , Dr. Peter Weaver, Thrity Vakil, and Bridget McNassar.

Figure 3. Puerto Rico Hardwoods Team, 2021. L-R: Tom Marvel, Thrity Vakil, and Andrés Ruá.

up and down the forested slopes to measure the DBH (i.e., diameter at breast height) of our line-planted hardwoods, such as *Hibiscus elatus* (Blue Mahoe) or *Swietenia aubrevilleana* (Mahogany) in meticulously measured, randomly chosen one-acre plantation plots. We used measuring tapes to measure tree canopies, clinometers to determine tree heights, and a basal prism to estimate canopy cover. Each measured tree received an aluminum tag marked with a plot number etched using an old ballpoint pen nib on the soft metal. It was challenging on the slopes, where we often spent hours in the pouring rain. In addition, it was dangerous at times when minor squalls swept across the mountains, making the steep terrain muddy underfoot.

With frog specialists from the University of Puerto Rico, we surveyed frog populations crawling at night on all fours with headlamps. I fell in love with the forest, feeling so profoundly touched by its fragility, power, mystery, beauty, and magic. Before I realized it, I was an investigator for Las Casas de la Selva's varied scientific research projects, which have already produced two significant contributions:

1) "*Enriched secondary subtropical forest through line-planting for sustainable timber production in Puerto Rico*" (*Bois et Forêts des Tropiques*; available at https://ecotechnics.edu/wp-content/uploads/2011/12/BFTpublishedpaper2011.pdf);
2) "*The Impact of Hardwood Line-Planting on Tree and Amphibian Diversity in a Secondary Subtropical Wet Forest of Southeast Puerto Rico*" (*Journal of Sustainable Forestry*; available at https://www.tandfonline.com/doi/full/10.1080/10549810903479045).

I discovered that Puerto Rico's forest cover was rapidly increasing compared to the agricultural and deforested terrain that existed for most of the twentieth century. According to Frank Wadsworth, 25% of the island would need to be left as a forest to protect Puerto Rico's soils and watersheds fully.

Every article I read in our forest library referred to Frank. So when I met him at the International Institute of Tropical Forestry (IITF) library in San Juan, I was prepared with thought-provoking questions about the forest I was working and living in. This is a forest in which I spent much time admiring its large trees, like the Ausubo, Tabonuco, Majo, Caoba, Grenadillo, Motillo, and Caracolillo, as well as what potential line-planting and forest enrichment opened for the future.

Frank pointed me to the IITF's Forest Service publications, which appeared like a never-ending treasure trove of gold nuggets, and Peter Weaver would give me several publications to take away every time I visited the San

Figure 4. Thrity Vakil with wood piles at Puerto Rico Hardwoods, Caguas, after Hurricane María, 2017.

Juan library. When Frank talked about the potential output of tropical secondary forests, he always lit up. Frank was concerned that timber should be managed ethically and that Puerto Rico might have a small wood industry without contributing to deforestation in other countries by importing millions of dollars of wood from other countries. So we were motivated to read (aloud) Frank's book "*Forest Production in Tropical America*", to gain knowledge.

Andrés Ruá, from Marin, Patillas, joined the Las Casas de la Selva team in 2005 and was also inspired. He received directional felling training from US Forest Fire Fighters, and we learned about and practiced selective harvesting, low-impact felling, and extraction of trees, as well as milling and wood drying processes. As a result, Andrés built wonderful furniture and other items primarily out of Blue Mahoe hardwood grown at Las Casas, and we successfully sold wood from our plantations on and off the island from 2003 to 2017. Wood-turners from PR and mainland USA were particularly great customers, and Frank spoke about all the items that could be made that fit in a suitcase for the PR tourist industry to embrace, rather than coqui frogs and mugs made in China! In addition, Grupo Guayacan (a nonprofit organization dedicated to educating and developing local entrepreneurs in PR) awarded us their sustainability prize in 2016.

Frank ignited my interest in sustainable forestry, ecology, and biodiversity. Frank also enthusiastically supported our research initiatives (e.g., botanical, ornithological, mycological, and herpetological) and was astounded by the level of citizen scientists participating in them. However, Frank shared with us his frustrations. As a passionate and practical forester, he believed forests should be used for timber and recreational enjoyment, watershed protection, and habitat preservation. He would say with a laugh that he helped create beautiful forests all over Puerto Rico, but then they became so "protected" that none of its beautiful wood could be sustainably harvested.

We began a Liberation study, which followed Frank's strategy for increasing the growth of valuable trees for timber, habitat, or rarity within the secondary forest, thus increasing their economic worth. Unfortunately, Hurricane María interrupted this research in 2017.

We chatted quickly and passionately whenever we could meet at conferences and meetings. They were always memorable encounters because Frank was a knowledge transmitter. Nearby was Frank's great love, his wife Isabelita, who gave me the devotion of a mother and sister and welcomed me into their home with incredible warmth and openness.

They celebrated my unusual background; I was a Zoroastrian Iranian born in Nairobi, Kenya, lived in London from age 10 to 23, and then traveled widely

Figure 5. Woodpiles at Puerto Rico Hardwoods, Caguas, after Hurricane María, 2017.

Figure 6. Milled *Pterocarpus indicus* (from Hurricane María) at Puerto Rico Hardwoods' woodyard, 2018.

in Europe, the United States, India, and Nepal, before spending three years at sea. Frank was an ally to me as an outsider in a strange nation; every connection with Frank and Isabelita made my heart and head soar.

Together, they made multiple journeys to Las Casas de la Selva in Patillas over the past 20 years, and after Hurricane María, they came to see and support our budding enterprise, Puerto Rico Hardwoods (www.prhardwoods.com), in Caguas. We had gone into overdrive to collect hundreds of hurricane-felled logs from the streets and debris dumps, real treasure on the ground that mostly was lost all over the island after the disaster, discarded as trash by government agencies ironically tasked with safeguarding natural resources! Frank was similarly heartbroken when we published photographs and video footage of thousands of tons of priceless wood crushed and tossed into a landfill in the aftermath of Hurricane María. Nevertheless, he was a great supporter of our cause, and we kept him up to date on our wood production, forestry, tree-growing, and planting efforts until the end of his 106 years of earthly life.

He was delighted when Las Casas was certified as a Stewardship Forest, registered as an Auxiliary Forest, and when we received approval for our "*Sustainable Forestry Stewardship Management Plan*" (available at https://docplayer.net/87032298-Forest-stewardship-program.html). The dream and vision were becoming real. Frank Wadsworth's legacy lives on through the initiatives and people he inspired. He was a genuinely remarkable man and forester who introduced sustainable forestry to Puerto Rico, the Caribbean, South America, and worldwide. He adored Puerto Rico and its forests, many of which he helped to develop. In this section of the Puerto Rican rainforest that I live in, love, and protect, his life continues to inspire me—fare forward, traveler.

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FRANK H. WADSWORTH: CULTIVÓ LA CONSERVACIÓN EN PUERTO RICO

Ariel E. Lugo

Científico Emérito
USDA Forest Service

El Dr. Wadsworth llegó a Puerto Rico en barco el 27 de enero de 1942. Su plaza en Puerto Rico con el Servicio Forestal federal era una de dos opciones que la agencia le ofreció cuando contrajo matrimonio con la hija de su supervisor. En su juventud ya había trabajado en Alaska donde tenía opciones de trabajo, pero se decidió por la aventura del trópico.

Puerto Rico fue el ganador ya que, por los próximos 79 años, el Dr. Wadsworth enfocó su enorme energía, talento y disciplina en el desarrollo de la dasonomía tropical, una profesión con orígenes europeos que no existía en los trópicos del nuevo mundo en ese momento.

Gracias al Dr. Wadsworth y su colaboración con el gobierno y la academia de Puerto Rico, se desarrolló en Puerto Rico un movimiento de conservación enfocado en el uso sabio de sus recursos naturales, particularmente la tierra y sus bosques. La tesis doctoral del Dr. Wadsworth (Wadsworth 1949) sirvió de guía a la Junta de Planificación para planificar los usos de terrenos rurales y para proteger la periferia de El Yunque.

El Dr. Wadsworth fue instrumental en el desarrollo de la política pública que dio paso a la Junta de Calidad Ambiental, el Departamento de Recursos Naturales y a la Ley de Bosques de Puerto Rico. Además, apoyó la educación ambiental a través de sus esfuerzos con la Sociedad de Historia Natural de Puerto Rico, los Niños Escuchas de América, y el Centro Ambiental Santa Ana, en Bayamón.

Durante su incumbencia como empleado del Servicio Forestal federal, el Dr. Wadsworth fue silvicultor, líder de proyecto, y director del Instituto de Dasonomía Tropical cuando todos los programas de la agencia, incluyendo la supervisión del Bosque Nacional del Caribe (ahora El Yunque), estaban bajo su dirección. Terminó como voluntario de la agencia luego de su retiro.

Viajó el mundo representando al gobierno federal. En Latinoamérica, lo recuerdan porque estableció la práctica de la dasonomía tropical y fue responsable por el desarrollo de dasónomos que entrenaba en Puerto Rico y de escuelas de dasonomía tropical en varios países de Centro y Sur América. Escribió libros sobre los árboles de Puerto Rico, la isla de Mona, y la producción forestal de la América tropical. Fue protector de El Yunque asegurando que sus terrenos fuesen designados como un lugar para la investigación científica, la conservación del agua y la vida silvestre y la protección perenne de sus bosques históricos. Comenzó el esfuerzo de investigación sobre la Cotorra de Puerto Rico que evitó su extinción. El Dr. Wadsworth estableció las investigaciones ecológicas a largo plazo en El Yunque décadas antes de que los científicos se dieran cuenta de la importancia de ese enfoque de investigación.

La obra del Dr. Wadsworth sentó las bases para que tengamos en Puerto Rico los fundamentos técnicos para reforestar la tierra, optimizar la productividad de los bosques, conocer los árboles y saber qué arboles sembrar y donde, conocer las características de las maderas del país, y la importancia de la conservación del paisaje. Cinco universidades, incluyendo tres en Puerto Rico, le otorgaron doctorados honoris causa.

A través de los años, el Dr. Wadsworth se convirtió en un puertorriqueño y en el momento de su retiro recordó las bellezas de Puerto Rico que él tuvo la

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oportunidad de conocer, apreciar y conservar. Gracias a su labor, los puertorriqueños entendemos el valor y beneficios de los árboles y abogamos por el verdor de Puerto Rico. La semilla que el Dr. Wadsworth sembró durante su carrera profesional ha germinado en todos nosotros.

Testimonio Personal

El Dr. Wadsworth tocó a cada uno de nosotros, pero de manera distinta.

Quiero ofrecer testimonio de cómo me tocó a mí y cómo lo hizo sin llamarme la atención para darme una lección o un consejo. Las lecciones y consejos que me dio me las dio con sus acciones y ejemplo.

Colegialidad

Antes de trabajar en el Instituto, fui secretario auxiliar del Departamento de Recursos Naturales y en múltiples ocasiones recibí formalmente al Dr. Wadsworth en mi oficina. Era el director del Instituto, reconocido como la figura central del Servicio Forestal en Puerto Rico, pero siempre venía acompañado del supervisor del bosque y no entendía porqué. Lo entendí diez años después cuando fui director. Entendí la importancia de la colegialidad entre compañeros de trabajo para asegurar el funcionamiento de una institución. El Dr. Wadsworth era un empleado modelo porque entendía y practicaba la colegialidad. Era el único que leía y comentaba todos los manuscritos que producían los científicos del Instituto. Me enseñó una lección indispensable para ejercer la posición de liderato en la agencia.

Renunciar o compartir el crédito para acelerar el éxito

El Dr. Wadsworth no buscaba crédito personal o institucional por los logros que él hacía posible. Lean los 13 volúmenes del *Caribbean Forester* y pregúntese cómo es posible que tantos forestales de otros países pudiesen publicar tanto. La respuesta es que era el Dr. Wadsworth el que convertía notas y observaciones de otros en manuscritos científicos sin que en ningún lugar apareciese crédito por lo que hacía. ¿Quién escribió la Ley de Bosques de Puerto Rico? ¿Quién definió el concepto del Departamento de Recursos Naturales y de la Junta de Calidad Ambiental? No fueron las personas que recibieron el crédito. Imagínense mi sorpresa al descubrir en los archivos del Instituto la correspondencia donde el Dr. Wadsworth enviaba los borradores ya terminados para que otros estamparan sus nombres en las iniciativas. Tanto el Dr. Wadsworth, como mi mentor el Dr. Howard T. Odum, libremente compartían datos e ideas con otras personas para avanzar la interpretación científica de los datos y la misión de la ciencia y de la Institución. Una persona sola, no importa cuan brillante sea, puede lidiar con toda la complejidad de los sistemas naturales que estudiamos; los colaboradores son necesarios y tienen un precio y el Dr. Wadsworth pagó a expensas del crédito que se merecía con tal de avanzar la misión de conservación que tenía.

Ética gubernamental

No creo que nadie aquí puede imaginarse como me sentí cuando me di cuenta de que sería el supervisor del Dr. Wadsworth. Particularmente en el gobierno federal donde el supervisor tiene que sentarse cara a cara con el empleado varias veces durante el año para planificar, verificar y finalmente juzgar el trabajo del empleado. Nadie lo entrena a uno para llevar a cabo tal labor. Existe solo una regla absoluta en el servicio federal: traqueteas con el tiempo o el dinero, so pena de perder el empleo. En una época sin computadoras o cajeros automáticos, los empleados llevaban el récord de sus horas trabajadas en papel. Dentro de la jornada de trabajo los empleados tenían cierta libertad con el uso del tiempo, excepto que si se pasaban de 15 minutos, tenían que pedir vacaciones por el tiempo utilizado y el supervisor tenía que aprobar el pedido firmando una *Standard Form* 71. Una tarde al principio de mi incumbencia en el Instituto llega a mi escritorio una SF 71 firmada por el Dr. Wadsworth pidiendo 15 minutos de vacaciones. Tome la forma y fui directo a su oficina para preguntarle el significado de tal pedido que consideraba innecesario. Me explicó que durante la hora del almuerzo fue al banco pero la fila era muy larga y se pasó de la hora que tenía. Me dijo que de acuerdo con las regulaciones, era necesario reportarlo para mantener la integridad de su horario. ¡Cuánto aprendí en ese momento!

Conservación y Manejo

Los forestales y los ecólogos siempre han estado en conflicto. Se entrenan en las mismas universidades pero en facultades distintas con cursos distintos sobre el mismo sistema de estudio, los bosques. Cuando se gradúan entran en conflicto porque tienen diferentes puntos de vista sobre el manejo y conservación de los bosques. Siendo ecólogo, ¿Cómo iba a dirigir una organización forestal? El Dr. Wadsworth me reeducó con su ejemplo y conlos comentarios que le hacía a mis manuscritos. A veces eran tan contundentes que me obligaban a repensar las cosas y poco a poco entender dos puntos centrales que transformaron mi entendimiento:

a. La conservación no es exclusiva a los ecólogos, está compartida con la dasonomía la cual está fundamentada en la conservación;
b. El manejo profesional es conservador y por lo tanto sinónimo con la conservación. El error esta en llamar “manejo” a actividades explotadoras justificadas por motivos ajenos a la conservación.

El Dr. Wadsworth promovió la conservación de los bosques de Puerto Rico sin sacrificar los servicios ecológicos que los bosques proveen. Estableció sistemas de manejo forestal basados en la ecología, sin ser el un ecólogo de profesión, pero era más ecólogo que los ecólogos formados. A todos nos dio clase y nos demostró que el uso de los bienes ecológicos no es incompatible con la conservación, que es posible sembrar y cortar árboles en forma sustentable, que hay espacio para todo lo que tenemos que hacer para vivir siempre y cuando lo hagamos profesionalmente. Necesitamos honrar el legado del Dr. Wadsworth profesionalizando la conservación de los bosques de Puerto Rico.

¡Que el bosque esté con él!
May the Forest be with him!

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DASONOMÍA TROPICAL A LO BORICUA: DESDE LA SEGUNDA GUERRA MUNDIAL HASTA LA GUERRA FRÍA

Jorge Nieves Rivera[1]

[1] Estudiante doctoral de Historia y Estudios Contemporáneos de la Universidad Jaume I, Castellón de la Plana, España.
* Correspondencia: jorgenr1081@gmail.com

El advenimiento de la Segunda Guerra Mundial trajo un manejo distinto a los bosques de los Estados Unidos. La escasez de materia prima a causa de la Guerra en Europa y Asia hizo que el gobierno estadounidense pusiera en función de la Guerra a todas sus agencias para cumplir con la exigencia de alimentos, minerales, energía y madera que requerían las industrias bélicas y civiles. Estó permitió que el Servicio Forestal de los Estados Unidos y el "War Production Board" trabajaran mano a mano para cumplir con las expectativas de extraer billones de pie tablal. Para lograr las altas cifras, los Bosques Nacionales se convirtieron en una fábrica de recursos naturales para la industria de guerra (Hirt 1994). En el Bosque Nacional El Yunque (antes Bosque Nacional del Caribe), por ejemplo, se estableció una industria para extraer madera para carbón entre el 1940 a 1944, que aportó unos 3 255 997 de pie tablal para tales fines (Robinson et al. 2014). Por estas razones, la madera, llegó a ser clasificada como material crítico para la guerra en el 1942 en los Estados Unidos de América (EE. UU.).

Bajo este escenario llegó a trabajar a Puerto Rico como investigador en la recién fundada Estación Experimental Tropical Forestal el científico estadounidense Frank Howard Wadsworth. Contaba con un bachillerato y maestría en dasonomía de la Universidad de Michigan, con enfoque en la ecología de Alaska; sin embargo, nunca había visitado el trópico. Gracias a la ayuda del asistente de investigación, el silvicultor José Marrero, Wadsworth se empapó de los esfuerzos realizados por diferentes científicos predecesores y emprendieron una relación profesional que duró décadas y que transmitieron un caudal de información sobre nuestros bosques a futuras generaciones.

José Marrero y Frank H. Wadsworth comenzaron, a partir del 1942, estudios para mantener a salvo las plantaciones realizadas por el Cuerpo Civil de Conservación (CCC) desde 1934 a 1941. Muchas plantaciones habían fracasado por haberse sembrado en condiciones no aptas para las especies nativas o exóticas. Por lo tanto, se dieron a la tarea de investigar el por qué las plantaciones no habían prosperado. El objetivo del estudio sobre la regeneración y reforestación a gran escala implementada consistió en resumir toda la evidencia con respecto a la relación entre diferentes especies sembradas y su medioambiente (Marrero 1950). Para examinar este objetivo, establecieron una serie de clasificaciones de acuerdo al lugar y condiciones en los que estaban sembrados: el clima, la fisiografía, características edáficas y la biología serían las variables principales de estudio (Marrero 1950). Desde entonces, aplicaron dicha metodología y objetivo a los bosques insulares descubriendo importantes hallazgos sobre la supervivencia de las plantaciones con árboles nativos y exóticos de los trópicos tales como la caoba (*Swietenia mahogoni*) y el árbol de Maga, *Thespesia grandiflora* (antes *Montezuma speciosissima*). Las diferentes parcelas de investigación de árboles se podían encontrar desde condiciones extremadamente secas, como en el bosque de Guánica, hasta en condiciones más húmedas, como las del Bosque Nacional El Yunque. Sin embargo, para conocer la adaptación de árboles tanto nativos como exóticos en zonas del carso norteño, el Servicio Forestal aprovechó un desembolso de fondos de emergencia por motivos de guerra y terrenos cedidos por la Autoridad de Tierras para crear el Bosque Experimental de Cambalache en el 1943 (Domínguez Cristóbal 2000).

El progreso de las plantaciones fue tal que ganó notoriedad dentro del campo del manejo de bosques tropicales en el Servicio Forestal de los Estados Unidos. Por tal razón, una vez terminada la Segunda Guerra Mundial, el modelo de dasonomía "*a lo boricua*" será exportado a diferentes países tropicales tanto de América como de África, Asia y Oceanía. Los diferentes programas científicos, militares y acuerdos de colaboración entre los EE. UU. y sus aliados, permitió un intercambio de conocimiento sin precendetes en materia del manejo de bosques tropicales con fines científicos, comerciales y hasta militares.

Cabe señalar que para lograr tal hazaña de reforestación y regeneración a nivel insular no solamente se logró gracias a la observación y medición. Hubo además una revisión de literatura de parte de los científicos locales que sin duda nutrió y enriqueció la investigación. Los artículos publicados por los científicos extranjeros sobre los bosques tropicales del Caribe sirvieron como referencia para la ciencia forestal boricua. Los estudios de los científicos ingleses tales como John Beard, John Carter y R. L. Brooks sobre el Caribe, ayudaron a conocer a fondo cómo aplicar técnicas de dasonomía y silvicultura en suelos tropicales (Steen 1998). Fueron ellos los responsables de establecer las primeras plantaciones de árboles de Teca (*Tectona grandis*) en el Caribe, a través de Trinidad y Tobago en el 1913 (Steen 1998). Arthur Beaven, el primer director de la Estación Experimental de Bosques Tropicales, fue uno de los primeros estadounidenses en establecer contacto con dicha academia. Sin embargo, estos lazos se fortalecieron durante y pasada la Segunda Guerra Mundial.

Como parte de los acuerdos de cooperación establecidos por Gran Bretaña y EE. UU., las ciencias, y sobre todo la dasonomía y la silvicultura, lograron tener su propio lugar. La Comisión Anglo-Americana del Caribe (CAAC) creada desde el 1942, abrió un espacio de cooperación en donde investigadores puertoriqueños intercambiaban conocimiento científico-técnico. El fin de esta comisión era estimular y fortalecer la cooperación socioeconómica entre los EE. UU. e Inglaterra y sus territorios en el Caribe (Rosario Urrutia 1993). En el marco de la Segunda Guerra Mundial, EE. UU. buscó la forma de asegurar aliados dentro del Gran Caribe con el objetivo de redoblar la defensa y seguridad de la región ante la amenaza de los submarinos nazis en las Antillas. La construcción de bases en las Antillas Menores, tales como en Trinidad, fueron parte de este sistema defensivo. De la misma forma, el panamericanismo lanzado por los EE. UU. durante la conferencia de Río de Janeiro en el 1942, estableció acuerdos similares con Suramérica que le garantizaba además de aliados políticos, económicos y militares, aliados científicos. La CAAC contó con un concilio de investigación caribeña como parte de sus cuerpos auxiliares. Fue allí donde hubo un espacio para que la ciencia criolla se exportara e intercambiara conocimientos sobre dasonomía tropical de los EE. UU. En 1945, estos cuerpos se integraron a varios puertorriqueños incluyendo a figuras de renombre tales como Carlos Chardón, Pablo Morales Otero y a Rafael Picó. Aunque aún no hemos encontrado los nombres de Marrero y Wadsworth como parte de los miembros, sí encontramos la participación de puertorriqueños en los comités de forestación que estableció el concilio de investigación (Rosario Urrutia 1993).

A partir del fin de la Segunda Guerra, el tema forestal continuó presente en la política exterior de los Estados Unidos, sobre todo para la región del Caribe y Latinoamérica. Diferentes comisiones fueron creadas con el fin de dar apoyo cientifico-técnico al continente en búsqueda de perpetuar sus aliados en la zona. Una vez finalizada la guerra y los nazis fuera del panorama, un nuevo paradigma surgió en términos de defensa y seguridad. La continua búsqueda de aliados en contra de los posibles nuevos enemigos de EE. UU. tales como la Unión Soviética, fomentó el estrechar más aún los lazos de cooperación en todas las áreas posibles con los países del Caribe y de Latinoamérica ante la llegada de una guerra fría y la polarización del planeta.

Según la filosofía desarrollista imperante en la época, la asistencia en tecnología y ciencias permitía "un desarrollo económico y social" en la posguerra que solo debía ser ilustrado por las dos super potencias vencedoras de la Segunda Guerra: la Unión Soviética y los Estados Unidos (Funes Monzote 2019). De esta forma surgieron organismos de parte de EE. UU. y los aliados tales como lo fue la "Food and Agriculture Organization of the United Nations", el "Latin American and Caribbean Forestry Commission" en el 1948 y el programa del Punto IV en el 1949. Mediante estos organismos y sus programas se otorgaron becas a personal latinoamericano y caribeño para ser adiestrado bajo las técnicas del servicio forestal estadounidense. El tema de la agricultura y el manejo forestal, serán una plataforma para lograr posicionar a Puerto Rico como la "*vitrina del manejo de bosques tropicales a lo boricua*" para Latinoamérica y el Caribe a través del Punto IV. El nombre del programa, se derivó del cuarto objetivo establecido por el Presidente de los EE. UU., Harry S. Truman, como parte de su política exterior. En resumen, además de promover los valores y costumbres estadounidenses por toda América, dicho punto planteaba cómo la asistencia técnica de parte de EE. UU. a países subdesarrollados les ayudarían a alcanzar la industrialización y el urbanismo necesario para la prosperidad.

El dasónomo estadounidense Frank H. Wadsworth fungió como respresentante de los EE. UU. en ambos programas. Participó por más de una década en decenas de reuniones en Chile, Argentina, Brasil y Centroamérica promocionando los avances científicos-técnicos logrados en el Caribe. El exitoso programa de regeneración y reforestación tanto de bosques insulares como federales, fueron carta de presentación y se impulsó como modelo a seguir para la danomía de Latinoamerica y otras partes del trópico.

Uno de los medios que facilitó la difusión de la información fue la Estación Experimental de Bosques Tropicales en Río Piedras (cambia su nombre a Instituto Experimental de Bosques Tropicales en el 1955 y luego, en 1992, adquiere su nombre actual Instituto Internacional de Dasonomía Tropical). La Estación fue creada en el 1939 y su objetivo principal fue investigar sobre la dasonomía tropical y difundir sus hallazgos con el resto del Latinoamérica y el Caribe (vea frontispicio de *The Caribbean Forester* 1939; disponible en https://www.biodiversitylibrary.org/item/161188#page/1/mode/1up). El contraste de la estación experimental con las otras estaciones experimentales creadas a principios de siglo era que se dedicaba en su totalidad a la investigación sobre los bosques tropicales tanto en manos públicas como privadas. Desarrolló una cooperación académica con la Universidad de Puerto Rico y adiestró a personal gubernamental y dueños de fincas privadas sobre el nuevo modelo forestal boricua desarrollado por el binomio Wadsworth–Marrero. Por esa razón, se va a convertir en el centro académico principal para llevar a cabo los adiestramientos, talleres e internados a los estudiantes y personal forestal auspiciados con fondos del Punto IV y otros programas.

Según un artículo publicado en la revista *Caribbean Forester* en abril de 1950, titulado: *Adiestramiento forestal en Puerto Rico bajo el programa del "Punto Cuarto"*, Puerto Rico, ofrecía oportunidades únicas para estudiar ciencia forestal. Desde la Isla del Encanto, se podía estudiar cuatro aspectos de la dasonomía: 1) administración forestal, 2) investigación forestal, 3) dasonomía de extensión 4) e inter-relaciones de la dasonomía con otros usos del terreno (Anónimo 1950a). Sin embargo, una de las razones principales para estudiar la dasonomía tropical de la isla era la similitudes de especies que existían entre las más de 100 000 000 de hectáreas que compartía el Gran Caribe (Anónimo 1950a). Además, agregaba que, la escasez maderera que había en la isla producto de la densidad poblacional era un problema común en latinoamérica. Por tal razón, los esfuerzos realizados en la ciencia forestal puertorriqueña debían servir de modelo para el resto de la región (Anónimo 1950a).

Las gestiones de promoción llevadas a cabo por Wadsworth a través de las diferentes reuniones llevadas a cabo en diferentes países permitió la asistencia técnica a países como Costa Rica, Ecuador, Chile e Islas Vírgenes. Además, se recibió a estudiantes y personal relacionados a los bosques becados con fondos de Punto IV de Cuba, Bolivía, Haití, Costa Rica y Venezuela (Anónimo 1950b). Los internados tenían una duración de 13 meses y se utilizaba como parte de los laboratorios a los bosques insulares y federales. El recién inaugurado Bosque Experimental de Cambalache, el Bosque Nacional del Caribe (El Yunque), el Bosque de Toro Negro y los 11 bosques insulares servían de salón de clases para conocer sobre dasonomía tropical caribeña. Por otro lado, se le proveyó plataformas académicas para publicación de investigaciones e intercambiar conocimiento científico. En el 1939, surgió la revista *Caribbean Forester* como medio oficial para publicar investigaciones realizadas por la Estación Experimental de Bosques Tropicales (su lema es "*It is my pride and joy to be the shepherd of my country's trees*"). No obstante, también se invitaba a participar a científicos e investigadores del Caribe. Su publicación fue muy importante debido a que se convirtió en el primer foro académico en compartir investigaciones tanto del Caribe hispano como del Caribe inglés y francés escritas en sus respectivos idiomas. Por más de una década, Wadsworth se convirtió en su editor principal y en uno de sus autores. Sin embargo, aunque sus escritos son menos conocidos, José Marrero publicó una serie de artículos científicos relacionados a los estudios realizados sobre ciencia forestal puertorriqueña.

Las investigaciones realizadas por el binomio Wadsworth–Marrero desde el 1942 sobre los bosques tropicales de la isla llevó a recopilar suficiente información para desarrollar la tesis doctoral de Wadsworth, sobre dasonomía tropical, tomando como ejemplo el Bosque Nacional El Yunque y para que José Marrero terminara sus estudios de maestría en la Universidad de Michigan. Pero también produjo una de las publicaciones más significativas de mediados del siglo en colaboración con el científico estadounidense Elbert L. Little, Jr.: *Árboles comunes de Puerto Rico y las Islas Vírgenes en 1967.*

A partir del 1950, la Estación cambió su nombre de estación por Instituto debido a rol educativo-científico que había tomado durante la posguerra y el Yunque se convirtió en bosque experimental en su totalidad. Wadsworth pasó a ser el director de ambas divisiones del servicio forestal en Puerto Rico desde el 1956 (Robinson et al. 2014). A partir de ese momento, Wadsworth se convirtió en la figura más influyente y determinante de todos los bosques públicos a nivel insular, tanto estatales como federales, hasta el 1973. Fue durante ese periodo que se llevaron a cabo los controversiales estudios con rayos gamma en El Yunque (aplicar radiación a una parte del bosque tropical) y también el uso de defoliadores químicos como Agente Naranja durante la década de los 60. Por otra parte, José Marrero se retiró de su servicio como silvicultor del Servicio Forestal en el 1965.

Los programas de internado y cooperación se enmendaron pero continuaron por un tiempo. No obstante, a pesar de los esfuerzos de colaboración hubo diferencias entre los participantes de la Latin American Forestry Comissions. Todo parece indicar, que tanto aspectos sociopolíticos como científicos fueron parte de las desavenencias entre los países miembros. No todos los miembros estaban de acuerdo en tomar como bandera infalible los avances realizados por los estadounidenses desde Puerto Rico. Diferencias políticas, sociales y económicas se sumaban a la lista de contrastes entre la Isla del Encanto y Latinoamérica. También, se reclamó la continua explotación de recursos naturales por parte de los Estados Unidos a raíz de la gran aceleración industrial que experimentó a partir de mediados del siglo XX. Sin embargo, las aportaciones que realizaron ambos científicos para la dasonomía tropical fueron pieza importante para posicionar a los EE. UU. y a Puerto Rico dentro los países claves para estudiar dicha materia. Sus hallazgos son todavía hoy fuente primaria de consulta para los estudios de la ciencia forestal en los trópicos.

Por las razones antes expuestas, y en el contexto histórico correcto, es importante darle una nueva mirada a las aportaciones realizadas por ambos científicos a la luz de nuevas fuentes y nuevas vías de estudio tales como la historia ambiental. Sin duda, el conocimiento producido por Frank H. Wadsworth y José Marrero traspasó las fronteras académicas de las ciencias naturales y debe ser estudiado a fondo por las ciencias sociales y la historia, no solamente de Puerto Rico sino de Latinoamérica.

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APUNTES BIOGRÁFICOS DEL DR. FRANK H. WADSWORTH: UN GRAN PUERTORRIQUEÑO

Elsie Rivera Ocasio[1,*] and Neftalí Ríos López[2]

[1] Departamento de Biología, Universidad de Puerto Rico en Bayamón, 170 Industrial Minillas, Carr. 174, Bayamón, Puerto Rico, 00959-1911.
[2] Departamento de Biología, Universidad de Puerto Rico en Humacao, Avenida José E. Aguiar Aramburu, Carr. 908, km 1.2, Humacao, Puerto Rico, 00792.
* Correspondencia: elsie.rivera@upr.edu

Este breve ensayo biográfico-histórico está principalmente basado en el libro autobiográfico "A Forestry Assignment to Puerto Rico – Forestry Memoirs of Frank Wadsworth" (2014).

Frank Howard Wadsworth nació el 26 de noviembre de 1915 en Chicago. Pasó su infancia en el lado noroeste de Chicago donde vivió con su madre y su padre. Estudió desde edad preescolar hasta octavo grado en Norwood Park Elementary School y más tarde hizo su escuela superior en en la escuela pública Carl Schurz High School en Portage Park, Chicago, Illinois. A sus 13 años tuvo su primera experiencia en los niños escuchas en la Tropa 899. No obstante, su interés por la biología inició luego de acompañar a su amigo de Tropa, Donald Duncan y su padre –que era maestro de biología– a una charca cercana donde aprendió sobre aves y su entorno natural. Más adelante, estas experiencias recurrentes al campo le sirvieron como motivación para elegir su carrera profesional en silvicultura.

En 1935 comenzó estudios en la escuela forestal y de conservación de la Universidad de Michigan en Ann Arbor donde aprendió identificar árboles y aves, así como realizar inventarios forestales, a utilizar el hacha y la sierra (instrumentos esenciales en el campo) y a combatir fuegos forestales, entre otras destrezas. En el verano de 1936 fungió como asistente de un profesor de la Universidad de Michigan, recolectando hongos de árboles en Alaska y estudiando la regeneración y sucesión de árboles en bancos de arena reciente a lo largo del río Yukon.

En 1937 se graduó de bachillerato en manejo forestal con créditos avanzados del Instituto Lewis (hoy el Illinois Institute of Technology en Chicago) y una tesis en el trabajo de Alaska, obtuvo al mismo tiempo un grado de maestría en forestal. Sus estudios doctorales los completa luego de haber trabajado en Puerto Rico por 5 años. Guiado por su profesor de manejo forestal de la Universidad de Michigan, el profesor Donald Matthews –quien al visitar la isla de Puerto Rico orientó al joven Wadsworth a completar un grado doctoral sobre el crecimiento de los bosques y el mantenimiento de cosechas sustentables de madera– presenta y publica su disertación en el 1949 (Wadsworth 1949), bajo la dirección del profesor Samuel T. Dana, en la Universidad de Michigan.

Una vez graduado, trabajó para la compañía Evergreen Lumber en el lado sur de Chicago; luego fue asistente temporal de Gustavo Adolfo Pearson, Director del Servicio Forestal en la estación Southwestern Forest and Range Experiment Station en Fort Valley, Flagstaff, Arizona. Como parte del registro de servicio

Figura 1. Hojas y frutos de *Byrsonima wadsworthii* Little, 1953 (nombre común: Almendrillo); Maricao, Puerto Rico. Crédito: Pedro Acevedo-Rodriguez, hosted by the USDA-NRCS PLANTS Database (2022); provista con permiso por Smithsonian Institution, Department of Botany.

civil, trabajó como asistente semiprofesional en Nebraska y luego pasó a ser investigador forestal profesional en Bosque Experimental Fort Valley (Wing Mountain Unit). Allí participó del Cuerpo Civil de Conservación cuando fueron llevados a Flagstaff para ayudar en la expansión de facilidades, edificios y estructuras del lugar durante los 1930s. Fue ahí, y como parte de dicha experiencia, donde compartió con el doctor Elbert L. Little, Jr., un botánico de la Universidad de Chicago y con quien le tocó compartir su cabaña en el lugar. Años más tarde, como compañeros de colectas botánicas en Puerto Rico, Elbert describiría y nombraría en su honor *Byrsonima wadsworthii* (Little 1953; Figura 1), una especie rara de árbol, distinguible de otras *Byrsonima* spp. en Puerto Rico por sus hojas elípticas y coriaceas cubiertas, en la parte inferior, de muchísimos tricomas ("vellos") grisáseos y muy finos, así como por sus flores pequeñas con pétalos blancos que se tornan rosados con la madurez previo a la fructificación.

En 1941 se casó con Margaret Pearson, hija de uno de sus antiguos supervisores, con quien estuvo casado por 43 años, hasta el 1983 cuando enviudó. En 1941 pasó a ocupar la posición dejada por Leslie Ransselaer Holdridge en la Estación Experimental del Servicio Forestal Tropical (y quién llegara a Haití en octubre de 1941 como Manejador de la División Forestal de la Sociedad Haitiano-Americana de Desarrollo Agrícola). Indica Wadsworth en su autobiografía (p. 10; Wadsworth 2014) que llegó a Puerto Rico el 27 de enero de 1942 y luego pasó a vivir en un apartamento en la avenida Ponce de León en Río Piedras.

Inicialmente, el Dr. Wadsworth se encontró con una isla bien modificada por el hombre – tal y como describiría Rexford Guy Tugwell en su libro “The Stricken Land” (entonces designado Rector de la Universidad de Puerto Rico en 1941 y el mismo año gobernador de Puerto Rico hasta 1946) – y con la influencia de los estragos y secuelas de la Segunda Guerra Mundial en su apogeo. Por tanto, Puerto Rico era un reto extraordinario para cualquier ingeniero forestal, iniciativa socioeconómica y esfuerzo de bioconservación. Presumiblemente, al Dr. Wadsworth debió inundarle la misma sensación que Tugwell plasmaría en su discurso inicial al ser designado Gobernador de Puerto Rico (Gobierno de Puerto Rico, 1945):

> *“What can a Governor of Puerto Rico say on his inaugural day? He is not yet fully aware of his responsibilities; he has not yet tested the capacities of his office. He cannot therefore forecast much detail what he will do. He can, however, express his sense of dedication to the duties which lie ahead and point out certain of the problems to whose solution will turn first.” (p. 5, Inaugural Address, September 19, 1941; Gobierno de Puerto Rico 1945).*

En resumen, Wadsworth encuentra un Puerto Rico que:

> …cerca de un tercio de la isla era cuencas de montaña para las reservas para la irrigación, para el consumo humano y para la producción de energía. La agricultura de subsistencia exponía el suelo a erosión desmedida en las montañas. La producción comercial de tomate en las pendientes arenosas era apoyada por el servicio de conservación de suelos; se producía tabaco en las pendientes y la caña de azúcar en los valles, interiores y en zonas costeras, donde incluso se drenó la inmensa mayoría de manglares a estos fines y por consideraciones “salubristas”. En resumen, una isla esencialmente deforestada con gran erosión en el suelo, incluyendo las cuencas de los ríos, lo cuales se teñían de rojo por el sedimento que sin embargo, también se dirigía a las reservas de agua.
>
> Igualmente, más del 70% de la población de entonces era rural y vivía en las montañas expuestas a los huracanes en casas de madera y palma, sin servicio sanitario. Las poblaciones de aves estaban devastadas y los bosques solo se mantenían donde la agricultura era prácticamente imposible, en las pendientes más extremas y en los climas más secos o en terrenos salinos y salobres. Aún en las áreas del carso y sus suelos escabrosos y rocosos, había cultivos extensos donde se producía café con algo de sombra, no por bosques, sino por una o dos especies de árboles. Aún en las reservas de bosques públicos había cientos de familias viviendo y cultivando. Muchas compañías de madera local apoyaban la industria de los muebles, ya que había más de 200 fábricas de muebles que empleaban a más de 2600 trabajadores a tiempo completo.

Tal era el reto que el doctor Wadsworth se enfrentaría en lo forestal. Sin embargo, él facilita el inicio de la construcción de viveros de plantas para aumentar la cubierta forestal en bosques públicos y en terrenos recién adquiridos para reducir la erosión del suelo; esto, junto al grupo de empleados de su agencia y con colaboración de la estación experimental agrícola de la Universidad de Puerto Rico e inicialmente, en el contexto de un gobierno muy consciente de los retos socioeconómicos del Puertorriqueño pero que vería los recursos naturales como materia para “intensificar su explotación de manera que aumentara las fuentes de empleo e ingresos económicos” (Tugwell 1947). Balancear el manejo y conservación del paisaje forestal en el entorno sociopolítico de entonces era un acto de malabarismo en si mismo … y requería de la más efectiva planificación para su consecución y, de paso, la protección misma de nosotros.

De 1943 a 1952 el doctor Wadsworth dedicó gran parte de su tiempo a la investigación forestal junto a un grupo de científicos y de trabajadores del servicio forestal que lograron identificar múltiples especies que estaban adaptadas para las condiciones del Puerto Rico de esa década. Separaron áreas de exclusión donde no se podía modificar la vegetación, incluso para la experimentación. Por tanto, su conexión con la historia forestal en Puerto Rico incluye el establecimiento del Bosque Estatal de Cambalache en Arecibo en 1944; a poco más de dos años de su llegada, Wadsworth publicaría los resultados de su gestión en la Estación Experimental de Cambalache (*The first year in the Cambalache Experimental Forest*, traducido al español y francés en el mismo volumen; Wadsworth 1944). Prosiguió el desarrollo y reforestación de otros bosques que eventualmente entraron a la red de bosques estatales tales como el bosque de Guajataca, Guilarte, y el Bosque de Toro Negro; este último canjeado con el gobierno de Puerto Rico a cambio una extensión adicional de terreno designado en Luquillo.

Evidentemente, el Dr. Wadsworth fue testigo de eventos históricos tales como la guerra, los cambios de gobiernos en Puerto Rico y sistemas políticos en Latinoamérica y el mundo. Estos cambios también operaron sobre otros científicos en general y de alguna manera influyeron sobre la comunicación y colaboración de la ciencia en Puerto Rico, el Caribe y en el resto del mundo. En lo particular, y siendo parte fundamental del Servicio Forestal de Estados Unidos en Puerto Rico, el Dr. Wadsworth colaboró y aportó al adiestramiento y educación de nuevos científicos forestales ofreciendo – como esfuerzo ejemplar para la silvicultura Latinoamericana y mundial – cursos especializados en lo forestal a sobre 253 estudiantes, muchos extranjeros, y de sobre 15 países. Participó además de múltiples foros internacionales de relevancia mundial en temas forestales y de agricultura.

Igualmente, fue pionero en estudios forestales sobre la estructura de los bosques y las tasas de crecimientos de especies nativas en Puerto Rico. Aportó significativamente a la conservación de los bosques y a la recuperación de la cubierta forestal en gran parte de Puerto Rico; junto a otros empleados del Servicio Forestal participó en la siembra de sobre 5 millones de árboles en distintas áreas en Puerto Rico.

Ha promovido el respeto a la naturaleza y a la educación ambiental a través de las experiencias con los Niños Escuchas de América (Boys Scouts of America) en Puerto Rico y que desde su infancia lo influyó significativamente en su carácter como ciudadano ejemplar. Fue fundador del campamento de los Niños Escuchas en Guajataca, donde ayudó a la reforestación de la cuenca que aporta agua al lago Guajataca. En su relación con esta organización fue el líder y responsable de 50 años continuos de la organización del “Nature Team” que aparte del campamento anual en Guajataca, incluía un viaje a la Isla de Mona. A su retiro dejó como legado un Manual de la Naturaleza para que continuaran con las iniciativas en la organización.

Igualmente, como director del Servicio Forestal no solo contribuyó a la ciencia, sino que además participó en diversas luchas ambientales como lo fue la oposición al uso del Cañón de San Cristóbal como vertedero municipal e iniciativas de política pública (Lugo 2022, este volumen). El Dr. Wadsworth fue además miembro activo de la Sociedad de Historia Natural de Puerto Rico, y como parte de su participación en esta sociedad es uno de los fundadores del Centro Ambiental Santa Ana, ubicado en el Parque Nacional Julio Enrique Monagas en Bayamón, Puerto Rico. También ha pertenecido a infinidad de organizaciones dedicadas al estudio y conservación del ambiente, entre estas; Les Voyageurs de la Universidad de Michigan, International Society of Tropical Foresters, The Society of American Foresters, American Foresters, the Forest History Society of the United States, The Caribbean Conservation Association, Island Resource Foundation, Fideicomiso de Conservación de Puerto Rico, Sociedad de Historia Natural de Puerto Rico, Puerto Rico Council, Overseas Arrowman

Association of the Boys Scouts of America, Oficial voluntario del IITF y Asociación Nacional de Retirados del Servicio Forestal.

Entre los premios y reconocimientos que ha recibido estan: The forestry profession, USDA Forest Service (Research Forester; USDA Forest Service Superior Service Award [twice]; Bernhard Fernow Award for Foreign Forestry Service; Chief's Award for New Century of Service; Emeritus Scientist of International Institute of Tropical Forestry); Renewable Natural Resources Foundation (Sustained Achievement); Society of American Foresters (Fellow); New York State College of Forestry and Environmental Sciences (Doctor honoris causa); Universidad de Puerto Rico–Mayagüez (Doctor honoris causa); Universidad de Puerto Rico–Cayey (Doctor honoris causa); Universidad del Sagrado Corazón, San Juan (Doctor honoris causa); Boy Scouts of America (Chicago – Lone Scout to Eagle Scout, Ordeal Member, Order of the Arrow; Puerto Rico – Cub master and Scoutmaster, Yokahu Lodge Order of the Arrow Founder, Brother and Vigil Member, Order of the Arrow, Distinguished Member-Order of Arrow, Silver Elephant-the Overseas Order of the Arrow, Silver Beaver, Chairman-Council Camping Committee; Northeastern Region, New York – Hero, National Council, Hornaday Award); Puerto Rico Natural History Society (Member Emeritus); International (UN-FAO-Latin American Forestry Commission, Six-year Chairman-Regional Committee on Forest Research); Centro Agronómico Tropical de la Investigación y Enseñanza, Costa Rica (Doctor, honoris causa); Puerto Rico (Premio Trayectoria Extraordinaria Doctor Agustín Stahl - 2020).

Para finalizar, destacamos la sabiduría que resultó del acto de malabarismo que antes mencionamos y culminamos reproduciendo su "*Punto de Vista sobre la Silvicultura para Puerto Rico*" (Wadsworth 2014) y algunas metas que recomienda don Frank Howard Wadsworth para actuales y futuros silvicultores, conservacionistas y hacedores de política pública en un Puerto Rico para todos:

A Viewpoint on Forestry for Puerto Rico

Forests returned painlessly to the mountains
Forests are now visibly key to freshwater
Acceptance of forests is now de facto
All native tree species are still here
These are prospects for forestry.

Some goals for future foresters:

General

Keep abreast of relevant forestry progress
and technology elsewhere
Preserve somewhere the complete variety
of mature native forests
Exploit the outspoken love of Puerto Rico
for forest appreciation
Expose school students repeatedly to forests
and their benefits
Harmonize forest conservation
and economic development

Specifics

Claim for forests rural lands unsuited
or for sustainable agriculture
Increase government incentives for private
forests above reservoirs
Increase watershed coverage of public forests
Introduce into public forests native tree species
now not therein
Increase trees that support wildlife
Utilize wood sustainability for artisans, furniture,
structures, charcoal.

From the Arrow I received self-confidence,
From forestry and the Service, I saw potentials,
And from Puerto Rico what and how to approach.

Frank H. Wadsworth

Figura 2. Firma doctor Frank H. Wadsworth –

El Dr. Wadsworth, junto a su segunda esposa y compañera de viaje, Isabel Colorado Laguna, siempre disfrutó de la siembra en las tierras que ambos cosechan. Una vida ejemplar con un mensaje profundo para todos en el país – gracias por estar, don Frank.

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SURVEYS IN UNPROTECTED AREAS YIELD ADDITIONS TO THE NON-NATIVE FLORA OF PUERTO RICO

Steve Maldonado-Silvestrini[1,2,*], Johann D. Crespo-Zapata[1], and William A. Gould[1]

[1] USDA Caribbean Climate Hub, U.S. Department of Agriculture Forest Service, International Institute of Tropical Forestry, Río Piedras, PR 00926.
[2] Herbarium, Department of Biology, University of Puerto Rico-Rio Piedras Campus, San Juan, PR 00931.
* Author for correspondence: silvestrinistiv@gmail.com

Abstract

For centuries, the Caribbean island of Puerto Rico has been subjected to the introduction of non-native plant species. Various human-related activities such as agriculture, horticulture, and ornamental landscaping have resulted in the naturalization of numerous species, some of which are now representative of the island's natural landscape. Recent floristic surveys in anthropized areas across the island yielded three new non-native plant records. We present the first reports with vouchers of *Asystasia gangetica* (L.) T. Anderson subsp. *micrantha* (Nees) Ensermu, *Emilia praetermissa* Milne-Redh., and *Acanthocereus tetragonus* (L.) Hummelinck for Puerto Rico. We review their geographic distributions, status on the island, and introduction pathways, and offer comments on the importance of surveying disturbed and unprotected areas.

Keywords: *Acanthocereus tetragonus*, *Asystasia gangetica* subsp. *micrantha*, *Emilia praetermissa*, naturalized plants, floristic inventories, non-native flora, Puerto Rico.

Resumen

La isla caribeña de Puerto Rico ha estado sujeta a la introducción de especies de plantas no nativas durante siglos. Varias actividades relacionadas con el ser humano, tales como la agricultura, horticultura, y paisajismo ornamental, han resultado en la naturalización de numerosas especies de plantas, algunas de las cuales hoy en día son representativas del paisaje natural de la isla. Inventarios florísticos recientes en áreas antropizadas de la isla han arrojado tres nuevos registros de plantas no nativas. Presentamos los primeros informes con colectas de *Asystasia gangetica* (L.) T. Anderson subsp. *micrantha* (Nees) Ensermu, *Emilia praetermissa* Milne-Redh., y *Acanthocereus tetragonus* (L.) Hummelinck para Puerto Rico. Repasamos sus distribuciones geográficas, estado en la isla, vías de introducción, y ofrecemos comentarios sobre la importancia de realizar inventarios en áreas perturbadas y no protegidas.

Palabras clave: *Acanthocereus tetragonus*, *Asystasia gangetica* subsp. *micrantha*, *Emilia praetermissa*, flora no nativa, inventarios florísticos, plantas naturalizadas, Puerto Rico.

INTRODUCTION

The Caribbean island of Puerto Rico has been subjected to the introduction of non-native plant species for centuries (Hill 1899; Birdsey and Weaver 1982; Dietz 1986; Miller and Lugo 2009), which now account for a significant proportion of its documented flora (Axelrod 2011; Acevedo-Rodríguez and Strong 2012; Gann et al. 2022; USDA-NRCS 2022). The majority of non-native plants in the region have been intentionally introduced (i.e., deliberately brought in and planted or dispersed by humans; Rojas-Sandoval and Acevedo-Rodríguez 2015), and their presence on the island is the result of a variety of practices, including the cultivation for agriculture, forestry, horticulture, and ornamental landscaping (Little and Wadsworth 1964; Little et al. 1974; Schubert 1979; Francis and Liogier 1991; Rojas-Sandoval and Acevedo-Rodríguez 2015). Nevertheless, a considerable number of species have escaped from cultivation, subsequently naturalizing and conspicuously integrating into the island's natural landscape (Little and Wadsworth 1964; Little et al. 1974; Francis and Liogier 1991; Miller and Lugo 2009). On the other hand, the presence of non-native plants in the region have also been attributed to unintentional or accidental introductions to a lesser extent (i.e., inadvertent contaminants or stowaways; Rojas-Sandoval and Acevedo-Rodríguez 2015; Rojas-Sandoval et al. 2017).

We report three new non-native plant records from Puerto Rico, one of which was discovered through ongoing floristic inventories conducted on the island as part of a collaborative project (Ecological Site Descriptions-ESDs) between the USDA Natural Resources Conservation Service (NRCS) and the USDA Forest Service-International Institute of Tropical Forestry (FS-IITF). Ecological Site Descriptions (ESDs) are reports designed to assist landowners seeking to improve their land-use management activities, address conservation planning, and implement alternative practices to mitigate the effects of extreme weather events. All records correspond to plant specimens collected growing naturally in the wild during 2021 and 2022, two of which resulted from fieldwork for Ecological Site Descriptions (ESDs). The specimen vouchers and identifications were determined by SMS and are deposited at the Herbarium of the University of Puerto Rico-Río Piedras Campus (UPRRP).

METHODS

Review of Literature, Digital Herbarium Collections, Online Databases, and Social Platforms

We reviewed the island's most comprehensive and recent botanical checklists (e.g., Liogier and Martorell 2000; Axelrod 2011; Acevedo-Rodríguez and Strong 2012), as well as literature from journal articles and other sources (e.g., books, government reports), and conducted a search on local collection records in the digital databases of the following herbaria: MAPR (https://herbaria.plants.ox.ac.uk/bol/MAPR), NY (http://sweetgum.nybg.org/science/vh/), UPR and UPRRP (http://herbario.uprrp.edu/), and US (https://collections.nmnh.si.edu/search/botany/) to determine whether our contributions herein represent taxa not previously reported from or collected in Puerto Rico. For the same purpose, we also searched the following online checklists and databases: Flora of the West Indies by the Smithsonian National Museum of Natural History (https://naturalhistory2.si.edu/botany/WestIndies/catalog.htm), Plants of the Island of Puerto Rico by The Institute for Regional Conservation (IRC; https://www.regionalconservation.org/ircs/database/site/IntroPR.asp; cited in this article as Gann et al. 2022), and the PLANTS Database (http://plants.usda.gov; cited in this article as USDA-NRCS 2022). Furthermore, the species checklists portal of the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/) and The Plants of the World Online database by Kew Science (POWO; https://powo.science.kew.org/) were used to obtain additional information on current taxonomic statuses and geographic distributions. Lastly, the citizen science platform iNaturalist (https://www.inaturalist.org/) and local social media groups (e.g., Biodiversidad de Puerto Rico, https://www.facebook.com/groups/PRNatural/?fref=nf; Plantas en Puerto Rico / Plants in Puerto Rico, https://www.facebook.com/groups/AmigosDePlantasDeBoriken) were also accessed for insights on unconfirmed reports and natural history observations. Based on our review, the records below represent the first reports with vouchers of *Asystasia gangetica* subsp. *micrantha*, *Emilia praetermissa*, and *Acanthocereus tetragonus* for Puerto Rico.

RESULTS AND DISCUSSION

ACANTHACEAE

Asystasia gangetica (L.) T. Anderson subsp. ***micrantha*** (Nees) Ensermu in J. H. Seyani & A. C. Chikuni (eds.), Proc. XIII Plenary Meet. AETFAT, Zomba, Malawi. 1: 343. 1994. Native to Africa, India, and Sri Lanka (Hsu et al. 2005). Introduced in Malaysia (Kiew and Vollesen 1997), Singapore (Pandit et al. 2006), Taiwan (Hsu et al. 2005), Indonesia, Australia, Papua New Guinea, and the Pacific Islands (CRC Weed Management 2003), including the Solomon Islands (Westaway et al. 2016), Hawaii (Starr and Starr 2016), and French Polynesia (Vitrac et al. 2019). It is also introduced in Central and South America (Mocharla and Aluri 2021), including Venezuela (Luján et al. 2011), as well as North America (Florida, U.S.A.; Wunderlin et al. 2022). In addition, it has been observed (i.e., unconfirmed reports) in the Caribbean islands of Cuba (iNaturalist.org/observations/136175544; iNaturalist.org/observations/136722917, both accessed 21 October 2022), and Trinidad and Tobago (iNaturalist.org/observations/65532537, accessed 21 October 2022), but has not been reported in the literature for the Caribbean region. It is widely regarded as a serious invasive weed, particularly in Southeast Asia and Australia.

New report for Puerto Rico. Initially observed by SMS and JDCZ on June 23, 2021. Naturalized herb on the grounds of the Lajas Agricultural Experimental Station in the southwestern town of Lajas. Discovered and later collected in the understory of a *Swietenia macrophylla* plantation, near a grazing field intermittently used by cattle for shade and resting. It was probably introduced inadvertently through the sowing of forage grasses, which is a common practice at the location. It is distinguished from the widely distributed and abundant *Asystasia gangetica* (L.) T. Anderson in Puerto Rico by having broadly lanceolate or elongated acuminate leaves, and a white corolla that is generally under 25 mm long with purple blotches or spots on the lower lip. The distinctive purple markings of the bottom petal lobe have been remarked by several authors as a notable feature to distinguish this taxon (see Kiew and Vollesen 1997; Hsu et al. 2005; Luján et al. 2011; Danthanawanit et al. 2015) (Figure 1A).

Record voucher: PUERTO RICO. Lajas, Bo. Sabana Yeguas, Estación Experimental Agrícola de Lajas, 42 m, 10 Sept. 2021, *Steve Maldonado Silvestrini & Johann D. Crespo 937* (UPRRP). **Note:** This taxon has been incorrectly referred to as *Asystasia intrusa* (Forssk.) Blume; this issue has been previously noted by different authors (see Kiew and Vollesen 1997; Thye 1997).

ASTERACEAE

Emilia praetermissa Milne-Redh., Kew Bull. 5: 375. 1951. Native to Africa (Olorode and Olorunfemi 1973; Chung et al. 2009). Introduced in China (He et al. 2020), Taiwan (Chung et al. 2009; Wu et al. 2010; Wang and Wang 2018), North America (Florida, U.S.A.; Wunderlin et al. 2022), and the Caribbean islands of Saint Lucia, Saint Vincent, and Martinique (Dumbardon-Martial and Delblond 2019). Nonetheless, it has also been observed (i.e., unconfirmed reports) in multiple countries of Central America and northern South America (e.g., Panamá, Ecuador, Venezuela, among others; iNaturalist.org/observations/114475270; iNaturalist.org/observations/66471567; iNaturalist.org/observations/126720029, all accessed 21 October 2022). Also found on several other Caribbean islands such as Hispaniola (iNaturalist.org/observations/116718578, accessed 26 October 2022), Montserrat (iNaturalist.org/observations/125607427, accessed 21 October 2022), and Trinidad and Tobago (iNaturalist.org/observations/108173978; iNaturalist.org/observations/73765145; iNaturalist.org/observations/91408437, all accessed 21 October 2022).

New report for Puerto Rico. Initially observed by SMS on May 12, 2020, as a naturalized herb in the mountainside town of Adjuntas. Nevertheless,

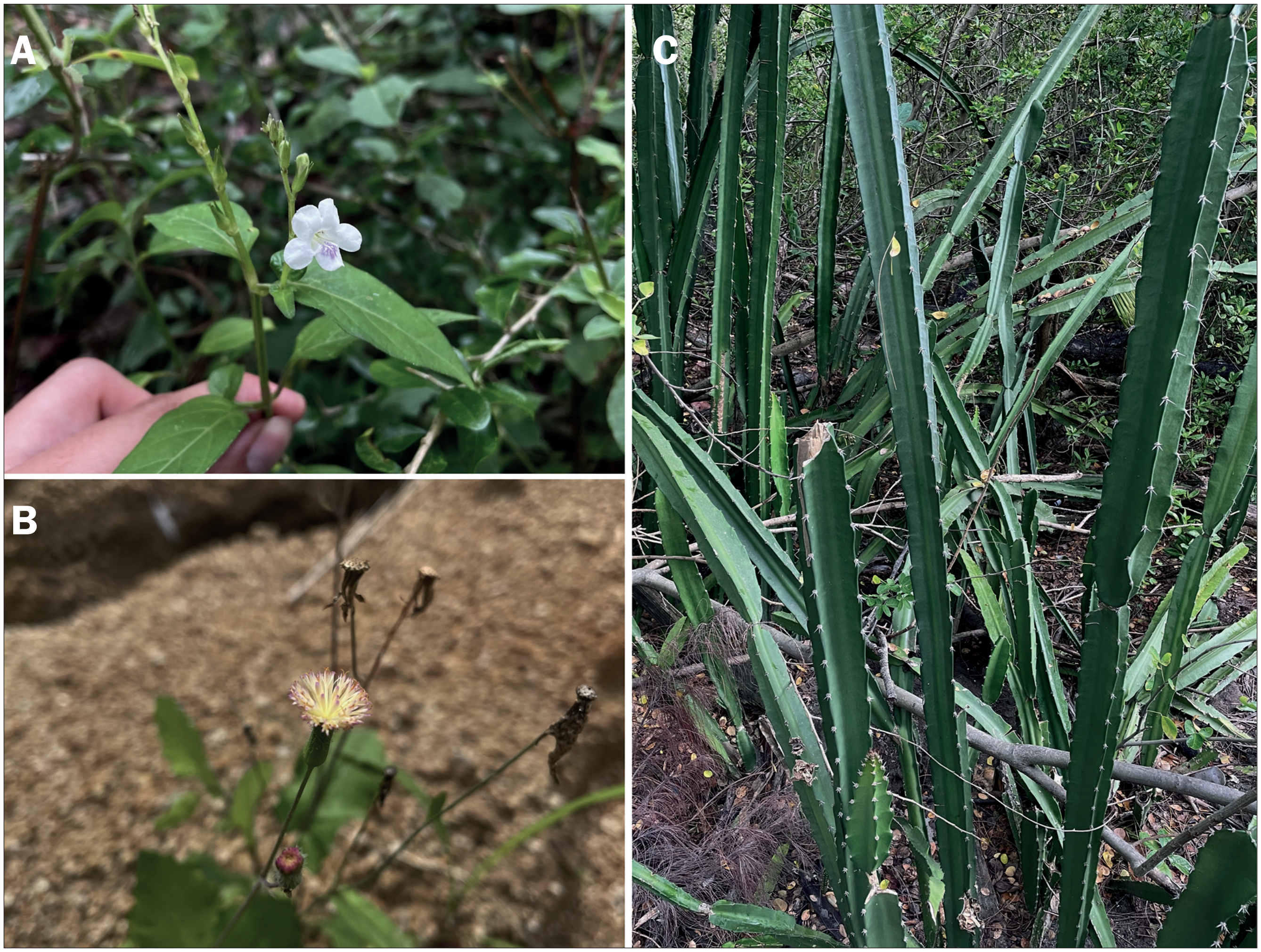

Figure 1. A) *Asystasia gangetica ssp. micrantha* flowering in the shaded understory of a *Swietenia macrophylla* plantation (Lajas, southwestern Puerto Rico); B, *Emilia praetermissa* growing on sandy soils in a private agricultural farm (Utuado, Central Puerto Rico); C, *Acanthocereus tetragonus* growing among mangroves and other coastal vegetation (Isabela, northwestern Puerto Rico). Photos: SMS.

previous photographic documentation of the species from the neighboring town of Lares, dating back to 2019 and 2017, was found on social platforms, but it was not properly identified at the time the photos were posted online (iNaturalist.org/observations/24835453; facebook.com/photo/?fbid=10213074430242551&set=gm.1916491575302278, both accessed on October 26, 2022). It is widely naturalized on disturbed sites in the Cordillera Central and other mountainous areas of Puerto Rico (e.g., Adjuntas, Ciales, Comerío, Naranjito, Patillas, and Utuado; SMS and JDCZ, personal observations), but also occurs in lesser disturbed natural areas in the northern karst region and coastal lowlands (e.g., Arecibo, Florida, Isabela, and Vega Alta; SMS, personal observation). Collected in an open field growing among sedges and grasses, primarily *Andropogon bicornis*. It is morphologically similar to *Emilia fosbergii* Nicolson and *Emilia sonchifolia* (L.) DC., both of which also occur on the island across different elevations and habitats but are distinguished by having paler capitula that range from light orange or yellow to cream-white colors, with darker-colored anthers, as well as deeply-dentate leaf margins (Nicolson 1980; Lisowski 1997; Chung et al. 2009; Mapaya and Cron 2016; Dumbardon-Martial and Delblond 2019) (Figure 1B). It has been remarked that when dried, specimens lose their florets' distinctive color and become "nearly indistinguishable" from *E. fosbergii* (Chung et al. 2009). Nonetheless, when examined under a microscope, dried specimens of *E. praetermissa* appear best distinguished by having persistent papillose to pilose involucres (SMS, personal observation).

The resemblance of *Emilia* species has been widely acknowledged by researchers for decades, leading to numerous cytological studies on the genus, with *E. praetermissa* being proposed and generally accepted as originating from hybridization between the palaeotropical natives *Emilia coccinea* (Sims) G. Don and *E. sonchifolia* (Olorode 1973; Olorode and Olorunfemi 1973). However, recent phenetic and phylogenetic works have addressed and debated the subject (see Mapaya and Cron 2016; Mapaya 2017).

Record voucher: PUERTO RICO. Vega Alta, Bo. Sabana, Ciénaga Prieta, 5 m, 7 Oct. 2021, *Steve Maldonado Silvestrini & Amelia Merced 971* (UPRRP). **Note:** This herb has been most recently collected in the mountain town of Utuado (23 Mar. 2022) (*Acevedo-Rodriguez, P. 17425* [US]).

CACTACEAE

Acanthocereus tetragonus (L.) Hummelinck, Succulenta (Netherlands) 20: 165. 1938. Native to the Caribbean islands of Cuba, Dominica, Grenada, Guadeloupe, Martinique, Saint Lucia, Trinidad and Tobago, Aruba, Curaçao, and Margarita, as well as northern South America, Central America (Acevedo-Rodríguez and Strong 2012), and North America (Mexico; Acevedo-Rodríguez and Strong 2012; Gann et al. 2022; also Florida and Texas, U.S.A.; Gann et al. 2022; Wunderlin et al. 2022). It is introduced in India (Karthigeyan et al. 2013; Patel et al. 2016; Subitha et al. 2016), Australia (Randall et al. 2007; McFadyen 2012), New Caledonia (Beauvais et al. 2006; Hequet et al. 2009), Hawaii (Lorence et al. 1995), and the Caribbean islands of Saint Croix and Saint Thomas (Acevedo-Rodríguez and Strong 2012). It is also reportedly introduced in Europe (e.g., Sicily and Malta; Tela Botanica 2018; Mifsud 2022).

New report for Puerto Rico. Initially observed by SMS in 2017 under cultivation near Jobos Beach in the northwestern town of Isabela, and subsequently on August 31, 2019, also cultivated in the eastern town of Fajardo. Discovered naturalized by SMS on April 11, 2021, in the same location where it was initially observed, at the edge of a disturbed mangrove forest dominated by *Avicennia germinans* before being severely damaged by Hurricane Maria in 2017. Collected on August 15, 2022, at the same location, where it is propagating vegetatively and growing naturally among wild coastal vegetation (e.g., *Avicennia germinans*, *Coccoloba uvifera*, *Cocos nucifera*, *Conocarpus erectus*, *Pithecellobium dulce*, *Terminalia catappa*, *Thespesia populnea*, among others). This cactus was originally planted as an ornamental in the front patios of properties bordering the mangroves, and it most certainly escaped from cultivation, possibly after the hurricane's disturbance. It is distinguished from similar Cactaceae on the island (e.g., *Leptocereus* spp. and *Selenicereus* spp.) by being columnar with stems up to 3 m long, usually four-winged and flanked by spines, prone to arching and occasionally scandent (Figure 1C).

This species was most likely present on the island earlier and had not been properly reported or documented. It is absent from Puerto Rico's most recent floristic summaries but is listed as "cultivated" in the online records (digital checklist version) of the *Catalogue of Seed Plants of the West Indies* (cited in this article as Acevedo-Rodríguez and Strong 2012). The species' entry in the digital checklist is noted as last edited on May 28, 2009 (https://naturalhistory2.si.edu/botany/WestIndies/getonerecord_Emu.cfm?ID=2284), three years prior to the date of publication (2012). Two references pertaining to Puerto Rico are cited only in the digital records: Britton and Wilson (1923-1926) and Otero et al. (1945), of which the former lists the species as *Acanthocereus pentagonus* (L.) Britton & Rose (a taxonomic synonym) for the Caribbean islands of Saint Croix and Saint Thomas. The basis for the inclusion, however, relies on the second reference (see Otero et al.

1945) due to the assumption that the species was present in Puerto Rico as it was included with the common name *'Dildo espinoso'* (P. Avecedo-Rodríguez, personal communication with SMS).

After Britton and Wilson (1923-1926) and Otero et al. (1945), another catalog checklist was published on the common and scientific names of the island's flora (Martorell et al. 1981), in which the species was included based on the latter reference. It is noted that José I. Otero based his checklists and reports partly on his collections deposited at the former herbarium of the Experimental Agronomic Station in Río Piedras, which have been integrated into the UPR herbarium. Nonetheless, no collections by J. I. Otero or anyone else referable to this species were found in our search. Moreover, the primary authors in Martorell et al. (1981) published a systematic synopsis of the island's flora nineteen years later (Liogier and Martorell 2000), in which the species is absent.

We think that the original inclusion of this species to the Puerto Rican flora was an error in Otero and Toro (1931) (the first edition version of Otero et al. 1945), which relied on Britton and Wilson (1923-1926) as the primary reference for species inclusion, thus being added based on its presence in the U.S. Virgin Islands and not Puerto Rico. The species was eventually listed in references that cited Otero et al. (1945) (see above paragraphs for examples). However, it was probably not included in most of the subsequent botanical summaries and checklists due to the dubious nature of the report and the absence of a record voucher. We confirm its presence on the island with a photograph (Figure 1C) and specimen voucher of a naturalized population.

Record voucher: PUERTO RICO. Isabela, Bo. Bajura, PR-466: Km 7.9, 6 m, 15 Aug. 2022*, Steve Maldonado Silvestrini & Johann D. Crespo 1244* (UPRRP).

CONCLUDING REMARKS

Recent studies and reports on the spread and naturalization of non-native plants in Puerto Rico show that the flow of such species into the island is ongoing (e.g., Ackerman and González-Orellana 2021). Other recent, local studies and assessments on the topic, including urban and protected natural areas (e.g., Meléndez-Ackerman and Rojas-Sandoval 2021; Zimmerman et al. 2021), support the assertion that human-related activities strongly influence their introduction and naturalization. While some may not persist, others might establish and eventually become invasive, potentially causing negative impacts on multiple factors, including the local biodiversity, natural resources, and economy. For instance, in recent years, *Salvinia molesta*, an aquatic fern listed as one of the IUCN's 100 most invasive species (Luque et al. 2013), established in Lago Las Curias (a waterbody in the metropolitan area of San Juan) and caused detrimental effects locally for several years (Wahl et al. 2020).

Some of the taxa herein reported have already been recorded or confirmed in neighboring Caribbean islands (see Results). We are confident that the local naturalization of one species, *Acanthocereus tetragonus*, is of horticultural origin, whereas the others may have arrived naturally or unintentionally by different pathways. The latter is most likely the case of *Asystasia gangetica* subsp. *micrantha*, a naturalized herb on the grounds of an agricultural experiment station that conducts a variety of farming activities, thus probably entering by accident through the sowing of a contaminated seed batch or another similar source, which is an introduction method previously suggested for other African-native plants recorded near the location (e.g., McKenzie et al. 1993). It is a highly invasive weed that primarily affects oil-palm plantations in Southeast Asia and adjacent countries (CRC Weed Management 2003; Wahyuni et al. 2015).

In contrast, a presumption on the arrival and naturalization of *Emilia praetermissa* is more challenging and involves other possibilities. For example, *Emilia* spp. and other similar Asteraceae rely primarily on wind currents as their main dispersal mechanism (Sorensen 1986; Adedeji 2005; De-Paula et al. 2015), which significantly facilitates their ability to spread over long distances and expand their geographic distributions. Notably, other African-native species of Asteraceae similar to *Emilia* have been added to the Puerto Rican flora in the last decades (e.g., *Crassocephalum crepidioides*; Axelrod and Taylor 1993). It is also worth noting that Asteraceae is the third taxonomic family with the largest number of non-native plant species in Puerto Rico and the Virgin Islands, surpassed by Fabaceae and Poaceae (Rojas-Sandoval and Acevedo-Rodríguez 2015). The expansion and naturalization success of non-native Asteraceae on the island appears to be best explained by the advantages of dispersal adaptations they possess, which may explain why some of these species are expanding naturally via wind through the Caribbean region.

The records presented herein were discovered initially in highly disturbed areas near urban development and notably distant from protected nature reserves. Even though several floristic surveys in natural protected areas of Puerto Rico have previously yielded notable contributions to its native and non-native flora (e.g., Monsegur-Rivera 2009; Padrón-Vélez and Ricart-Pujals 2015), the most recent discoveries of endemic species have taken place in non-protected areas (Ackerman and Ortíz-Jordan 2021; Gdaniec et al. 2022). Consequently, farms, neglected terrains, and other anthropized vegetated areas without a protection designation and with a history of agriculture or other land uses may yield significant discoveries of native and non-native plant species and should also be considered in conservation and management efforts. Also, local farmers and residents can be valuable for identifying areas that require such attention and evaluation, and citizen scientists should be included in this process. More efforts should be made to explore and research outside of protected areas, including those with ongoing disturbance by human land use, because it may result in botanical additions to the region, ultimately enriching our understanding of plant biogeography, species diversity, natural history, and conservation.

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RESPONSE CAPACITY OF STAKEHOLDERS IN THE FORESTRY SECTOR TO THE IMMEDIATE EFFECTS OF HURRICANE MARÍA: IMPLICATIONS FOR COMMUNITY FOREST MANAGEMENT

Jennifer Rivera-San Antonio[1,*] and Oscar J. Abelleira Martínez[1]

[1] Department of Agro-Environmental Sciences, University of Puerto Rico, Mayagüez, P.R., 00681
* Author for correspondence: jennifer.m.rivera-sanantonio@usda.gov

Abstract

Climate change is expected to alter the frequency and intensity of hurricanes, and it is crucial to understand the aftermath of these disturbances to promote a fast recovery and more efficient use of resources. Unfortunately, the information on the salvage of downed trees, possible uses for woods, and associated best management practices were not immediately available in the aftermath of Hurricane María in Puerto Rico. The need to document wood salvage efforts for future reference and management plans became evident. We used an online survey to understand the perception that Hurricane María left on stakeholders in the forestry sector of Puerto Rico. The survey included two groups of participants: academics and professionals in forestry. We found no difference between the two groups of responders in the capacity to respond and recover from the effects of the hurricane. However, surveyed participants concluded that the effects of the hurricane did not discourage them from replanting trees. Responders were highly encouraged to plant trees to increase food security and obtain additional ecosystem services. There was no novel uses for downed trees, and only 37% of downed trees on lands managed by respondents were used for crafts and firewood. This survey highlights the importance of planning for future hurricane disturbances to increase the adaptative capacity of the forestry sector and communities that manage forested lands in Puerto Rico and the Caribbean.

Keywords: Hurricane response, resilience, socio-ecological response.

Resumen

Se espera que el cambio climático altere la frecuencia e intensidad de los huracanes, y es crucial comprender las secuelas de estas alteraciones para promover una recuperación rápida y un uso más eficiente de los recursos. Desafortunadamente, la información sobre el rescate de árboles caídos, posibles usos para las maderas y las mejores prácticas de manejo asociadas no estuvo disponible inmediatamente después del Huracán María en Puerto Rico. Se hizo evidente la necesidad de documentar los esfuerzos de rescate de maderas para futuras referencias y planes de manejo. Utilizamos una encuesta en línea para comprender la percepción que dejó el Huracán María en los actores del sector forestal de Puerto Rico. No detectamos diferencia alguna entre los dos grupos de participantes que incluían académicos y profesionales forestales en cuanto a la capacidad de responder y recuperarse de los efectos del huracán. Sin embargo, los participantes encuestados concluyeron que los efectos del huracán no los desanimaron a resembrar árboles. Los participantes compartieron interés en futuras siembras de árboles con el propósito de aumentar la seguridad alimentaria y obtener servicios ecosistémicos adicionales. No encontramos usos novedosos para los árboles caídos a causa del huracán y solo el 37% de los árboles caídos en terrenos manejados por los encuestados se utilizó para artesanías y leña. Esta encuesta resalta la importancia de la planificación para futuros huracanes con el fin de aumentar la capacidad adaptativa del sector forestal y comunidades que manejan terrenos en Puerto Rico y el Caribe.

Palabras clave: Respuesta a huracanes, resiliencia, respuesta socio-ecológica.

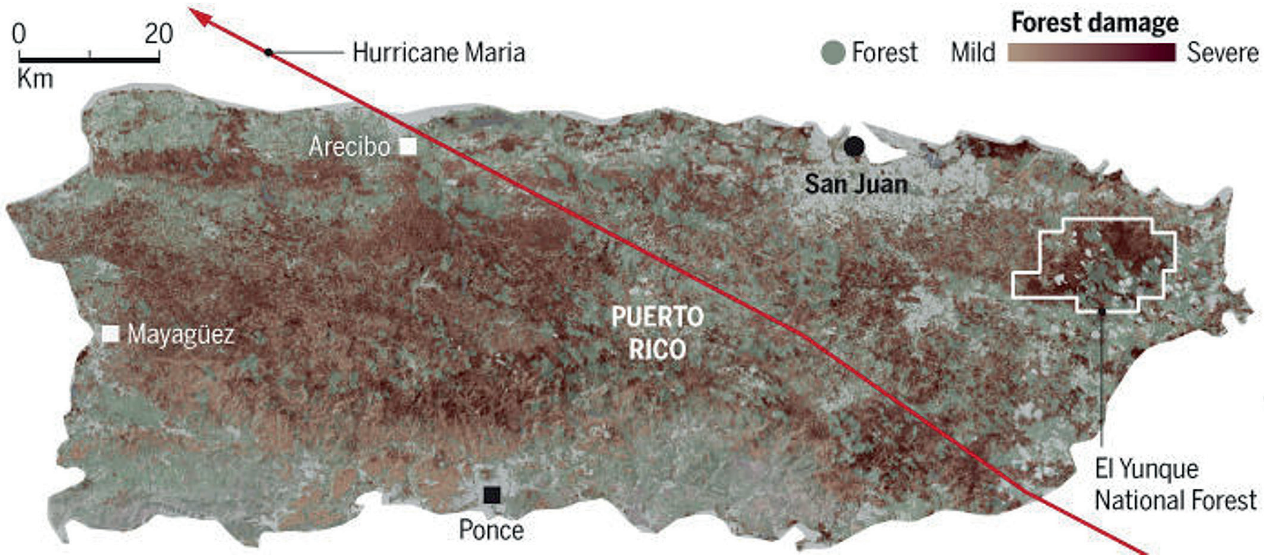

Figure 1. Calibrated and corrected Landsat 8 image composites for the entire island's forest damage caused by the path of Hurricane María (Feng et al. 2018).

INTRODUCTION

The aftermath of a disturbance can be assessed, evaluated, and viewed in many ways. Natural disaster aftermaths unfold in a discriminatory manner in which the pre-existing structure and social conditions determine the form and degree to which members of a community will be affected (Oxfam 2005; Kleiner 2011). The capacity of communities to adapt to and effectively respond to disturbances will vary according to their relationship and knowledge of social and ecological processes as affected by disturbances and the ability to match responses to the spatial scales in which the disturbances and processes act (Nelson et al. 2007; Ostrom 2009; Fremier et al. 2013). The management of natural disasters can include five phases (*sensu* Moe and Pathranarakul 2006): (1) prediction, (2) warning, (3) emergency relief, (4) rehabilitation, and (5) reconstruction. In the rehabilitation and reconstruction phases, technical information that increases adaptive capacity and response efficiency is beneficial to communities that need to rebuild homes and infrastructure and use the resources available in the aftermath of a disturbance.

On 20 September 2017, Hurricane María made landfall in Puerto Rico. The eye of the hurricane made landfall on the southeast coast near the municipality of Yabucoa around 10:15 UTC (Coordinated Universal Time). The hurricane's trajectory crossed Puerto Rico and exited from the island near the northern city of Arecibo (Figure 1). The hurricane's maximum winds were near 69 m/s (155 mph) as it crossed the island just below the threshold of a category-five hurricane on the Saffir-Simpson Scale (Pasch et al. 2018). After the hurricane, the island had limited access to food supplies, communications, and water (Lugo 2020; Wiener et al. 2020). There were also significant effects on the island's vegetation, with an estimated 21 to 31 million trees suffering structural damage in defoliation, canopy branch loss, and main trunk collapse (Feng et al. 2018; Báez et al. 2021). The hurricane's winds caused extensive tree falls and snapping of branches, which led to significant damage to electric power lines and, consequently, electricity outages that residents throughout the island suffered.

A large number of downed trees and coarse woody debris that resulted from Hurricane María posed challenges to the government, institutions, and communities that manage farms, forests, and privately owned lands with significant tree cover. An estimated 84% of forests in Puerto Rico are privately owned (Marcano-Vega 2017). Given the near absence of a wood products-based industry and market in Puerto Rico (Wadsworth 2012), little could be done locally to find immediate uses for fallen wood. In addition, since communications were limited, assessments and skilled personnel to conduct wood salvage operations were not readily available. Furthermore, in Puerto Rico, at least after the mid-twentieth century, wood-based end-products from local woods that could substitute imports have scarcely been developed (Francis 1995; Wadsworth 2012). Thus, much of the downed wood resources went unused in the aftermath of Hurricane María.

This situation is not new in Puerto Rico. In 1961, Longwood indicated that the utility of Puerto Rican woods had been depreciated due to the lack of information concerning the drying, handling, and machining properties of locally abundant woods. Back then, fewer than a dozen tree species were utilized appreciably for timber and wood-derived similar products. Most species were either not used at all or were used for fuel, charcoal production, or other low-value products (Longwood 1961). Almost six decades later, the overall condition of the Puerto Rico wood industry is nearly the same, obscuring the potential contributions the forestry sector can provide to the island's economy. Between 2014 and 2018, 44.5% of the population and 40.9% of the families lived in poverty in Puerto Rico's highly subsidized economy, highlighting the need for locally-based economic development (González and Ma 2017; CENSO 2021).

To provide solutions after Hurricane María, the USDA Caribbean Climate Hub (CCH), the International Institute of Tropical Forestry (IITF), and the US Forest Service convened a meeting titled *Recovery and re-use of wood from fallen trees after the hurricane* (in Spanish, "Conversatorio Adapta: Recuperar y reutilizar madera de árboles caídos después del huracán") on November 21, 2017, one month after this hurricane. The objectives of this meeting were to:

1. present options and opportunities for salvaging wood and developing wood products from downed trees and branches;
2. Facilitate connections between people and organizations that share this interest;
3. Compile a directory of interested people and organizations (i.e., stakeholders) to be able to share information on how to salvage downed wood;
4. Gather comments on opportunities and challenges for using locally-salvaged wood products as a sustainable economic benefit and ecosystem service in Puerto Rico.

A decision flow-chart for the salvage of downed trees was created as a workshop effort, and educational materials were provided to guide in deciding how to process and what to produce with downed wood. Following the meeting, there was an increased interest in understanding the adaptive capacity and effectiveness of stakeholder response to the immediate effects of the hurricane, especially on issues related to downed trees and wood salvage.

The objective of this study was to gather information on the adaptative capacity and response effectiveness of individual stakeholders from community, public, state, federal and private institutions associated with the forestry sector in Puerto Rico. Specifically, we asked for information on the ease or difficulties posed when implementing management activities aimed at salvaging wood from downed trees in the aftermath of Hurricane María to groups that included academics (e.g., university faculty, researchers, and students), artisans, professionals from the forestry sector (e.g., arborists, sawmill operators, private and public land managers) and retired individuals. In addition, we used online surveys administered to participants of the CCH meeting mentioned in the paragraph above and follow-up workshops to gather information on uses given to downed wood, costs of tree and wood recovery operations, access to information and interest in forest recovery activities, such as tree planting and wood salvage, after the hurricane. Our study provides information to managers and policymakers on the adaptive capacity and response effectiveness of stakeholders in the forestry sector. Also, it underscores gaps that need to be covered by institutions to increase the response capacity and preparedness of local communities and governance systems to extreme hurricane events.

METHODS

Stakeholder survey

An online questionnaire was created to gather information on the perceived capacity of individuals to respond to, and recover from, the immediate effects of Hurricane María (Appendix 1). The questionnaire consisted of 22 questions that were focused on aspects that included land ownership, tree identification skills, immediate hurricane responses, tool accessibility, and uses for recovered wood. In addition, participants were asked about their knowledge of the Río Hondo Community Forest (RHCF) in Mayagüez, Puerto Rico, which was acquired for conservation by the Municipality through the communities' application and securing of funds through the USDA Forest Service Open Space and Community Forest Program. The managers of this community-managed forest faced significant difficulties carrying out trail-clearing and wood salvage operations and were also included as questionnaire participants. The questionnaire consisted of close-ended, open-ended, multiple-selection, and rating-scale questions. The questionnaire was uploaded to the "Survey Monkey, Inc." website for five months (March-August of 2018) and shared via email to participants of the CCH workshops (> 90 contacts), members of the RHCF (> 25 contacts), and subscribers of the Forest Stewardship Program of IITF, USDA Forest Service, which includes land owners and managers in the private forestry sector (> 100 contacts).

Data analysis

The survey participants were grouped into academic, artisan, professional, and retired individuals. We used word-cloud figures to visualize the frequency of responses to open-ended survey questions. Differences in questionnaire responses among groups were evaluated with Pearson's X^2-test and adopted a level alpha of significance equal to and less than 0.05. The artisan and retired groups were excluded from the test due to insufficient sample size. The statistical analyses were conducted using Infostat Statistical Software (Di Rienzo et al. 2016).

RESULTS

Thirty participants from various groups completed the survey, including nine "academics," two "artisans," 18 "professionals," and one from the group "retired." We found no differences between groups "academics" and "professionals" in the knowledge of wood uses ($X^2 = 0.10$, $p = 0.75$, $n = 27$), ability to upkeep or prune trees ($X^2 = 1.85$, $p = 0.17$, $n = 27$) and damage to property as an effect of Hurricane María ($X^2 = 2.41$, $p = 0.12$,

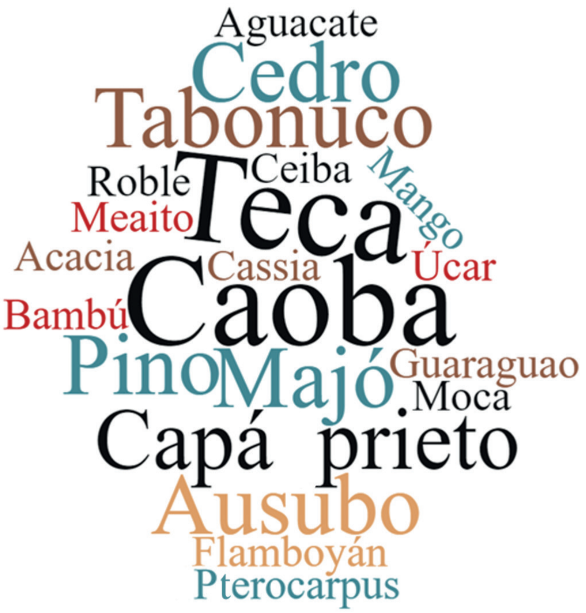

Figure 2. Word cloud of response frequency of tree species available for uses in woodworking and other end uses mentioned (open-response) in a survey of 30 stakeholders in Puerto Rico after Hurricane María. Species in larger letters were frequently cited.

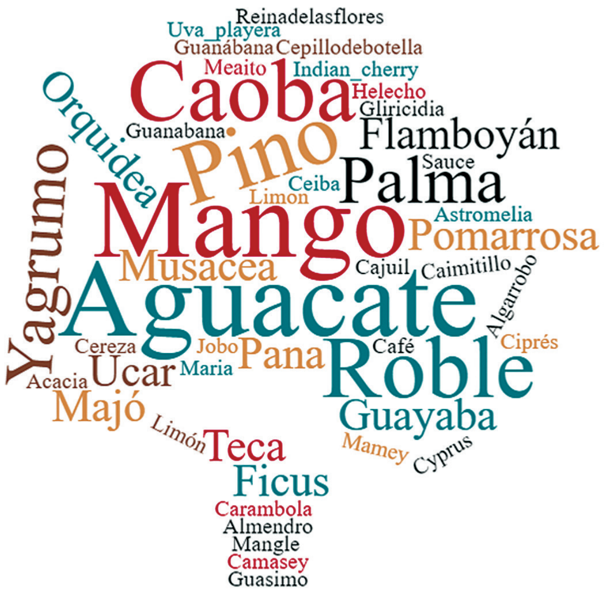

Figure 3. Word cloud of open-ended response frequency of stakeholder-identified tree species storm-downed or affected as a direct effect of Hurricane María. Responses were from a survey of 30 participants.

n = 27). We also found no differences between these groups in the capacity to identify the species of downed trees ($X^2 = 0.96$, $p = 0.34$, $n = 27$) and possible uses for wood from downed trees ($X^2 = 0.32$; $p = 0.57$, $n = 27$). Likewise, we found no differences between these groups in the interest of re-planting trees ($X^2 = 0.75$, $p = 0.38$, $n = 27$).

Nearly 74% of surveyed participants indicated that they had previous knowledge of tree species grown in Puerto Rico with woodworking qualities (i.e., elaboration of houses or furniture). Participants identified species such as "caoba" (*Swietenia mahagony* and *S. macrophylla*), "teca" (*Tectona grandis*), "majó" (*Hibiscus elatus*), "ausubo" (*Manilkara bidentata*), and "pino" (*Casuarina equisetifolia*) (Figure 2): The wood characteristic most valued by participants was color (24%) followed by strength (20%), working resistance (15%), firmness (13%), drying capacity (11%), odor (11%), and (5%) reported that desirable wood characteristics were unknown to them.

After Hurricane María, participants identified edible fruit tree species such as "mangó" (*Mangifera indica*) and "aguacate" (*Persea americana*), softwood conifers (e.g., *Pinus caribaea*), and the Australian pine (*Casuarina equisetifolia*) as species which were frequently downed (Figure 3): Only 37% of participants knew the location of sawmills nearby or within their municipality. There was a range of one to five trees that were downed in participants' properties due to the effects of the hurricane, and only 37% of the participants used downed trees for handcrafts and firewood.

Trees caused property damage to 26% of participants (Figure 4), and removal of downed trees was primarily

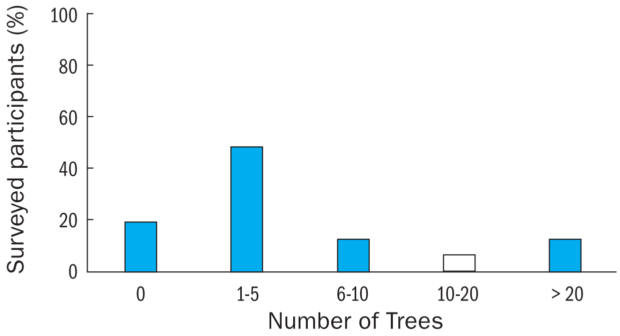

Figure 4. The estimated number of downed trees due to Hurricane María near participants' properties.

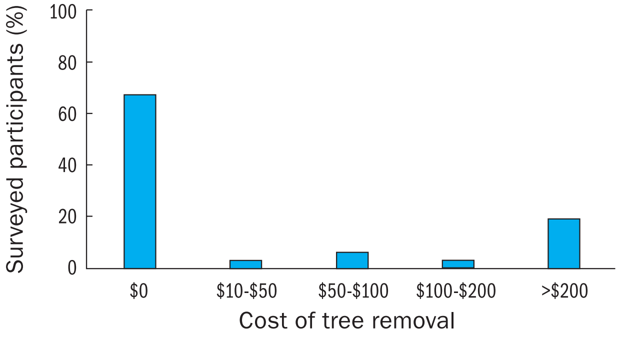

Figure 5. The estimated cost of tree removal to 30 surveyed participants in response to the immediate consequences of Hurricane María that affected them.

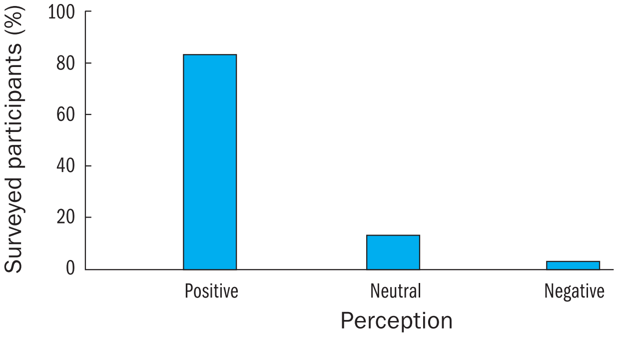

Figure 6. The perception of surveyed participants to efforts and tree removal costs after Hurricane María.

conducted by these participants (40%) and community members (31%), whereas family members (17%), municipality (6%), and paid services (6%) accounted for the rest. The paid services charged an average of $50.00 per service, and the highest amount paid by any individual was over $500.00 (Figure 5). Participants sometimes purchased public liability insurance to protect employees during tree removal. Despite the monetary expenses and individual tree removal efforts, about 71% of surveyed participants had decided to re-plant trees after the hurricane.

Considering all the costs and efforts brought about by tree recovery and removal activities, the perception of participants towards trees was largely favorable (84%), whereas some participants maintained a neutral perception (13%), and few had an unfavorable view of trees (3%) after Hurricane María (Figure 6). Even so, the motivation for planting trees after the hurricane was unanimously supported by the participants. Out of the ecosystem services that could be improved by tree planting (Appendix I), participants consistently mentioned food security as the most desirable; recreation was the least desirable service.

The tools available to participants to deal with downed trees aftermath of the hurricane consisted of machetes (32%), pruning shears (26%), chainsaws (19%), wheelbarrows (13%), and sawmills (2%). Eight percent of participants indicated they had no equipment, and none of the participants owned tree mulchers. After the hurricane, there was an interest in buying portable chainsaws (22%), tree mulchers (14%), machetes (14%), sawmills (11%), pruning shears (5%), and wheelbarrows (6%), but a high percentage of participants had no interest in purchasing equipment (28%). Half (50%) of the participants knew about the RHCF.

DISCUSSION

The survey revealed that participants could not find any timely or innovative uses for downed trees, and only a small percentage of salvaged wood was used for firewood and handmade crafts. This may reflect a lack of technical knowledge, access to, or interest in utilizing available wood resources for activities or needs such as cooking, carpentry, and woodworking. The results from our survey are consistent with Longwood's (1961) documentation that fewer than a dozen timber native to Puerto Rico were utilized, mainly for fuel, charcoal production, or other low-value products. The most identified downed trees by participants were edible-fruit trees, particularly avocado and mango, which can reflect participants' lack of skill in tree identification and the abundance of these trees near homes in urban and rural areas. Leaf morphology and canopy structure are essential for tree species identification, but defoliation is a common direct effect of hurricanes, making identification more difficult and based mostly on bark, branch, and wood characteristics such as color and texture (Bates 1930; Wadsworth and Englerth 1959).

To remedy the lack of tree identification skills and uses for wood from downed trees, institutions can help communities, including academics and professionals, by providing tools to help identify the trees species, health, degree of damage to wood, and possible uses for wood, including the trunk and branches, and other non-wood tree products that may be salvaged (e.g., resins). Printed or online guides to identify tree species based on wood characteristics can increase the capacity and efficiency of salvage efforts. In the aftermath of a major hurricane, Kampf et al. (2007) suggest that it is helpful to sort out trees into two priority groups: (1) trees that require urgent attention and (2) trees that need to be monitored and treated later. This can be a useful first step in the decision process when acting immediately in the aftermath of hurricanes, allowing for the selection of trees to be recovered and treated later and those that can be turned into other products such as mulch, biochar, charcoal, and firewood.

In order to remedy the immediate demand for knowledge and tools for handling trees, wood, logs, and other vegetative material after Hurricane María in Puerto Rico, the CCH created an informative newsletter in 2017 with recommendations ("*Caribbean Climate Hub Fact Sheet: How to salvage fallen trees after Hurricane Maria 2017*"). These recommendations included saving valuable logs that were over 12 inches (35.5 cm) in diameter and 12 feet (3.7 m) long, cutting fallen wood to dimensions of 4 feet (1.2 m) to 8 feet (2.4 m) in length, and that artisans could potentially use logs smaller than 4 inches (~10 cm) in length. The CCH informative newsletter also encouraged the salvage of valuable woods from the following tree species (common name in Spanish followed by scientific name in parentheses): acacia (*Albizia* spp.), almendro (*Terminalia catappa*), ausubo (*Manilkara bidentata*), algarrobo (*Hymenaea courbaril*), caoba (*Swietenia* spp.), capá prieto (*Cordia alliodora*), caracolillo (*Homalium racemosum*), cedro hembra (*Cedrela odorata*), eucalipto (*Eucalyptus robusta*), granadillo (*Buchenavia capitata*), guaraguao (*Guarea guidonia*), mangó (*Mangifera indica*), moca (*Andira inermis*), maría (*Calophyllum calaba*), maricao (*Brysonima spicata*), roble (*Tabebuia heterophylla*), pino (*Pinus caribaea*), and úcar (*Bucida buceras*). Some of these species, such as acacia, almendro, guaraguao, moca, and mangó, are highly abundant in urban and rural areas of Puerto Rico. In contrast, others species such as algarrobo, ausubo, cedro hembra, and granadillo, are of low abundance and have limited geographic distributions (Marcano et al. 2015). We note that re-planting efforts should focus on species of low abundance and limited distribution that need active restoration efforts to expand their populations.

Community self-organization

After the hurricane, participants were inclined to purchase new equipment and machinery for future hurricane events, with a particular interest in portable sawmills. Previous studies have found that an individual's ability to carry out some action during a crisis brings about a sense of empowerment, thus creating an impression that the individual has some control over the situation (Spence et al. 2007; Seeger et al. 2003). Aside from the urgent need for increasing stakeholder capacity for individual and community response and future preparedness, our study indicates that the aftermath of Hurricane María brought some sense of empowerment. There were few reports of trees being associated with property damage, and the overall perception of trees was positive, indicating stakeholders are also willing to learn, develop and apply knowledge and skill for a faster and more efficient recovery of downed trees and forestry-related activities in anticipation of extreme hurricanes in the future.

The neighborhood of La Rambla in the municipality of Ponce (southern Puerto Rico) provides an example of fast and efficient tree removal efforts conducted by community members who self-organized to solve

Figure 7. Photos were taken days after Hurricane María hit Puerto Rico, showing evidence of the (A) obstruction of main residential roads two days after Hurricane María, (B-C) community members conducting tree removal activities in main roads and residential properties, and (D) contractor removing palm trees from private property. The photos were kindly provided by Elma Santiago (2017), taken in Ponce, Puerto Rico.

problems and attain common goals. Vegetative material and downed tree removal comprised the exchange of resources, including equipment and labor, among community members. The priority of the community was to regain access to main roads to access resources (e.g., potable water and food) and provide means of communication and access to treat emergencies (Figure 7). In addition, community members would cut down trees structurally affected by the hurricane and pose a danger or obstacles and collect and deposit all vegetative matter in nearby municipal parks using their vehicles. These actions were performed with the expectation that the proper removal of the material from the sites designated by municipal authorities would eventually be carried out by municipal, state, or federal institutions.

Caveats and Recommendations

During the five months that the survey was available to interested participants, Puerto Rico suffered a major power outage. As a result, nearly 1.5 million customers lost electricity, causing the largest blackout in US history. Furthermore, it took 11 months for electric power to be fully restored in Puerto Rico after Hurricane María (Fernández Campbell 2018). This situation limited the study to 30 participants who could access and complete the questionnaire out of >200 who were contacted to complete it online. Nevertheless, our results support the following recommendations to increase the capacity of communities to respond effectively to the effects of extreme hurricane events.

Preparedness in the form of skills to identify valuable species of trees and woods can aid the general public and increase the amount and efficiency of the use of wood and other products derived from downed trees. In addition, tools such as guides and mobile applications could help prepare stakeholders and communities for future events. For example, TreeSnap (https://apps.apple.com/us/app/treesnap/id1226499160) is a mobile application supported by a citizen science project created to improve forest health, information on pests, diseases and spreading, and location of healthy trees to help assist ongoing genetic diversity research and build better tree breeding programs (Croker et al. 2020). In addition, this application enables stakeholders to easily submit global positioning system (GPS) coordinates, photos, and observational information about trees of interest to scientists and practitioners (Crocker et al. 2020). An additional example would be Seek by iNaturalist (https://apps.apple.com/us/app/seek-by-inaturalist/id1353224144), which uses image recognition technology to identify plants and animals. Also, online tools like this could enable stakeholders to take an active part in tree identification in Puerto Rico. In a study by Roman et al. (2017), stakeholders participated in an urban tree inventory with species identification resources (e.g., applications and handouts) that were used during fieldwork. They found that 90% of the information recorded by participants was consistent with that of experts for the type of site, land use, presence of tree dieback, and genus identification. In addition, participants recorded the same species as experts for 84.8% of trees within the correct genus. This result is helpful because it provides baseline information and represents the first step toward tree recovery and wood-salvage operations.

The desire of participants to purchase equipment, such as portable sawmills and chainsaws, could be limited by high costs (ranging from $1,700 to $50,000 based on estimates from Lumbertmen online [https://www.lumbermenonline.com], obtained April 2021). Incorporating community-based tool-lending cooperatives or libraries could increase access to tools for community members. Tool-lending libraries contribute to community sustainability by lowering economic barriers to home improvement, reducing tool consumption, and improving home energy efficiency (Tabor 2013).

About half of the survey participants knew about the Río Hondo Community Forest project. Although this project was located distant from the participant properties, it could serve as a hub spot of technical information in western Puerto Rico. The RHCF could have demonstrative representations of tree and forest management in preparing for predicted aftermaths of hurricanes, akin to that needed in privately owned lands or backyards, as education and training resources available to communities in Puerto Rico.

More documentation on the uses of downed trees and wood in Puerto Rico and the Caribbean after extreme hurricane events can increase the information that can benefit communities. The availability of information for communities plays a vital role in response to such a catastrophic event. The development and use of educational videos that explain how to treat, dispose of, or use the wood of common tree species can help make information more available. In addition, the availability of such information, tools, and resources could increase the interest in communities in conserving trees and salvaging wood and decrease the inappropriate disposal of vegetative material that includes woods of high value for the production of many end-use products.

CONCLUSION

Our survey found no differences among academics or professionals in responses in the aftermath of Hurricane María, which can reflect common knowledge, capacity, and resources to respond to the event. We found relevant information on the preparedness and response to Hurricane María based on the questionnaire responses of 30 participants. Since more than 84% of Puerto Rico's forested land is privately owned land (Marcano-Vega 2017), this study emphasizes critical needs that stakeholders face amid an extreme hurricane event with direct effects on such lands. On average, stakeholders had to remove one to five downed trees from their properties, mainly identified as popular edible-fruit trees by participants, which reflects the use of these trees as part of their livelihoods and underscores the need for tools for the identification of trees and wood that may not be as common and knowledgeable but can be of very high-value.

A major objective of the survey was to identify any innovative and novel uses for downed trees and salvaged wood. Unfortunately, participants could not identify innovative and readily executable uses for trees or logs. This limitation could result from the low-profile and near-absence of the timber industry in Puerto Rico, which feeds back into the lack of knowledge and technical expertise for using wood and other forest products. Future preparedness efforts to increase the capacity for response to hurricanes should focus on activities to capacitate communities and stakeholders in implementing sound practices for recovery and wood salvage of downed trees to increase resource use efficiency and minimize vegetative waste ending up piled in publicly designated areas until mulched. Communities and individuals can benefit from downed trees and salvaged wood, and more so if end-use products, and the network of forestry professionals and entities that can ease the process of turning salvaged wood into such products, can be easily identified by individuals and communities, improving their response capacity to extreme hurricane events.

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APPENDIX I
Example of distributed survey to stakeholders

The purpose of this questionnaire is to know the effect before and after the hurricane on the uses of wood in Puerto Rico. At no time are you asked for your name on the questionnaire, making it completely confidential. It will only take you about 8 to 10 minutes to complete the questionnaire. You can stop and not continue answering the questionnaire at any time if you wish.

City: ____________________________

Job: ____________________________

1. Select the age range that best identifies you:

☐ 21–29 ☐ 30–49 ☐ 50–59 ☐ 60–69 ☐ > 70

2. Do you know about the Río Hondo Community Forest Project, Mayagüez P.R.?

☐ Yes ☐ No

3. Do you own a farm or a piece of land?

☐ Yes ☐ No

4. Do you know of sawmills near your municipality?

☐ Yes ☐ No

5. What wood characteristics would you look for? (Select all that apply)

Hardness ☐
Firmness ☐
Color ☐
Smell ☐
Easy to air dry ☐
Easy to work ☐
☐ Other: ____________________________

6. Do you know of any type of tree present in Puerto Rico that its wood is ideal for the construction or elaboration of houses, furniture, or other uses?

☐ Yes ☐ No

¿Which? ____________________________

7. Before the Hurricane, did you carry out tree trimming?

☐ Yes ☐ No

8. After the Hurricane, was your home affected? (On a scale of 1 to 5 mark with an “X” 1 if the damage is low and 5 if it is a lot)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

9. Was some of the damage caused by trees?

☐ Yes ☐ No

10. Were you able to identify some of the tree species that were affected?

☐ Yes ☐ No

¿Which? ____________________________
____

11. Select the number of downed trees in your home:

☐ 0 ☐ 1–5 ☐ 6–10 ☐ 10–15 ☐ > 15

12. How did you remove the trees?

Yourself ☐
Members of your community ☐
Relatives ☐
Municipality ☐
Private Agency ☐
Public Agency ☐
Professional service ☐

13. Did you have to pay for tree removal services?

☐ Yes ☐ No

14. Can you provide an estimate?

☐ \$10-\$50 ☐ \$50-\$10 ☐ \$100-\$200 ☐ >\$200

☐ Other: ______________________________

15. Select which of these tools you have.

Cart ☐
Machete ☐
Pruning shears ☐
Chain saw ☐
Tree shredder ☐
☐ Other: ______________________________

16. Were you able to take advantage of fallen trees in any of the following ways?

Firewood ☐
Stake ☐
Sherds ☐
Crafts ☐
Composting ☐
"Mulch" (Crushed) ☐
Storage (Drying) ☐
Fences (Living Gates) ☐
Deposited (Collection Centers) ☐
☐ Other: ______________________________

17. After Hurricane María passed, would you consider buying any of the following tools?

Cart ☐
Machete ☐
Pruning shears ☐
Chain saw ☐
Tree mulcher ☐
☐ Other: ______________________________

18. After the Hurricane, how would you rate your perception of trees? (In a scale from 1 to 5 mark with an "X" 1 if your perception is positive and 5 if your perception is negative)

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Positive *Negative*

19. After the Hurricane, have you planted trees?

☐ Yes ☐ No

20. If you answered No, would you consider planting trees?

☐ Yes ☐ No

21. If yes for what purpose did or did you plant trees?

Reforest ☐
Wood Use ☐
Beautify the landscape ☐
Promote Food Security ☐
Soil erosion control ☐
Replace damage to hurricane effect ☐
Regulate temperature ☐
Recreation ☐
Provide shade ☐

COURTSHIP CALL PHENOLOGY OF THE PUERTO RICAN PLAINS COQUI FROG, *Eleutherodactylus juanariveroi* (ANURA: ELEUTHERODACTYLIDAE)

Neftalí Ríos López[1,*] and Luis J. Villanueva-Rivera[2]

[1] Department of Biology, University of Puerto Rico in Humacao, Call Box 860, Humacao, Puerto Rico 00792
[2] Digitization Program Office, Office of the Chief Information Officer, Smithsonian, 600 Maryland Ave SW, Suite 810W, Washington DC 20024
* Author for correspondence: neftali.rios@upr.edu

Abstract

We used data from automated recording systems to describe the courtship call of the Puertorican Plains Coquí frog (*Eleutherodactylus juanariveroi*) and examined its calling phenology to make inferences about the species' system of acoustic communication. We also contrasted the phenology of courtship calling with published data on the species' advertisement call concerning projected climatic change and their implications for conservation. We found that the courtship call is short (0.86 sec) and consists of three to six notes with a short note repetition rate within the call. Most courtship calls are produced between 2100 h and 0800 h; monthly, more calls are detected between July and October. However, the number of courtship calls detected correlated with ambient temperature but not rainfall, which contrasts with published data about the species' calling phenology only using advertisement calls. Finally, we discussed our results on courtship calling phenology based on acoustic properties related to the physical environment, the behavior of calling males, the species' breeding biology, limitations of automated recording systems to detect the courtship call, and published inferences about the population status of the species based on acoustic analyses of only the species' advertisement call.

Keywords: acoustics, anurans, automated recording, coqui frogs, courtship, population declines.

Resumen

Describimos la llamada de cortejo del Coquí Llanero (*Eleutherodactylus juanariveroi*) utilizando datos obtenidos de sistemas automatizados de grabación de sonido y examinamos la fenología a base de la llamada de cortejo para inferir aspectos ecológicos y acústicos del sistema de comunicación de esta especie. También contrastamos resultados de esta fenología con resultados publicados a base de la llamada de anuncio en el marco de las projecciones de cambio climático y sus implicaciones para la conservación de la especie. Encontramos que la llamada de cortejo es una de muy corta duración (0.86 seg.) y consiste de entre tres y seis notas repetidas a una tasa muy corta por llamada. La mayoría de las llamadas de cortejo son producidas entre las 2100 y 0800 horas; mensualmente, se detectan mas llamadas de cortejo entre julio y octubre. No obstante, el número de llamadas de cortejo estuvo correlacionada con la temperatura del aire y no con la lluvia. Nuestros resultados contrastan con resultados publicados sobre las características acústicas de la llamada de anuncio de la especie así como la fenología en esta especie a base de su llamada de anuncio. Finalmente, discutimos nuestros resultados acerca de la fenología en la llamada de cortejo desde los contextos de las propiedades acústicas del hábitat de la especie, el comportamiento de machos cantores, la biología reproductiva de la especie, limitaciones en la detección de la llamada de cortejo por sistemas automatizados de grabación, e inferencias publicadas sobre el estatus poblacional de la especie basadas en análisis acústicos utilizando solamente la llamada de anuncio.

Palabras clave: anuros, acústica, coquí, cortejo, disminución poblacional, grabaciones automatizadas.

INTRODUCTION

Courtship calls by male frogs vary in the presence of a nearby female and include the lengthening of their advertisement call (which functions primarily to attract potential females for mating and male-to-male territorial interactions; Duellman and Trueb 1994), increasing calling rates, or modified versions of their advertisement call (Wells 2007 and references therein). This distinct type of call, strictly compared to the functions of the advertisement call, has been described in short-range courtship situations in which the male calls from a fixed location to attract the female, although they can occur in species in which the male leads the female to a selected oviposition site (Ovaska and Caldbeck 1997a; Gerhardt and Huber 2002; Wells 2007). In some instances, these courtship calls can be of lower intensity (i.e., softer calls; Ovaska and Caldbeck 1997b), presumably to prevent nearby males from becoming aware of an approaching female and interfere with a potential mating or to avoid detection by predators (Wells 2007; Toledo et al. 2015). While courtship calls play an essential role in the mating success of most anurans, vocalizations made during courtship are rarely documented (Owen and Tucker 2006; Wells 2007; Galvis et al. 2016).

In the insular Caribbean, courtship calls in *Eleutherodactylus* frogs have been documented only from five species (*E. antillensis*, *E. cochranae*, *E. coqui*, *E. johnstonei*, *E. schwartzi*: Townsend and Stewart 1986; Ovaska and Hunte 1992; Michael 1996; Bourne 1997; Ovaska and Caldwell 1997a,b, 1999; but see a 4-note call of *E. ligiae* in Incháustegui et al. 2015), which represents approximately 2.7% of species in the genus. However, Ríos-López and Villanueva-Rivera (2013; their Figure 4) documented a sequence of courtship behavior by the Puerto Rican Plains Coqui, *E. juanariveroi*. In this species, the body size is the smallest – on average, males reach ~14.7 mm in snout-vent length – and, consequently, has the highest-pitch call among Puerto Rican *Eleutherodactylus* (Ríos-López and Thomas 2007), which, to a researcher, could be challenging to detect in the field. Therefore, Ríos-López and Villanueva-Rivera (2013) were fortunate to detect and document its courtship behavior, which included a shift in the male's call from an advertisement call to a different type of call (from now on deemed courtship call) when a receptive female reached its territory to mate. The advertisement call consists of 4 to more than 20 notes organized in increasing subsets of single, duets, triads, and a long series of chirps per sequence of calls (Ríos-López and Thomas 2007). In contrast, this courtship call is much shorter and remains undescribed.

Herein we described this courtship call for *Eleutherodactylus juanariveroi* and used a 4-year audio database recorded on-site by the Automated Remote Biodiversity Monitoring Network (ARBIMON; Aide et al. 2013) to distinguish the species' courtship call from the conspicuous species' advertisement call. Also, we used results from Ospina et al. (2013) based on ARBIMON's recordings of the species' advertisement call to examine changes in the species' calling, from advertisement to courtship, on a 24-hr period. Finally, we used this database to determine if the species shows predictable changes in attributes of its courtship calls because of seasonality and make recommendations for the species' conservation based on automated-acoustic monitoring.

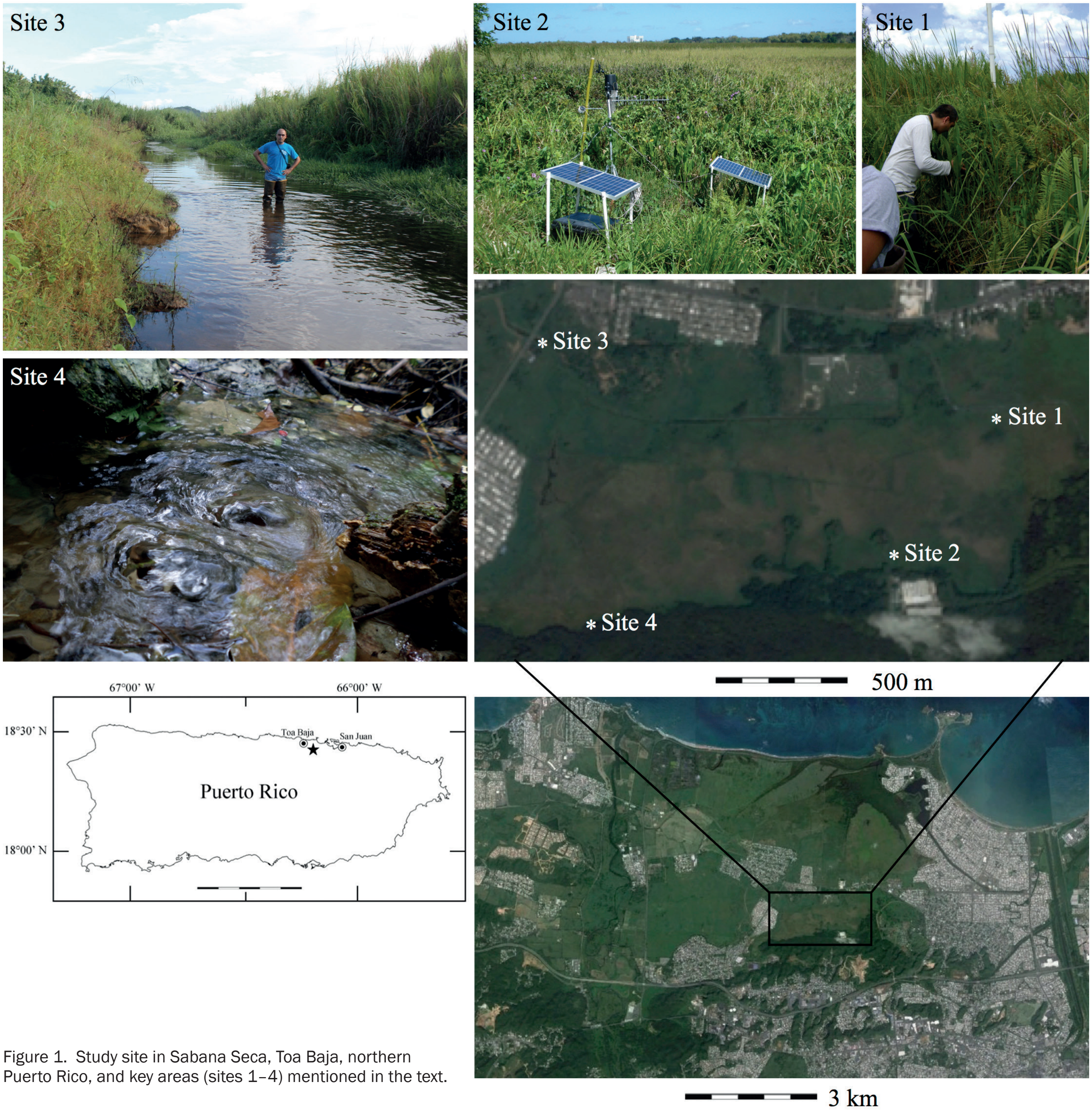

Figure 1. Study site in Sabana Seca, Toa Baja, northern Puerto Rico, and key areas (sites 1–4) mentioned in the text.

METHODS

Study Site

We conducted this study in a palustrine herbaceous wetland (ca. 260 ha; WGS84 18.434812°, -66.204709°) at an elevation ~0 m asl (above sea level), located in Sabana Seca, municipality of Toa Baja, northern Puerto Rico (Figure 1). This wetland is seasonally flooded with freshwater (Ríos-López et al. 2014), with a continuous contribution of groundwater from wells within the limestone formations (locally known as “mogotes”) to its south (Figure 1, sites 3 and 4). The soil consists of swamp and marsh organic deposits from Pleistocene and/or recent origin (Briggs and Akers, 1965).

We used climatic data from 2004 to 2015 available from the National Oceanic and Atmospheric Administration (NOAA) archives and recorded at the weather station "TOA BAJA LEVITTOWN, US" (WGS84: 18.4356°, -66.1678°; 8.5 m above sea level) from climatic variables (ambient temperature and rainfall) from 2004 to 2015. This station lies 3.9 km east of our study site, and its data was used to characterize the predominant climatic profile of Sabana Seca. Here, ambient temperature is mildly seasonal (average annual mean ± 1 SD = 25.2 ± 1.3 °C), and rainfall is mildly seasonal (average annual rainfall of 1,700 mm) (also see Eusse and Aide, 1999; Ríos-López and Villanueva-Rivera 2013; Ríos-López et al. 2014); relative humidity varies little (between 60% and 100% in the daytime and nighttime hours, respectively; Ríos-López et al. 2014). Most rain occurs from May to November, which is the warmest period.

Ríos-López and Thomas (2007), Ríos-López and Villanueva-Rivera (2013), and Ríos-López et al. (2014) provided species lists of vegetation in this wetland, with the most conspicuous herbaceous plants belonging to Cyperaceae (various genera and species), cattails (*Typha domingensis* Pers., Typhaceae), bull tongue arrowhead (*Sagittaria lancifolia* L., Alismataceae), and ferns (dentate or toothed midsorus *Blechnum serrulatum* Rich. and Willdenow's maiden *Thelypteris interrupta* [Willd.] K. Iwats., Polypodiaceae) (Figure 1, sites 1 and 2). In addition, the wetland is listed as Critical Habitat and *E. juanariveroi* as Critically Endangered (USFWS 2012).

Courtship call

We used the following terminology to identify signal structures in *E. juanariveroi* briefly: (1) a call, which consists of a group of notes regularly interspaced within a call; (2) a note, which is a single structure within a call; (3) call repetition rate refers to the periodicity of calls within a sequence of similar calls; (4) note repetition rate refers to the periodicity of notes within similar calls. Other terminology includes (5) amplitude (the loudness of a sound signal); (6) frequency (the number of waves per second, herein documented in kiloHertz [kHz]); (7) dominant frequency (the range of frequencies with the greatest amount of energy); (8) attenuation (reduction of energy of a sound wave).

We recorded the anuran chorus hourly, between 1700 h and 0700 h, during five consecutive days between February and March 2006 in the species' type locality in Toa Baja municipality, northern Puerto Rico (see Ríos-López and Villanueva Rivera 2013). We used a customized automated digital recording system (ADRS) placed at a height of 1.5 m within the vegetation at approximately 50 m from the wetland's edge. The recordings had a sampling rate of 48 kHz in 16-bit wav files, and once downloaded and stored, recordings were inspected for courtship calls indicative of courtship behavior documented by Ríos-López and Villanueva-Rivera (2013).

We used the software package Adobe Audition 1.0 (Adobe Systems Inc., California) to process recordings, including visually examining sonograms and filtering the range of frequencies that contained the courtship call. Specifically, each waveform was amplified by 15 dB to increase detection of this low-intensity call against the background soundscape, and once detected, we used Butterworth higher-order filter type with a transition bandwidth = 5 Hz and a window width = 50 ms following Ríos-López and Villanueva-Rivera (2013). We computed the root mean square or RMS power in decibels at the full scale (dBFS), which represents the power in a logarithmic scale in the digital file, for each hour to calculate the relative amplitude (%) of the courtship call. Finally, we used Raven 1.4 Beta Version, Built 34 (Cornell Lab of Ornithology, Ithaca, New York) to visualize the call, and oscillograms and sonograms were generated to describe signal structures and quantify several variables of the call.

Diel variation and calling phenology

We also used digital recordings from the field, which also were curated in a sound library created and maintained by Sieve Analytics (https://www.sieve-analytics.com/, ARBIMON team [Aide et al. 2013] and Rainforest

Connection at https://rfcx.org/). ARBIMON (Automated Remote Biodiversity Monitoring Network) combines hardware and software to automate data acquisition in the field, data management, and identify multiple species of amphibians, birds, insects, and mammals (Aide et al. 2013). For these analyses, we used 1-minute recordings every 10-minute interval between March 11, 2008 (2359 h) and July 19, 2011 (0000 h), totaling 108,987 files from the sound library. During that period, ARBIMON tagged 6,548 files positive for potential courtship notes of *E. juanariveroi* as part of the systems' early stages of validation (see Aide et al. 2013). Next, we visually inspected a subsample of 500 sonograms from recordings tagged 'positive' (the 6,548 files) and 494 sonograms 'negative' (102,439 files) for this call of *E. juanariveroi* to account for the uncertainty of detection of courtship calls by the automatized procedure. Once we detected courtship calls between subsamples, we used all recordings with these calls, counted them per recording, calculated detection frequency per hour (number of recordings with the call divided by the total number of recordings per hour to determine dial variation in calling activity), and used monthly counts of these calls to examine seasonality. Data on the detection frequency of advertisement calls were extracted from Ospina et al. (2013) and contrasted with our data on the detection frequency of courtship calls to examine the diel pattern of calling attributable to the function of a call. Also, we contrasted the phenology of courtship calls, which indicate oviposition as described by Ríos-López and Villanueva-Rivera (2013), with published results from Ospina et al. (2013) based on advertisement calls alone.

Climatic data and analyses

We used monthly mean minimum (nocturnal), maximum (diurnal) air temperature (°C), and rainfall data from the nearest weather station (~3 km east, Toa Baja Levittown NOAA weather station) between December 2004 and March 2015 to examine the relationship between monthly variation in courtship calling and climatic variables. We used Pearson's correlation after testing for normality assumption using the Wilk-Shapiro test and adopted a significance level $\alpha \leq 0.05$. Values are shown as mean ± standard deviation (S.D.) for all analyses unless otherwise specified.

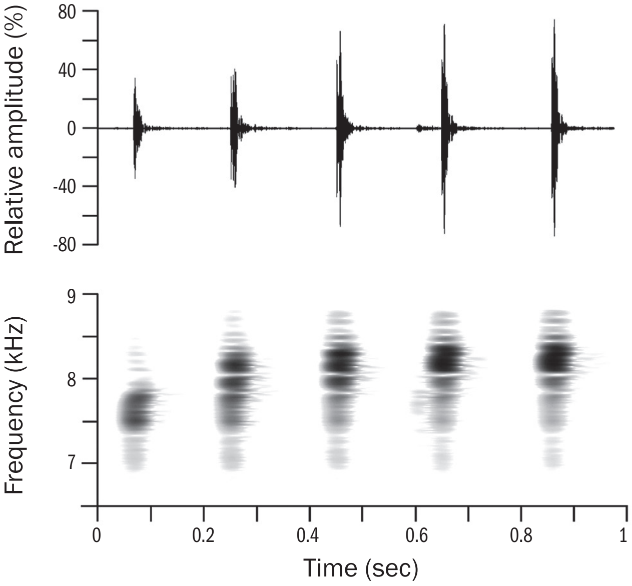

Figure 2. Courtship call of *Eleutherodactylus juanariveroi*. Top: oscillogram; Bottom: sonogram.

RESULTS

Courtship call

This call consists of three to six notes (4.63 ± 0.92 notes, n = 11 calls), which sequentially increase in amplitude and frequency (Figure 2). The frequency of this call ranged between 6.03 and 9.02 kHz, and its dominant frequency ranged between 7.44 and 8.39 kHz (7.88 ± 0.23 kHz, n = 51 notes). The duration of this call is between 0.42 sec and 1.1 sec (0.86 ± 0.21 sec, n = 11 calls), and that of the note was from 14 to 32 ms (milliseconds; 20.0 ± 4.3 ms, n = 51 notes). Call repetition rate varies widely (20.4 ± 16.2 sec., n = 11). In contrast, the note repetition rate varies slightly between consecutive notes within a call (212.2 ± 2.1 ms, n = 40 notes).

Diel variation

We found 275 true-positive recordings for courtship calls from 500 recordings tagged 'positive' (55.0% true

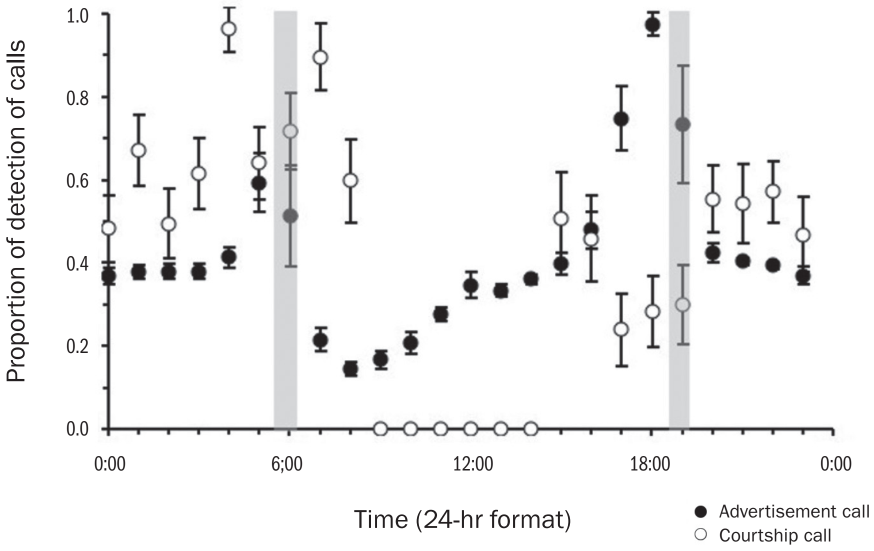

Figure 3. Diel variation in courtship calling (open circles; data from this study) and advertisement calling (filled circles; data extracted from Ospina et al. [2013] with permission to NR-L). Grey bars mark the approximate sunrise and sunset times in Puerto Rico.

positive). Also, we found 80 true-positive recordings for courtship calls from 494 recordings tagged 'negative' (16.2% false negative). The mean hourly detection of calls among recordings was 47.4 ± 34.9% and varied between 0% (around mid-day hours) and 91% (between late night and early morning hours). However, there was a significant correlation between the precision of detection per hour and the number of courtship calls per recording: higher precision of automated call detection resulted when more courtship calls were detected per 1-minute recording (rs = 0.8299, p < 0.0001, n = 24).

The diel variation in courtship calls showed a distinct pattern (Figure 3). No calls were detected between 0900 h and 1400 h, only to increase detection from ~24% to ~46% between 1500 h and 2000 h (Figure 3). However, from ~58% to >90% of recordings, most courtship calls were detected between 2100 h and 0800 h. Within the calling activity period, the lowest detection of courtship calls occurred from 1700 h to 1900 h and from 0500 h to 0600 h (Figure 3).

Calling phenology

The number of courtship calls detected per 1-minute recording varied with the month of the year (Figure 4). The higher mean count of monthly courtship calls (months with over four mean calls/min. recording) occurred from July to October, with 5.2 calls/minute ± 1.4 calls/minute, representing 48.0% annual courtship calling. September had the highest mean count of courtship calls, with 6.6 courtship calls/min (± 5.4 calls/minute), including the recording with most courtship calls (27) detected in 1 minute. In contrast, the lowest mean-count value in monthly courtship calls (months with ~2 mean calls/min. recording) occurred from December to February, with 2.1 calls/minute ± 0.6 calls/minute, representing 14.8% annual courtship calling. Months from March to June and November had 3.2 calls/minute ± 0.3 calls/minute, representing 37.2% annual courtship calling.

There was a correlation between monthly mean-courtship-calls/recording and monthly mean air-temperature (minimum [nocturnal] temperature: r = 0.7675, p = 0.0037, n = 12; maximum [diurnal] temperature: r = 0.8281, p = 0.0009, n = 12); more courtship calls are produced per unit of time with increasing mean monthly air-temperature (Figure 4). In contrast, there was no correlation between monthly mean-courtship-calls/recording and monthly mean rainfall (r = 0.3884, p = 0.3884, n = 12; Figure 4).

DISCUSSION

Courtship call

The species' courtship call is structurally simple, with an average number of notes per call of 4.6, a call duration of 0.86 sec, and a short note repetition rate within the call. In contrast, the advertisement call of *E. juanariveroi* is structurally complex, has an average number of notes per call of 23, a call duration of 10.9 sec, and a high

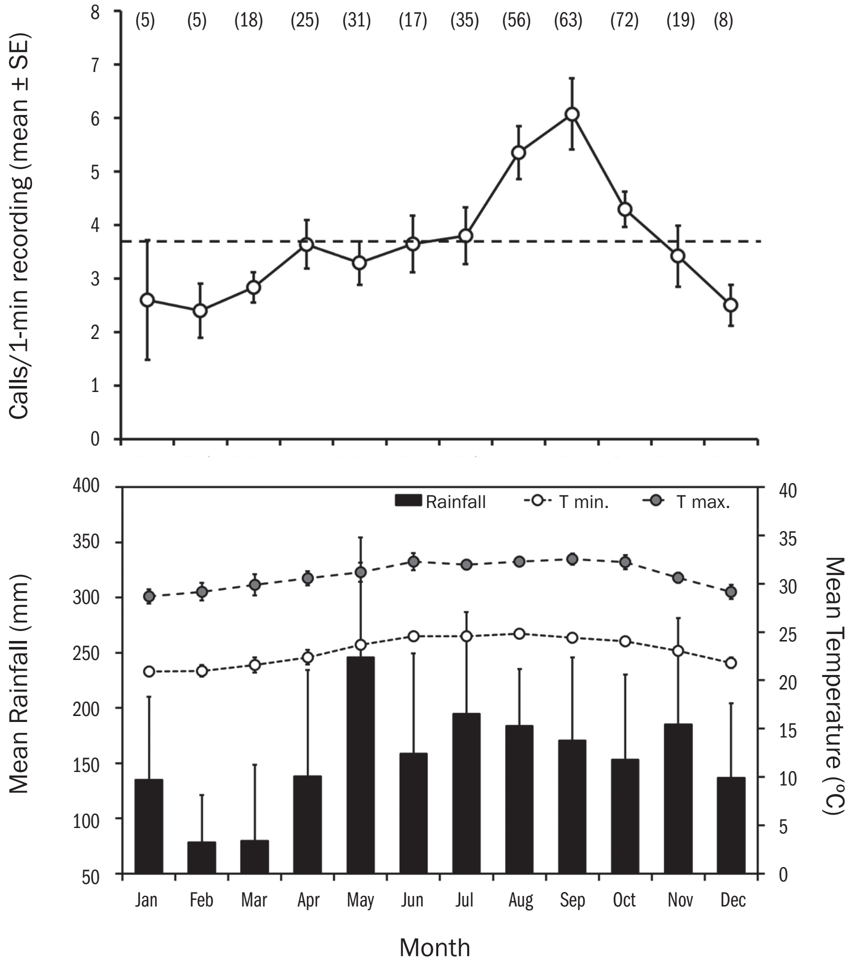

Figure 4. Calling phenology (top pane) and seasonality of climatic variables (bottom pane). Top pane: the number of recordings with courtship calls in parenthesis per month (provided by ARBIMON); the dotted line is the mean number of calls per 1-minute recording throughout months. Bottom pane: circles represent temperature data (T min. = minimum temperature, measured at night; T max. = maximum temperature, measured at day; top of columns represent mean rainfall in millimeters.

note-repetition rate within the call (Ríos-López and Thomas 2007). Nonetheless, both types of calls are of similar frequencies (between ~6 and ~9 kHz) and have a similar dominant frequency (courtship call ~7.9 kHz [this study] versus advertisement call ~7.7 kHz [Ríos-López and Thomas 2007]). However, the function of this courtship call and its advertisement call suggests an adaptive behavioral response in *E. juanariveroi* to the influence of microhabitat characteristics on its communication system (see next).

Gerhardt and Huber (2002) reviewed and discussed several physical attributes that influence the propagation of sound in frogs. Briefly, a major problem for effective communication in a small-body-sized frog emerges because of the inverse relationship between body size and frequency of the call: a small-body-sized frog produces a high-frequency call and vice versa (Gerhardt and Huber 2002; Wells 2007). Furthermore, these higher-frequency calls are subjected to more attenuation and degradation from vegetation (and other habitat-related variables) than lower–frequency calls from larger species (Erdtmann and Lima 2013). Consequently, small-body-sized frogs overcome limitations for long-range communication of high-frequency calls from their males by calling from elevated surfaces throughout their habitats (Gerhardt and Huber 2002; Erdtmann and Lima 2013). For example, in the very-small *E. juanariveroi*, Ríos-López and Thomas (2007) found that males of the species are frequently found producing their advertisement call from vegetation surfaces between 0.6 m and 1.2 m in height (maximum height of vegetation measured at this site was 2.1 m; Ríos-López et al. 2014). Therefore, Ríos-López and Villanueva-Rivera (2013) and Ríos-López et al. (2014) suggested that habitat use for advertisement calling is adaptive to increase long-range communication in *E. juanariveroi*.

Attenuation and distortion effects on high-frequency calls are usually magnified if at ground level or within relatively densely vegetation (Gerhardt and Huber 2002, and references therein), which are not microhabitats used by *E. juanariveroi* for advertisement, but for courtship rituals as described by Ríos-López and Villanueva-Rivera (2013). Also, this species shows microhabitat selection for oviposition, and oviposition sites are close to the ground (Ríos-López and Thomas 2007; Ríos-López et al. 2014). Therefore, a brief recollection of behavioral sequences from Ríos-López and Villanueva-Rivera (2013) is worth reproducing herein. These authors found that the male deliberately produced this courtship call frequently on vegetation surfaces near the ground until the pair entered the leaf axil for mating and egg-laying. This microhabitat for oviposition lies between 0.1 m and 0.2 m above the water level, which contrasts with the height range of 0.6–1.2 m for advertisement (see Figure 4 in Ríos-López and Villanueva-Rivera 2013). However, one consequence of calling near ground level in its habitat is that courtship calls are difficult to detect, either by conspecifics, the researcher, or automated procedures when sampling or monitoring higher above the vegetation layers in the wetland. Based on Ríos-López and Villanueva-Rivera (2013) and this study, *E. juanariveroi* seems to have a short-range low-intensity communication system for courtship situations, characterized by males leading a receptive female to a selected oviposition site, a system found in other species (e.g., Ovaska and Caldbeck 1997a,b; Gerhardt and Huber 2002; Wells 2007; Toledo et al. 2015). Similar to the advertisement call, we suggest that the production of its courtship call also seems adaptive to the influence of the physical environment in this small-sized *Eleutherodactylus*. However, we do not know if the species' calls – either advertisement, courtship, or other – also function for male-to-male communication as it exists in other *Eleutherodactylus* like *E. coqui* (Narins and Capranica 1978).

Diel variation

Diel variation in the activity based on the advertisement call in *E. juanariveroi* was described by Ospina et al. (2013) and Ríos-López and Villanueva-Rivera (2013). These studies showed that this activity has two peaks, a high one that spans four hours (from 1600 h to 2000 h) and a shorter one that spans two hours (from 0500 h to 0600 h), only to decrease before sunrise (Figure 3). Also, the activity from courtship calls showed two peaks, but of different distribution and duration throughout the night: a short one that spans from 1500 h to 2000 h and a higher and longer one that spans from 2000 h, increases to its highest values between 0400 h and 0700 h, and decreases by 0800 h. Therefore, the diel pattern of the courtship call differs from that of the advertisement call, which suggests a generalized pattern in the species' calling activity. In *E. juanariveroi*, males engage in advertisement calls during early hours at night (i.e., calls for long-distance communication) and shift their call to court females, if successful during the advertisement period. Therefore, this courtship call provides for short-distance communication during which males guide females to the selected oviposition site (Ríos-López and Villanueva-Rivera 2013; Ríos-López et al. 2014). Therefore, we suggest that most egg-laying occurs during the second and longer peak in the species' courtship-call period, between 2000 h and 0500 h; this is also when the anuran advertisement-chorus significantly decreases at this wetland (Figure 6 in Ríos-López and Villanueva-Rivera 2013).

Courtship calling phenology and its significance to the species' population dynamics

We believe that courtship-calling phenology adds to our understanding of the complex synergism between environmental variables, climate variables, and the species' population dynamics. For example, Ríos-López et al. (2014) suggested that the population dynamics of *E. juanariveroi*, measured as changes in abundance of individuals detected acoustically and visually monthly, might be best explained by synergism between variables related to climate, particularly seasonality in rainfall and oviposition/calling sites. Specifically, most of the variation in abundance of *E. juanariveroi* was significantly explained by rainfall but not by ambient temperature and relative humidity (Ríos-López et al. 2014), with the vast majority of individuals detected on certain vegetation surfaces more frequent than expected. Also, Ríos-López et al. (2014) conducted their study between 1830 h and 2330 h and detected the vast majority of frogs visually, including most advertising males that, when disturbed by an approaching observer, may stop calling but can still be seen. Those individuals detected acoustically are usually hidden within the higher layers of vegetation, where they make the advertisement call (see section Courtship call above).

Individuals of *E. juanariveroi* are of small body size, making them more susceptible to increasing evaporative water loss daily and seasonally compared to larger species of frogs. The increased threat of dehydration seems to result from the surface-to-volume ratio, which increases as body size decreases, and advertisement calling requires a considerable expenditure of energy to behaviorally reduce acoustic interference from herbaceous vegetation (see Ospina et al. 2013). Ríos-López et al. (2014) did not survey the vegetation layers close to the ground for individuals during nocturnal censuses. However, we know that ambient temperature increases and humidity decreases along a vegetation continuum, from close to the ground to the highest vegetation layers (mean height 1.7 m). Thus, evaporative water loss at higher vegetation strata may influence activity and reproduction, and, thus, finding mating individuals at these higher, exposed vegetation strata would be rare (e.g., Beuchat et al. 1984, Taigen et al. 1984; for oviposition in *E. juanariveroi* see Ríos-López and Thomas 2007 and Ríos-López et al. 2014; see Wells 2007 for a review). However, the advertising call may not lead to mating and oviposition (see next), and monitoring its calling activity to make inferences about future population dynamics in response to projected climatic change may be more complex than frequently acknowledged.

Ospina et al. (2013) found a negative relationship between the advertisement calling activity of *E. juanariveroi* and rainfall and temperature, which presents the species with a dilemma: increased communication distance to attract potential mates and reduce acoustic interference by vegetation surfaces. Thus, males face a cost-benefit situation during advertisement calling when climbing higher in vegetation surfaces for advertising while exposing themselves to higher dehydration risk. Based on projections of climatic change in the Caribbean, towards higher temperature and larger variation in the distribution of rainfall throughout the year, Ospina et al. (2013) found a population trend towards a decine that spanned their 4-yr study and suggested that increased dehydration of individuals of *E. juanariveroi* on hot days would ultimately lead to its extirpation. However, the advertisement calling activity of this species increased in the years that followed those examined by Ospina et al. (2013) (T. M. Aide, unpublished data; personal communication to NR-L). Notably, Quiñonez Márquez (2021) highlighted that projections of climatic change from global and/or regional climate models appear not to accurately simulate, for example, the amount of future rainfall on small islands like Puerto Rico; these models do not take into account the multiplicity of interactions of physical and microclimatic factors that influence the accuracy of predictions at small spatio-temporal scales. Also, we suggest that individuals of *E. juanariveroi* could adapt behaviorally to variations in microclimate by distributing throughout the vertical extent of the wetland's vegetation whenever needed. Consequently, different data sets – trends in advertisement and courtship calls relative to general climatic models – may lead us to different interpretations of the species' future population dynamics (see next).

Although based on one observation, Ríos-López and Villanueva-Rivera (2013) found that courtship calling activity related to egg-laying, which occurs close to the more-humid ground at the base of plants and on vegetation surfaces (97.7% and 2.3%, respectively; Ríos-López et al. 2014). However, this humid-saturated microhabitat is not exposed to direct rainfall and wind, while water from upwells constantly flows into the wetland (Figure 1, site 4), preventing the drying of the wetland's soil throughout the year (Ríos-López et al. 2014). Also, Ríos-López et al. (2014) measured relative humidity between 0.1 m and 0.2 m above the water level in the center of their census belt transects and found that monthly mean nocturnal-relative humidity reached 97.6% (± 2.7%) independent of the month of the year. These observations lead us to think that the influence of humidity – or other water-related variables – on the variation in the reproductive phenology of this species could be minimal, which may explain why courtship calling activity is related to fluctuations of ambient temperature and not rainfall. Also, the species' evolutionary breeding biology could play a more significant role in explaining the variation in its population dynamics than frequently acknowledged (see next).

A reproductive strategy that characterizes *Eleutherodactylus* frogs (Townsend 1996) is the direct development of embryos (and terrestrial eggs), which also is profoundly constraint by a high rate of evaporative water loss in terrestrial habitats (Taigen et al. 1984; Wells 2007). *Eleutherodactylus* frogs frequently engage in egg brooding, a parental-care strategy that reduces evaporative water loss and dehydration in terrestrial species. However, this strategy seems to be less significant in species from this and other genera that lay eggs in saturated humid microhabitats and environments (e.g., *E. cooki* in Burrowes 2000 and Rogowitz et al. 2001; *Cophixalus parkeri*, a microhylid frog from New Guinea in Simon 1983; review in Wells 2007). Notably, males of *E. juanariveroi* do not engage in egg brooding, and eggs and embryos develop healthily without brooding adults (Ríos-López et al. 2014). Ríos-López et al. (2014) also mentioned that the production of egg clutches is higher during months characterized by higher temperatures and more rainfall (e.g., October-November) and lower during months with lower temperatures and reduced rainfall (e.g., February-March). Closer to the ground, the ambient temperature may have a more-influencing role in its courtship calling phenology in this microhabitat of the wetland: here, we found that most of the variation in monthly courtship calling was best explained by temperature, in which increased calling activity occurs during months with higher temperatures, with little contribution from rainfall. We suggest that the wetland's vegetation layers at lower strata provide more humid and less variable microhabitat conditions suitable for reproductive activities other than advertisement, specifically mating and oviposition. Therefore, the detection of courtship calls from automated acoustic monitoring systems, like those used by Ospina et al. (2013), and this study could have more predictive power for oviposition and, thus, the species' breeding phenology in response to projected climatic change.

The automated acoustic monitoring technique provided much information in *E. juanariveroi* with little effort. However, if making inferences for conservation is a primary goal, this technique should combine with other monitoring techniques like field data based on visual detection animals. This combination leads to a broader and more complete understanding of the population ecology of this species and other *Eleutherodactylus.* As found in *E. coqui* (Townsend and Stewart 1986), we acknowledge that not all courtship events may conclude with oviposition, but courtship calling seems to lead a step closer to mating and oviposition than advertisement calling behavior. As shown, data from different variables and spatio-temporal scales generate different patterns and, thus, may lead us to different conclusions. Therefore, we recommend also surveying for courtship calls, rather than advertisement calls alone, for a better understanding of the population ecology of this species, with implications for conservation with projected climatic change.

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NOTES ON A FOREST WITHIN THE NORTHEAST ECOLOGICAL CORRIDOR NATURE RESERVE: AN INVITATION FOR A LONG–TERM RESEARCH AGENDA

Jonathan Paul Frye[1,*]

[1] Department of Natural Science, McPherson College, 1600 East Euclid Street, McPherson, KS 67460
* e-mail: fryej@mcpherson.edu

Abstract

The Northeast Ecological Corridor Nature Reserve near Fajardo, Puerto Rico, contains a subtropical dry forest patch that has not been cleared since at least 1931. In 2013, undergraduate students from UPR-Río Piedras, UPR-Humacao, and McPherson College, McPherson, Kansas, established two 0.10 ha plots in this forest and monitored the plots from May 2013 to December 2016 to assess the forest's structure, species composition, diversity, and stem growth. We identified at least 38 tree species and found that the preponderance of stem growth (cm^2/yr) occurred in the larger stems (DBH > 20 cm), although the majority of tree stems had a diameter at breast height (DBH) of < 5 cm. Our data provide a baseline against which to measure post-hurricane recovery in this subtropical dry forest.

Keywords: subtropical dry forest composition, growth, diversity, hurricane effects baseline

Resumen

La Reserva Natural del Corredor Ecológico del Noreste cerca de Fajardo, PR contiene un parche de bosque seco subtropical que no ha sido talado desde al menos 1931. En 2013, estudiantes universitarios de UPR-Río Piedras, UPR-Humacao y McPherson College, McPherson, Kansas, establecieron dos parcelas de 0.10-ha en este bosque y monitorearon las parcelas desde mayo de 2013 hasta diciembre de 2016 para evaluar la estructura del bosque, la composición de especies, la diversidad y el crecimiento de los tallos. Identificamos un mínimo de 38 especies de árboles. Aunque la mayoría de los tallos de los árboles tenían un diámetro a la altura del pecho (DAP) de < 5 cm, la preponderancia del crecimiento del tallo (cm^2/año) ocurrió en los tallos más grandes (DAP > 20 cm). Nuestros datos proporcionan una base de referencia para examinar la respuesta de estos bosques a los huracanes Irma y María a largo plazo.

Palabras clave: composición del bosque seco subtropical, crecimiento, diversidad, línea base de efectos de huracanes

INTRODUCTION

Land-use changes due to human activities (e.g., agriculture, urbanization) and other forest disturbances due to extreme climate events (e.g., hurricanes, wildfires) and prolonged droughts affect subtropical dry forests worldwide. The ability of forests to recover from such disturbances, as indicated by their accumulation of aboveground biomass, is of ecological interest. The carbon sequestration or growth rates (Mg C/ha•yr) of neotropical secondary forests can be more than ten times that of old-growth forests (Poorter et al. 2016). As a result, tropical forests play a significant role in the global atmospheric carbon cycle, which has consequences for projected trends of global warming (IPCC–Working Group II 2022).

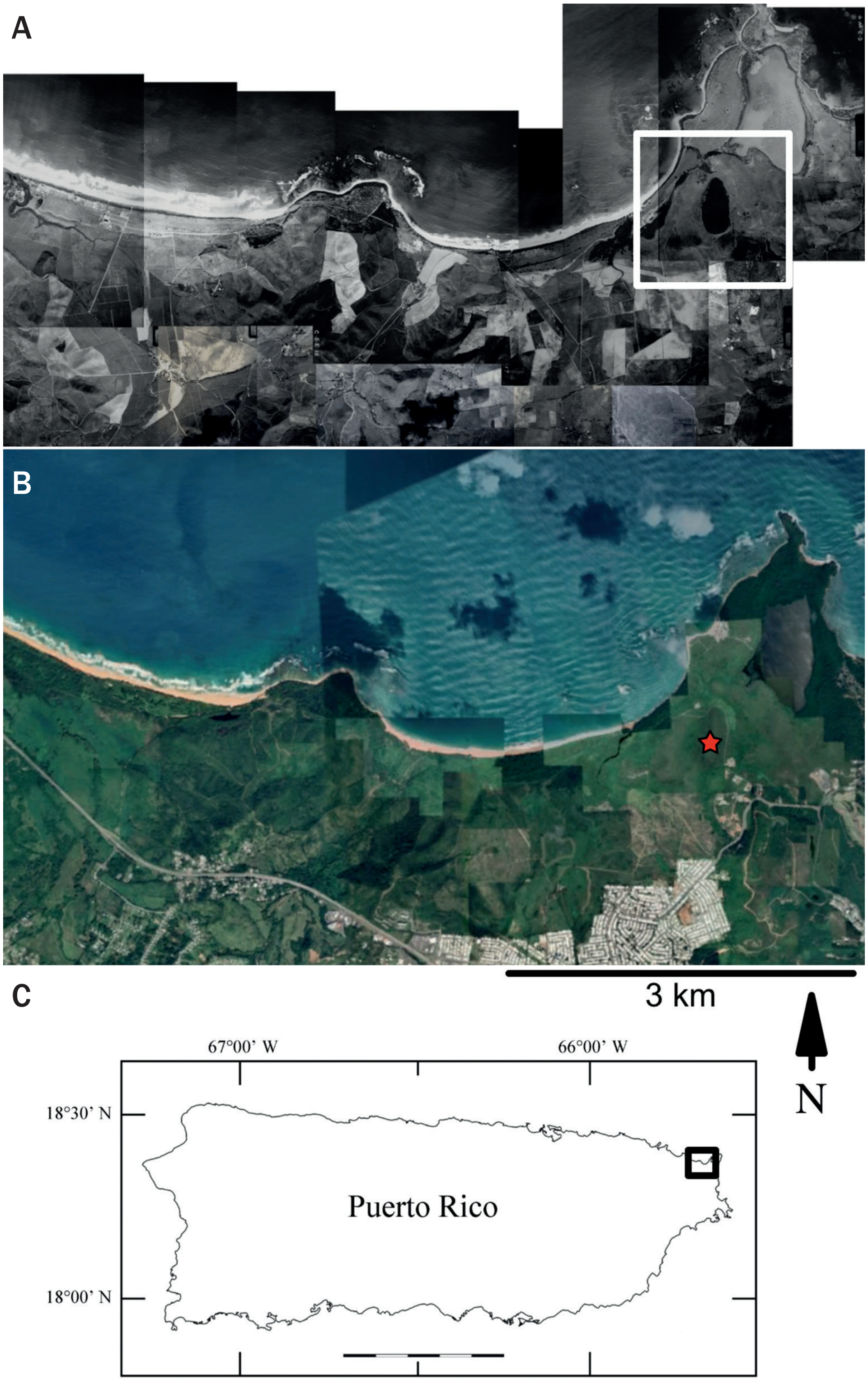

Figure 1. A) A mosaic of 1931 aerial photographs of the Northeast Ecological Corridor Nature Reserve, assembled by the "Oficina de Fotogrametría, Departamento de Transportación y Obras Públicas, 1931," as presented in Junta de Planificación (2015). The white square highligths the study hill described in the main text. B) The same area but as in 17 May 2021 (Scale line = 3 km); the red star higlights the top of the study hill as reference. C) Location of the Northeast Ecological Corridor Nature Reserve within Puerto Rico (Scale bar = 50 km).

Puerto Rico encompasses a wide diversity of landscape units defined by the intersections of climate (Holdridge life zones), substrate, and topography (Gould et al. 2008). Because of its location in the path of hurricanes forming in the tropical Atlantic and its relatively high human population density, most sites in Puerto Rico have a history of significant disturbances due to non-anthropogenic and anthropogenic phenomena. Setting some areas aside in Nature Reserves provides the opportunity both to observe the long-term recovery of an area from some anthropogenic disturbances and to observe the effects of non-anthropogenic disturbances and the dynamics of the ecosystem's response to those disturbances apart from the anthropogenic ones (Wood et al. 2019).

METHODS

Site Description

This forest research site lies within the Northeast Ecological Corridor Nature Reserve (NECNR) near Fajardo, Puerto Rico, at approximately 65°39.00' West by 18°21.75' North. The NECNR was established under the laws of Puerto Rico in 2013 (Gobierno del Estado Libre Asociado de Puerto Rico, 2013). The forested patch is located on a hill, approximately 0.5 km wide (east to west) and 1.0 km long (north to south), with a ridge elevation of approximately 40 m. Aerial photography from 1931 (Figure 1) indicates that the site was one of the few parts of the reserve area that was forested at that time.

The USDA-NRCS Soil Resource Report for the site, available online from http://websoilsurvey.nrcs.usda.gov/app/ and updated September 2016, indicates that the soil type is classified as YuF2 (Yunes silty clay loam). Boccheciamp (1977) describes this soil type as shallow (25–50 cm depth to paralithic bedrock), steeply sloped, eroded, and not prime farmland. For these reasons, the site was probably never cleared for agricultural use, as was most of the rest of the NECNR. This site represents one of the largest and oldest patches of lowland subtropical dry secondary forest on sloping volcanic and volcaniclastic soils in Puerto Rico (Gould et al. 2008). A rare tree species, *Eugenia fajardensis* (Myrtaceae), was rediscovered in this forest (Trejo-Torres et al. 2014).

Data collection and analyses

We used the verified citizen science method (Bonter and Cooper 2012) for data collection and validation. Consequently, citizen scientists generated the data herein, including undergraduate students of various science and non-science disciplines from the University of Puerto Rico at Río Piedras and McPherson College, McPherson, Kansas.

In May 2013, we established two 0.1-ha plots, each 20-m x 50-m, at the site. We oriented the long axis of each plot north-south, with one plot on the east-facing slope of the hill and one on the west-facing slope. We used a plot design that is a modification of the plans of Domínguez Cristóbal (2011) and Barone et al. (2008) to facilitate comparisons to similar data from other forests in Puerto Rico.

In May 2013, we tagged all trees within the plots whose height was ≥ 1.5 m and whose diameter at breast height (DBH) was ≥ 1 cm. We measured the DBH at the height of 1.4 m above the ground (Weaver and Rodríguez 2009), using vernier calipers for DBH ≤ 5.0 cm or DBH tapes for DBH > 5 cm. Each tree's basal area (BA) was calculated as $BA = \pi(DBH)^2/4$. We also estimated the height of each tree. Finally, for each plot, we counted the number of trees of each species and calculated the total BA of each species.

We collected voucher specimens of trees at the site as part of an initial site survey in January 2013. We collected additional specimens during May 2013 and January 2014 site visits. We pressed and dried the specimens and submitted them to the Herbarium of the University of Puerto Rico at Río Piedras for identification.

To quantify the species diversity and dominance characteristics of the two plots, we calculated the following indices (Brower et al. 1998):

Shannon's Diversity Index:

$$H' = (N \, Log \, N - \Sigma[n_i \, Log \, n_i]) / N$$

Simpson's Dominance Index: $l = \sum\left[\frac{n_i (n_i - 1)}{N(N-1)}\right]$

Simpson's Diversity Index: $D_s = 1 - l$

Simpson's Inverse Index: $d_s = 1/l$

We calculated Shannon's Diversity Index using the number of stems and the BA data for each species.

Finally, we calculated each tree's BA growth rate (GR) in cm^2/year using the least-squares linear regression of the BA data for each tree from all measurement dates (i.e., May 2013, January 2014, January 2015, January 2016, and December 2016).

RESULTS

Among the 792 stems tagged in the east plot, we identified 29 different species. Six individuals were identified only to the genus level or as distinct from other species in the same genus (e.g., *Cordia* spp. vs. *Cordia alliodora*). These six individuals represent four genera (*Cordia*, *Ocotea*, *Schoepfia*, and *Solanum*). There remain 161 tagged stems where we have been unable to positively identify the species without specimens of the flowers and fruit. These 161 individuals likely represent three different morphotypes based on their leaves and stems, which may raise the number of species detected to 36 in the east plot (Table 1).

Similarly, among the 814 stems tagged in the west plot, we positively identified 20 species. There remain 20 tagged stems where we cannot identify the species without specimens of the flowers and fruit. These 20 individuals represent four different morphotypes based on their leaves and stems, which may raise the number of species detected to 24 in the west plot (Table 2). Among these species, we found larger stems (i.e., DBH ≥ 10 cm) only among *Hymenaea courbaril*, *Tetragastris balsamifera*, *Bursera simaruba*, *Guapira fragance*, and one unknown. *Hymenaea courbaril* and *Tetragastris balsamifera* accounted for 89% of the total BA in the west plot, whereas 75% of the stems in the west plot were in the DBH ≤ 5-cm size class.

Table 1. The species composition of the forest tree community in a 0.1-ha plot on the east-facing slope of a hill in the Northeast Ecological Corridor Nature Reserve, Puerto Rico; measured in December 2016.

Tree Species	Stems/ha total	Stems/ha dbh<=5cm	Stems/ha dbh5-10cm	Stems/ha dbh10-20cm	Stems/ha dbh>20cm	BA (m^2/ha)
Amiris emilifera	50	40	10	0	0	0.04
Bursera simaruba	50	0	0	0	50	5.48
Casearia guianensis	10	10	0	0	0	0.01
Chrysophyllum argenteum	100	90	10	0	0	0.06
Coccoloba diversifolia	40	0	30	10	0	0.16
Cordia alliodora	20	10	0	0	10	0.34
Cordia spp.	20	10	0	10	0	0.13
Cynaphallo hastada	160	10	140	10	0	0.81
Erythroxylum areolatum	10	10	0	0	0	0.01
Erythroxylum rufum	10	10	0	0	0	0.01
Erythroxylum spp.	10	10	0	0	0	0.01
Eugenia ligustrina	360	340	20	0	0	0.28
Eugenia monticola	210	130	70	10	0	0.42
Eugenia pseudosidium	1940	1870	60	10	0	1.04
Guapira fragance	260	70	120	70	0	1.84
Hymenaea courbaril	100	0	0	60	40	3.48
Maytenus domingensis	420	320	90	10	0	0.69
Myrciaria floribunda	20	20	0	0	0	0.00
Nectandra coriacea	20	20	0	0	0	0.01
Neea buxifolia	30	30	0	0	0	0.00
Ocotea coriacea	380	180	80	120	0	2.07
Ocotea spp.	90	40	30	20	0	0.46
Ouratea litoralis	10	10	0	0	0	0.02
Quadrella indica	10	10	0	0	0	0.00
Quadrella synophallophora	0	0	0	0	0	0.00
Randia aculeata	30	30	0	0	0	0.01
Samyda dodecandra	100	100	0	0	0	0.04
Savia sessiliflora	660	520	140	0	0	0.89
Schoepfia spp.	20	20	0	0	0	0.01
Senegalia muricata	210	20	20	150	20	3.71
Solanum spp.	10	10	0	0	0	0.00
Tetragastris balsamifera	60	40	0	10	10	0.49
Trichilla pallida	100	100	0	0	0	0.11
Unknowns	1660	500	440	660	60	14.97
Totals	7180	4580	1260	1150	190	37.61

We found 5 species in the west plot and 17 species in the east plot, with several species shared between plots. Therefore, we found 16 species in both plots (excluding the unknowns). Also, the east plot's diversity is higher, whether the diversity index was based on the absolute number of species between plots (Tables 1 and 2), the size-class distribution of the number of stems per species (Figure 2), or the distribution of total BA of species between plots (Table 3).

Although we found fewer trees with a BA > 100 cm^2, they contribute significantly to the total growth of the forest (Figure 3). For example, in the east plot, the 91 trees with a BA > 100 cm^2 collectively grew 471 cm^2/year, whereas the 505 trees with a BA < 100 cm^2 grew only 268 cm^2/year. Similarly, in the west plot, the 60 trees with a BA > 100 cm^2 collectively grew 462 cm^2/year, whereas the 498 trees with a BA < 100 cm^2 grew only 271 cm^2/year.

DISCUSSION

Rather than being conclusive, this brief report provides baseline data for future studies aiming at examining responses of forests to natural phenomena, anthropogenic included. Specifically, since the study site has been forested continuously since at least 1931, it could be compared to adjacent patches of forest that

Table 2. The species composition of the forest tree community in a 0.1-ha plot on the west-facing slope of a hill in the Northeast Ecological Corridor Nature Reserve, Puerto Rico; measured in December 2016.

Tree Species	Stems/ha total	Stems/ha dbh<=5cm	Stems/ha dbh5-10cm	Stems/ha dbh10-20cm	Stems/ha dbh>20cm	BA (m^2/ha)
Bursera simaruba	120	0	40	60	20	1.62
Coccoloba diversifolia	10	10	0	0	0	0.01
Coccoloba rugosa	20	20	0	0	0	0.00
Eugenia ligustrina	150	140	10	0	0	0.07
Eugenia monticola	20	20	0	0	0	0.01
Eugenia pseudosidium	550	530	20	0	0	0.27
Faramea occidentalis	630	610	20	0	0	0.33
Guapira fragance	10	0	0	10	0	0.11
Hymenaea algarrobo	30	0	20	0	10	0.58
Hymenaea courbaril	580	40	80	240	220	24.28
Krugeodendrum ferrum	20	20	0	0	0	0.02
Maytenus domingensis	150	130	10	10	0	0.16
Myrciaria floribunda	480	440	40	0	0	0.32
Neea buxifolia	10	10	0	0	0	0.00
Ocotea coriacea	20	0	10	10	0	0.11
Randia aculeata	10	10	0	0	0	0.00
Samyda dodecandra	0	0	0	0	0	0.00
Savia sessiliflora	30	30	0	0	0	0.01
Tetragastris balsamifera	3780	2800	720	220	40	9.54
Trichilla pallida	120	110	10	0	0	0.09
Unknowns	310	280	20	10	0	0.38
Totals	7780	5860	1090	570	260	37.91

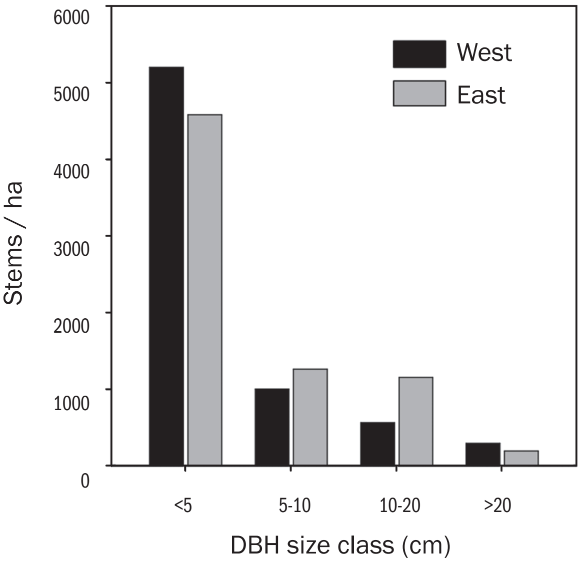

Figure 2. Size class distribution of forest tree communities in two 0.1-ha plots on the west-facing and east-facing slopes of a hill in the Northeast Ecological Corridor Nature Reserve, Puerto Rico, measured in December 2016.

Table 3. Comparison of forest tree community diversity and dominance indices between two 0.1-ha plots on the west-facing and east-facing slopes of a hill in the Northeast Ecological Corridor Nature Reserve, Puerto Rico; measured in December 2016.

	Plot Aspect	
Index	West	East
Shannon's H' (stems/ha)	0.76	1.04
Shannon's H' (BA)	0.47	0.95
Simpson's *I* (stems/ha)	0.31	0.16
Simpson's D = 1-*I*	0.69	0.84
Simpson's d = 1/*I*	3.18	6.29

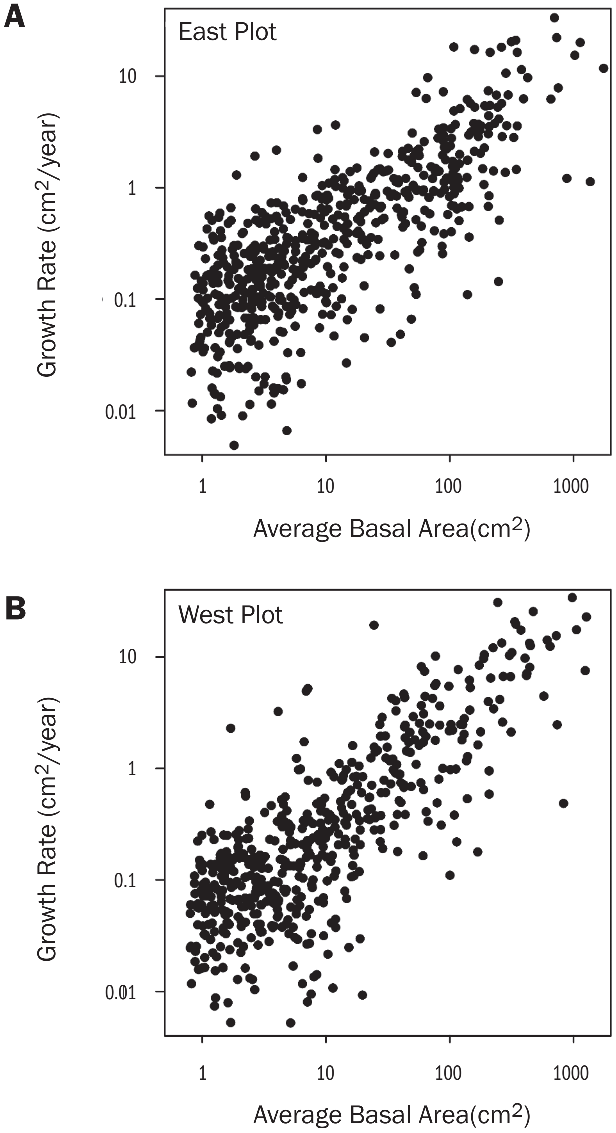

Figure 3. A logarithmically scaled plot of the basal area (BA) for each tree, averaged over the years of measurement, against the growth rate (GR) calculated for each tree. A) The $\log_{10}GR = -1.41 + 0.84\log_{10}BA$ for the East Plot ($r^2 = 0.58$). B) The $\log_{10}GR = -1.44 + 0.83\log_{10}BA$ for the West Plot ($r^2 = 0.62$).

have been more recently re-established on abandoned agricultural land. Also, since we made all of the measurements prior to the high winds and heavy rains of hurricanes Irma and María in September 2017, their effect on the forest's structure, species composition, diversity, and growth can be assessed by comparison with future studies on the same site. For instance, I visited the plots in December 2017 and noted that the storms had toppled several of the largest trees in the east-facing plot. Therefore, comparing the responses of biota on the east-facing and west-facing plots should be instructive for a better understanding of how various types of natural phenomena influence these (and other) ecosystems.

A first approximation may lead to suspect that these plots were differently affected by the hurricanes because of their species composition and size distribution differences. Nonetheless, future studies of the forest's structure, species composition, diversity, stem growth, and response to the effects of hurricanes Irma and María in each plot also may find otherwise. Consequently, by using the data herein reported as a baseline, this report is an invitation for a long-term research agenda that will be valuable to test for generalities and exceptions beyond speculation.

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COASTAL POND SALINIZATION: A CHALLENGE FOR THE CONSERVATION OF THE PUERTO RICAN CRESTED TOAD

Rita I. Cáceres-Charneco[1,*], Diane Barber[2], Jorge R. Ortiz-Zayas[3]
and Robyn Doege[2]

[1] Department of Biology, University of Puerto Rico in Cayey, 205 Ave. Antonio R. Barceló, Cayey, Puerto Rico 00736-9997
[2] Fort Worth Zoo, 1989 Colonial Parkway, Fort Worth, Texas 76110, USA.
[3] Environmental Sciences Department, University of Puerto Rico, Río Piedras Campus, Puerto Rico.
* Author of correspondence: rita.cacerescharneco@upr.edu

Abstract

Peltophryne lemur is the only endemic toad in Puerto Rico, and they breed in temporary coastal ponds in a sub-tropical dry forest. The ponds have experienced salt intrusion, which may affect tadpole development. We conducted a laboratory experiment to explore the effect of different salt concentrations (control, 2, 4, 6, 8, and 10-ppt) on the growth and survival of *P. lemur* tadpoles. The average time to complete tail reabsorption was 34 days and was not different among the control, 2, 4, and 6-ppt treatments. In contrast, tadpoles raised at 8-ppt salinity survived but developed slowly, and only one metamorphosed; at 10-ppt salinity, there was 100% mortality. In the field, salt concentrations were monitored in the natural breeding ponds from 2008 to 2014, and failed breeding events were documented due to increased salinity. Pond salinity concentrations varied from freshwater to brackish in any given year. However, if the pond accumulates more than 30 cm of rainwater, pond salinity may be diluted enough for successful tadpole development. Consequently, the results from our study revealed the importance of monitoring salt concentrations in a natural pond, and we call for habitat management practices that facilitate the successful breeding and development of a threatened amphibian species in a vulnerable habitat in light of projected climatic change.

Keywords: management, *Peltophryne lemur*, salinization, tadpoles, temporary freshwater wetlands, threatened amphibians.

Resumen

Peltophryne lemur es el único sapo endémico de Puerto Rico y se reproduce en pozas temporales en zonas costeras de bosque seco subtropical. Estas pozas han experimentado intrusión salina de manera recurrente, lo que podría afectar el desarrollo de sus renacuajos. Realizamos un experimento de laboratorio para explorar la respuesta de los renacuajos mantenidos a diferentes concentraciones de sal (control, 2, 4, 6, 8 y 10-ppt); las variables examinadas se relacionan con el crecimiento y supervivencia. El tiempo promedio para completar la reabsorción de la cola fue 34 días y no encontramos diferencias entre el control y los tratamientos 2, 4 y 6-ppt de salinidad. Sin embargo, los renacuajos mantenidos a una salinidad de 8 ppt sobrevivieron pero se desarrollaron lentamente y solo uno metamorfoseó; a 10-ppt de salinidad, todos los renacuajos murieron prematuramente. En el campo, desde 2008 hasta 2014, medimos la concentración de sal en las pozas naturales donde se registra la reproducción en esta especie y documentamos eventos fallidos de reproducción debido al aumento de la salinidad. No obstante, aunque notamos que la concentración de salinidad en estas pozas varían desde agua dulce hasta salobre entre años, descubrimos que cuando la poza acumula más de 30 cm de agua de lluvia, la salinidad se diluye lo suficiente como para permitir el desarrollo exitoso de los renacuajos. Por lo tanto, los resultados de nuestro estudio revelan la importancia de monitorear las concentraciones de sal en pozas naturales y requerimos prácticas de manejo de hábitat que faciliten la reproducción y el desarrollo exitosos de esta especie amenazada de anfibio a la luz del cambio climático proyectado.

Palabras clave: anfibios amenazados, humedal palustre estacional, manejo, *Peltophryne lemur*, renacuajos, salinización.

INTRODUCTION

Freshwater coastal wetlands are important habitats for many organisms. Today, these wetlands are being threatened by climate change and rising sea-level, converting them into brackish water habitats. In many freshwater coastal wetlands, increased sea-level and storm surges have provoked saltwater intrusion affecting the structure, abundance, richness, and distribution of flora and fauna typical of coastal ecosystems (Michener et al. 1997; Rivera-Ocasio et al. 2007; Schriever et al. 2009). For instance, the aquatic habitats occupied by amphibians can range from freshwater to brackish to saline water (Hopkins and Brodie 2015), and the whole community can drastically change after a change in water salinity (Schriever et al. 2009). Consequently, amphibians that live and breed in coastal wetlands are highly susceptible to changes in their habitat, and most cannot tolerate increases in water salinity concentration.

Although most amphibians, including adults, tadpoles, and eggs, have differing tolerances to saline environments, a recently published review identified at least 144 amphibian species that live within or near saline environments (Hopkins and Brodie 2015). As adults, amphibians can easily escape increasing salt concentrations in water. However, if they depend upon freshwater for reproduction, their eggs and tadpoles are highly susceptible to salinity (Chinathamby et al. 2006). In general, the majority of tadpoles would not be able to withstand an osmotically stressful environment, and this translates into reduced fitness in metamorphs and later as adults (Christy and Dickman 2002, Gomez-Mestre et al. 2004). Specifically, the increased water salinity affects tadpoles living near their physiological limit by reducing growth rate, delaying time to metamorphosis, generating physical abnormalities, and increasing mortality (Christy and Dickman 2002; Chinathamby et al. 2006; Rios-López 2008).

Temporary freshwater coastal wetlands, like ponds, can be a challenging habitat for breeding amphibians. Broadly, salt concentrations in a temporary pond can vary depending on filling and drying cycles, which affects organisms present in that pond, especially amphibians. In addition, the temporal nature of these habitats implies a time constraint over the period when water is available for developing and metamorphosing tadpoles. Also, their proximity to the coast implies a high risk of salinization of the wetland by the sea breeze, storm surge, and marine upwelling through the water table. As the water evaporates and the concentration of salt increases for extended periods, temporary coastal wetlands and ponds can become a very stressful environment for a developing tadpole. Consequently, the viability of a population in this type of habitat will depend on how well it can tolerate and adapt to changing conditions, including those of projected climatic change.

The Puerto Rican Crested Toad (*Peltophryne lemur*) is the only endemic toad of Puerto Rico. Its main population breeds in temporary coastal ponds subject to salinization during the year. The natural breeding population is restricted to the Guánica Commonwealth Forest (GCF) located southwest of the Caribbean island of Puerto Rico (Figure 1). The species was listed as threatened in 1987 because populations were decreasing due to habitat reduction and possible competition from the *Rhinella marina* (USFWS 1992, 2015). Current threats to the natural breeding population include localized changes in the pond's integrity, projected climatic variability, and sea-level rise. The pond area has undergone many changes since the establishment of the GCF, including salt mining operations, a small airplane runway, and a parking lot for beachgoers seasonally (Johnson 1990, Gjeltema et al. 2012, M. Canals-Mora pers. comm.). In addition, climatic variability influences the timing and quantity of precipitation, including the incidence and intensity of hurricanes and storms (Govender et al. 2013, PRCCC 2013), whose rains fill the ponds with fresh water.

Peltophryne lemur is an explosive breeder highly dependent on heavy rainfall for its reproduction (Rivero et al. 1980). Tamarindo (17°57.260 N, 066°50.903 W), Aroma (17°57.284 N, 066°51.048 W), and Atolladora (17°57.423N, 066°51.251W) are temporary coastal ponds located in the GCF (Matos-Torres 2006) used by the threatened *P. lemur* for reproduction (Figure 1). Pond formation in the GCF is highly dependent on extreme periods of rain, mostly associated with tropical depressions, hurricanes, or storm events. Pond water conditions, including salinity, have been described for three different breeding events in 1992 (Moreno and García 1992), 2002 (Matos-Torres 2006), and 2005

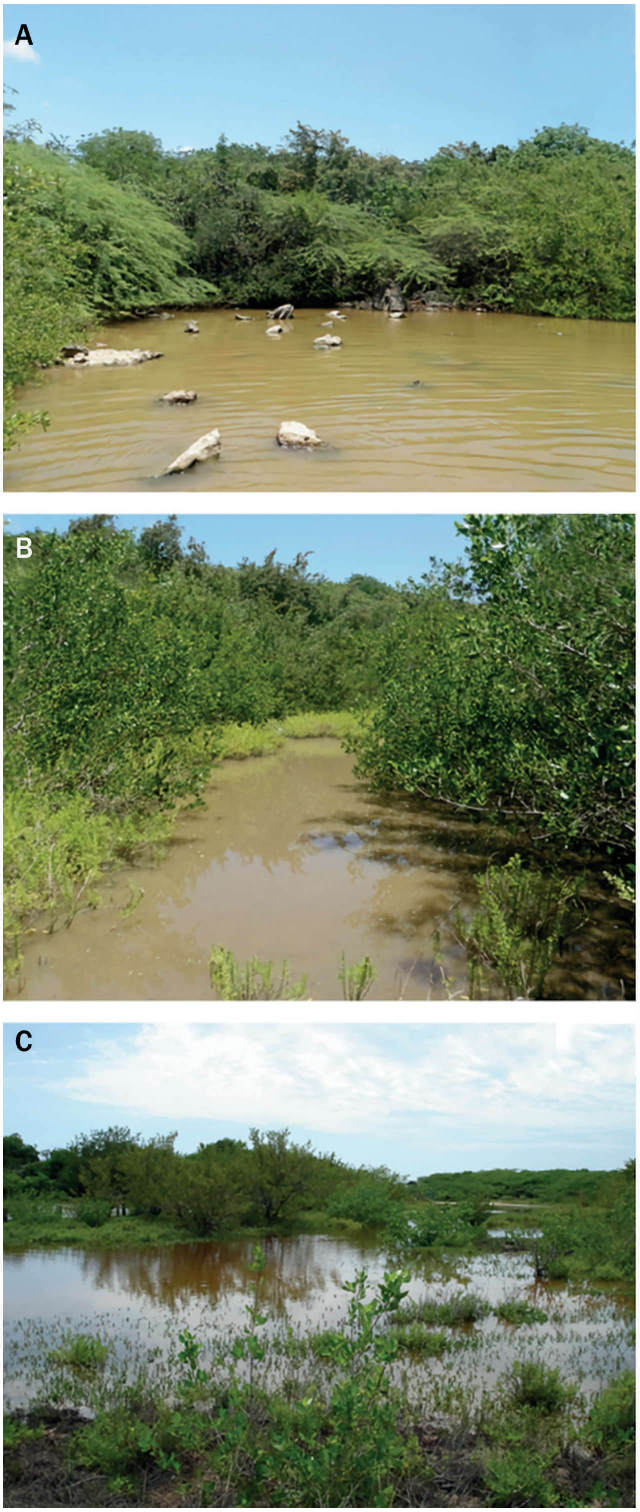
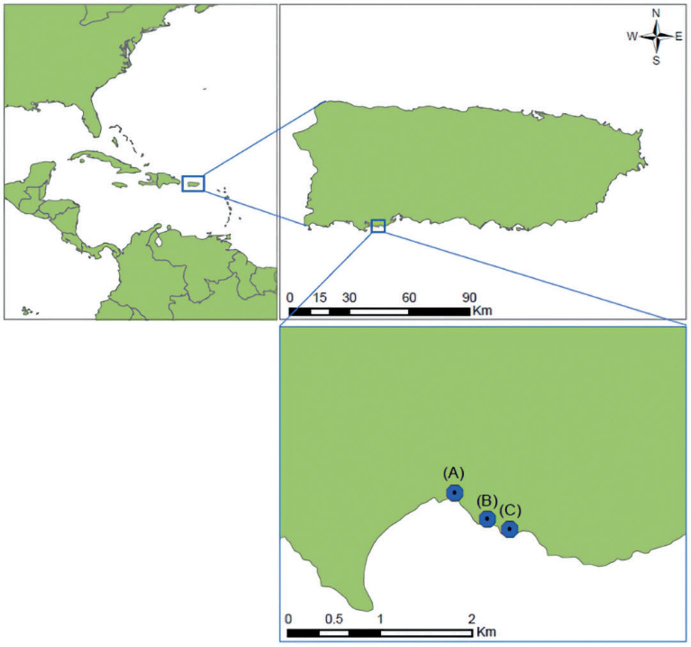


Figure 1. Geographic location of the study site in the Guánica Commonwealth Forest (southwest side of the island of Puerto Rico) and the temporary coastal ponds used by the Puerto Rican Crested Toad (*Peltophryne lemur*) during breeding events. (A) Atolladora pond, (B) Aroma pond, (C) Tamarindo pond.
Photographed by Rita I. Cáceres-Charneco.



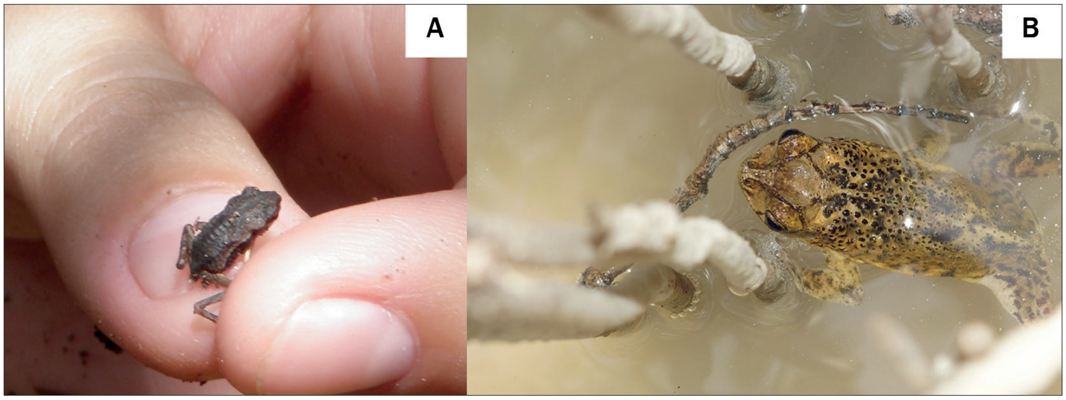


Figure 2. (A) Reduced size at metamorphosis (August 2010). (B) Adult male the Puerto Rican Crested Toad (*Peltophryne lemur*) during the failed breeding event in September 2013. Photographed by Rita I. Cáceres-Charneco.

(Blanco et al., unpublished data). During two reproduction events documented in 1992, the reported water salinity for Tamarindo was 2.1 ppt, while salinity at Aroma and Atolladora reached 5 ppt. In September 2002, the average water salinity in ponds at Tamarindo, Aroma, and Atolladora was 0.27, 2.16, and 1.57 ppt, respectively (Matos-Torres 2006). Average water salinity in the breeding event in October 2005 was less than 1 ppt in the Tamarindo pond, and 2.9 and 2.2 ppt in Aroma and Atolladora (Blanco et al., unpublished data). Additionally, the Tamarindo pond has been monitored after breeding events since 2008; the Aroma and Atolladora ponds have been monitored since 2009 (discussed in this paper).

Scientists worry about the short distance of the ponds to the sea (~100 m or less) and its consequences for the recovery of *P. lemur* (Johnson 1990). For example, reproductive events in these ponds have been affected by saltwater intrusion after intense storms historically. For instance, on October 6, 1985, pairs of breeding toads in Atolladora pond were washed to sea after coastal road damage during the precursor of tropical storm Isabel (US Fish and Wildlife Service 1992, M. Canals-Mora pers. comm.). After Hurricane Dean in 2007, storm surge contributed to the salinization of the ponds; initial salinity was 10, 9, and 7 ppt for Tamarindo South, Middle, and North ponds, respectively (M. Canals-Mora, unpublished data). Consequently, managers and personnel worked on adding 30,000 gallons (~114,000 liters) of freshwater to the Tamarindo pond to reduce the concentration of saltwater and improve the water conditions for the survival of tadpoles (USFWS 2015). Salt intrusion in Tamarindo pond also affected survival of egg (R. Cáceres-Charneco and C. Pacheco, unpublished data from a reproduction event in August 2008; R. Cáceres-Charneco, M. Canals-Mora, and C. Pacheco unpublished data from a reproduction event in September 2013) (Figure 2B), increased time to metamorphosis (M. Canals-Mora, unpublished data from a reproduction event in 2007), and decreased the body size at metamorphosis (R. Cáceres-Charneco, unpublished data from a reproduction event in August 2010) (Figure 2A). Ponds at Aroma and Atolladora have had higher salinity concentrations than the Tamarindo pond (Matos-Torres 2006), probably due to upwelling (Blanco et al., unpublished data). The higher water salinity concentration in the Aroma and Atolladora ponds may be a contributing factor that limits the use of these ponds by adult toads for reproduction (Blanco et al. unpublished data). Although the loss of one breeding event may not be detrimental to the population dynamics of some amphibians (Marsh and Trenham 2001), the loss of many breeding opportunities due to a combination of infrequent rain, saltwater intrusion, and unpredictable variation of hydroperiod could be detrimental for the persistence of *P. lemur* at the GCF.

The need for monitoring pond water quality of *P. lemur* breeding ponds, specifically water salinity concentrations, has been expressed in various reports

(Johnson 1990, Moreno and García 1992, USFWS 1992, Bloxam and Tonge 1995, Conservation Breeding Specialist Group 2006). For instance, anecdotal observations from the Tamarindo pond revealed tadpoles withstand 8 ppt salinity for a few days but metamorphose at 5 ppt (M. Canals-Mora, pers. comm.). Nonetheless, even though salinity in natural breeding ponds has been monitored, the accumulating effects of water salinity on the survival of tadpoles of *P. lemur* in the immediate future are unknown. Therefore, to fully understand the effects of increased water salinity on *P. lemur* tadpoles, a laboratory experiment was performed in 2009 at the Fort Worth Zoo (FWZ) in Fort Worth, Texas, USA. The objective of this study was to determine the effect of water salinity on the growth, time to metamorphosis, and survival of *P. lemur* tadpoles under laboratory conditions and compare results from measurements of water salinity in the natural ponds from 2008 to 2014.

METHODS

Laboratory experiment

Laboratory experiments were conducted at the Fort Worth Zoo, Texas. Three pairs of *P. lemur* adults were conditioned to breed (Lentini 2006), of which two pairs laid eggs on July 17, 2009. The eggs hatched 24 h post oviposition. Prior to the exposure to salinity treatments, tadpoles were housed together in freshwater tanks until reaching Gosner stage 24 – 26 (free swimming and feeding tadpoles). Later, tadpoles were assigned randomly to individual food-grade BPA-free plastic containers (20 cm x 13 cm x 5 cm) with the salinity concentrations (10 tadpoles per control and treatments: = < 1, 2, 4, 6, 8, and 10 ppt) within the range of water salinity concentrations documented in the Tamarindo pond (8ppt, M. Canals-Mora pers. comm.; R. Cáceres-Cherneco, this study). The endpoint salinity for each concentration level was achieved using Fritz ProAquatic's Marine Salt Mix diluted with reconstituted reverse-osmosis filtered water (with macro and trace elements added). Water salinity concentration in the containers was measured with PCTestr™ 35 Oakton® Waterproof Multi-Parameter Testr™. We used a 35-ppt (100% seawater) stock solution to generate the salt concentrations selected.

Each tadpole was fed daily, alternating between one flake of TetraMin® fish food or the same-sized blanched spinach leaf. Tadpoles were kept in a temperature and humidity-controlled room with a 12h:12h light-dark period. The average room temperature was 24.5 ± (SD) 1.4 °C with an average humidity of 69.7 ± (SD) 5.7%. All the water in the tadpole containers was manually replaced daily, and the water level remained constant. The containers were repositioned randomly on the shelves daily after servicing. The water in the containers was maintained at an average temperature of 23.9 ± (SD) 0.86 °C, and the average water pH was 7.82 ± (SD) 0.16 for the duration of the study.

Time to metamorphosis was taken from the day the tadpoles were exposed to the salinity treatments until forelimb emergence (Gosner stage 42) and later until full tail reabsorption (Gosner stage 46). Body mass measurements began after one week of salinity treatment exposure (July 29, 2009). Tadpole body mass was obtained every other day from the beginning of the experiment until the tadpoles metamorphosed.

Body mass was obtained by carefully removing each tadpole from its container, lightly blotting it on a non-bleached paper towel (wicking away excess water), and placing it within a new water-filled container set on a 300g x 0.01g precision balanced scale. Every other day, each tadpole was photographed for total body length measurements (snout to the tip of tail) and compared to a 1-cm reference scale using the software ImageJ (https://imagej.net/ij/index.html). Body mass and total body length at metamorphosis were recorded when tadpoles reached Gosner stage 42 and Gosner stage 46. Individual survival was recorded daily.

Tadpoles were exposed to the salinity treatments on July 22, 2009, and the experiment ran until October

4, 2009. However, on July 26, 2009, the water was not changed, and four tadpoles from the control group died; these tadpoles were not replaced. Another tadpole from the control group died for unknown reasons 21 days after the experiment began. Nine remaining tadpoles from the 8-ppt treatment were changed from their plastic containers to a five-gallon tank on October 3, 2009, but were found dead the next day. These deaths most likely ocurred as a consequence of husbandry-related mistakes (i.e., inappropriate acclimation to the new tank environment).

Field surveys

The GCF is a sub-tropical dry forest characterized by high temperatures with an annual average of 25 °C (range 19 and 32 °C) and an average annual precipitation of 860 mm (Lugo 2005; Colón-Torres 2009). The GCF has a prolonged dry season (6 months) and high evapotranspiration rates (Murphy and Lugo 1990). Annual rainfall in GCF is highly variable, experiencing year-to-year variation and accumulating between 50 and 55% of the annual rainfall during the wet months, August to November (Murphy et al. 1995; Colón-Torres 2009). Soil near the coast is described as Tuque clay loam, typical in the southern part of Puerto Rico, and the soil in the pond areas are described as tidal flats or swamp (USDA 2008). Pond formation occurs when rainfall from tropical waves, depressions, storms, or hurricanes generates runoff that fills land depressions (Govender et al. 2013; Van Bloem et al. 2005).

The three main reproduction ponds are Atolladora, Aroma, and Tamarindo (Figure 1). For this study, we divided the Tamarindo pond into North, Middle, and South sections. In general, the majority of reproduction events by *P. lemur* occur in Tamarindo pond (47 successful breeding events out of 65 sampling occasions in 31 years = 72.31%) compared with Aroma (28/65 = 43.08%) and Atolladora ponds (27/65 = 41.54%) (Conservation Breeding Specialist Group [2006], and M. Canals-Mora, unpublished data).

Within Tamarindo ponds, most breeding events of *P. lemur* are observed in sections North and Middle (Matos-Torres 2006). These two pond sections are surrounded by a mix of mangrove species, including black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*), and button mangrove (*Conocarpus erectus*). In addition, salt-tolerant shrubs (*Batis maritima* and *Sessuvium* spp.) are also present.

Tamarindo South pond is used as a parking lot during the dry season and is closest to the ocean. The deepest part of the pond is in Tamarindo North; occasionally, it can accumulate about a meter-dept of standing water. A staff gauge in Tamarindo North pond is used to record pond water depth. All sub-ponds connect when consistent heavy rainfall fills the pond, and the staff gauge indicates 50 cm or more of water accumulation. Sections within the Tamarindo pond, specifically the South and Middle, are also used by the introduced Cane Toad (*Rhinella marina*) for reproduction.

We defined a ponding event as an event where water accumulation formed a pond in Tamarindo, Aroma, and Atolladora, whether a reproduction event was detected or not. Ponding periods end when the pond dries. Ponding events in GCF were monitored systematically in 2008, 2013, and 2014. In 2008, the Tamarindo pond was visited twice per week. In 2013 and 2014, Tamarindo, Aroma, and Atolladora ponds were visited once per week from the beginning of the ponding period until three weeks after *P. lemur* metamorphs exited the pond. All three ponds were also monitored opportunistically during ponding events in 2009, 2010, 2011, and 2012. Water salinity and water depth were recorded during field visits. The water salinity was measured about 10 cm below the water surface. Measurements were taken randomly within each pond and sub-ponds. During most of our field visits, we used PCTestr™ 35 Oakton® Waterproof Multi-Parameter Testr™ to measure water salinity concentration. We also used a Hydrolab Quanta multiparameter water quality sonde during some field trips and a refractometer. We used a fiberglass folding ruler to measure pond water depth.

Statistical analyses

We use a Chi-square (χ^2) analysis to examine tadpole survival to exposure to various salinity levels. A non-parametric Kruskal–Wallis test was used to determine differences among treatments in tadpole time to metamorphosis (number of days to reach Gosner stage 42 and 46) and tadpole total length (at Gosner stage 42 and 46) attributed to treatments. Tadpole body mass at the time of metamorphosis (Gosner stage 42 and 46) had a normal distribution (Shapiro–Wilk normality-test, $p > 0.05$), which allowed us to conduct a one-way ANOVA to test for the difference among treatment means. We ran two one-way ANCOVA with salinity treatments as the independent variable, days of exposure as the covariate, and body mass and length as the dependent variables. A Tukey posthoc test was used to identify the differences between means of treatments on body mass and total length. Also, a Kruskal–Wallis ANOVA was used to test for differences in mean ranks of body mass for days 8, 18, and 28 since initial exposure and to test for differences in mean ranks of total length for days 1, 15, and 29 since initial exposure to the salinity treatments. A Kaplan–Meier survival log-rank test was performed to determine differences among groups for survival to metamorphosis. After metamorphosis, all metamorphs were placed in a 10-gallon tank where they were fed *ad libitum* until added to a zoo population of *P. lemur.*

Finally, a one-way ANOVA and ANCOVA were performed using years as a covariate to compare water salinity from the natural breeding ponds (Atolladora, Aroma, Tamarindo North, Tamarindo Middle, and Tamarindo South). In addition, a linear regression was performed between water salinity and pond water depth to determine a cutoff water depth where salinity would be within the tolerance by *P. lemur*'s tadpoles. We used the statistical program Infostat (http://www.infostat.com.ar) to analyze the data.

RESULTS

Laboratory experiment

The proportion of tadpoles that either survived or died depended on the salinity treatment ($\chi^2 = 37.78$, df = 5, $p < 0.0001$). The number of days to reach Gosner Stage 42 (forelimb emergence) was not significantly different between the control, 2, 4, and 6-ppt treatments (H = 1.13, df = 3, p = 0.7597). Likewise, the number of days to reach Gosner stage 46 (full tail reabsorption) after exposure to treatment was also not significantly different between the control, 2, 4, and 6-ppt treatments (H = 1.53, df = 3, p = 0.6661). Hence, the mean number of days to reach Gosner stage 42 was 30.94 ± (SE) 0.53 and 34.47 ± (SE) 0.53 days to reach Gosner stage 46. Only one tadpole from the 8-ppt treatment metamorphosed and was not included in this analysis. In 66 days, the tadpole from the 8-ppt treatment had reached Gosner stage 42, and by day 70, it had reabsorbed its tail. The tadpoles in the 8-ppt treatment were significantly underdeveloped compared to all the other treatments. Four tadpoles from the 8-ppt treatment had visible hindlimb buds by day 50.

There was a significant effect of the salinity treatment on tadpole body mass after controlling for days of exposure (ANCOVA: $F_{[5,\ 822]} = 159.10$, $p < 0.0001$) (Figure 3). The mean heaviest body mass was found from the 4-ppt and 2-ppt treatments (0.19 ± [SE] 0.004 g). The second largest mean body mass was from the tadpoles in control and 6-ppt treatments (0.17 ± [SE] 0.005 g and 0.16 ± [SE] 0.004 g, respectively). The smallest mean body mass was from the 8-ppt and 10-ppt treatments, 0.08 ± (SE) 0.003 g and 0.06 ± (SE) 0.01 g, respectively. A comparison of body mass after different days of exposure (days 8, 18, and 28) also showed a significant difference. A Kruskal-Wallis test revealed a difference in tadpole body mass for day 8, day 18, and day 28 since exposure to the salinity treatments (day 8: H = 25.98, df = 5, p = 0.0001; day 18: H = 7.98, df = 5, p = 0.0001; day 28: H = 26.57, df = 4, p = 0.0001) (Figure

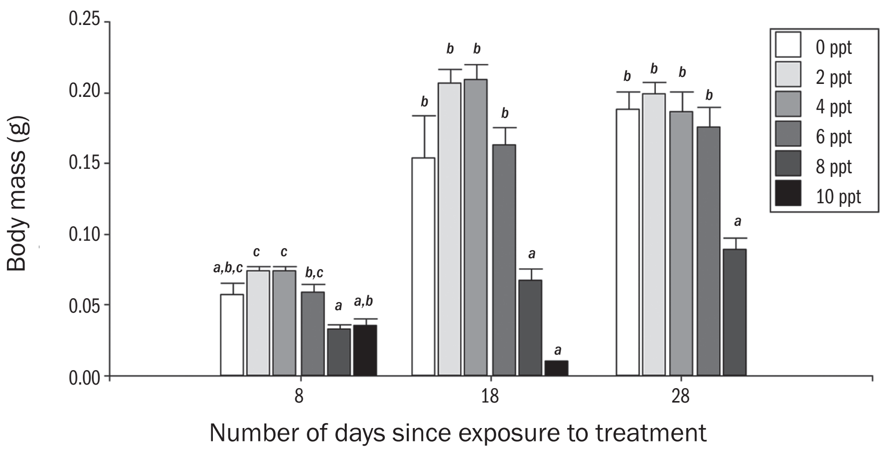


Figure 3. Tadpole body mass (mean ± s.e.) on days 8, 20, and 32 in the different salinity treatments. Different letters indicate significant differences (alfa = 0.05; Tukey test) among salinity treatments.

3). For all three days analyzed individually, the mean rank body mass of the 8-ppt and 10-ppt treatment was less than all other treatments. By day 28, the mean rank body mass of the control, 2, 4, and 6-ppt salinity treatments were significantly different from the mean rank of the 8-ppt treatment. Tadpole body mass at Gosner stage 42 was not significantly different between the control, 2, 4, and 6-ppt treatment (ANOVA: $F_{[3, 28]} = 2.10$, $p = 0.1228$) and was not significantly different at Gosner stage 46 ($F_{[3, 28]} = 2.66$, $p = 0.0674$). Furthermore, when comparing body mass at Gosner stage 46 between treatments, including the only tadpole that metamorphosed from the 8-ppt treatment, there was no significant difference ($F_{[4, 28]} = 2.02$, $p = 0.1187$). Mean body mass at Gosner stage 42 ranged from 0.14 to 0.29 g, and at Gosner stage 46, 0.10 to 0.24 g (Table 1).

Tadpole total length was significantly affected by the salinity treatment after controlling for the exposure time (ANCOVA: $F_{[5, 680]} = 540.60$, $p < 0.0001$). A Tukey posthoc test showed that tadpoles in the 8-ppt and 10-ppt treatments were the shortest, with a mean total body length of 1.63 ± (SE) 0.03 cm and 1.73 ± (SE) 0.06 cm, respectively. They were followed by the mean total length of the tadpoles in the 6-ppt treatment (2.05 ± [SE] 0.03 cm) and control (2.06 ± [SE] 0.04). The mean total body length of the 2-ppt treatment (2.16 ± [SE] 0.03 cm) was not different from the control, 4-ppt, and 6-ppt treatments. Tadpoles in the 4-ppt treatment had the longest bodies among treatments: mean total body length was 2.25 ± (SE) 0.03 cm. When evaluating the total body length of particular days, we found that on the first day of the experiment, all tadpoles had similar total body lengths ($H = 4.84$, $df = 5$, $p = 0.4128$) (Figure 4), ranging from 0.70 to 1.20 cm. However, as time progressed, there was a significant statistical difference at day 15 ($H = 26.83$, $df = 5$, $p = 0.0001$) and day 29 of exposure ($H = 12.97$, $df = 4$, $p = 0.0114$). By day 15, only two tadpoles of the 10-ppt

Table 1: Mean time to reach metamorphosis for the different salinity treatments, and mean body mass and mean total body length to reach metamorphosis (at Gosner stage 42 = GS 42) and until full tail reabsorption (at Gosner stage 46 = GS 46). Mean ± S.E. followed by range in parentheses.

Salinity treatments	To metamorphosis (GS 42)			To full tail reabsorption (GS 46)		
	Mean time (days)	Mean body mass (g)	Mean total body length (cm)	Mean time (days)	Mean body mass (g)	Mean total body length (cm)
0 ppt (control, RO water)	31.60 ± 1.83 (28–38)	0.20 ± 0.01 (0.18–0.22)	2.64 ± 0.31 (2.00–3.80)	35.00 ± 1.87 (31–41)	0.15 ± 0.01 (0.12–0.17)	1.64 ± 0.20 (1.30–2.40)
2 ppt (5.7% seawater)	31.14 ± 0.86 (28–34)	0.19 ± 0.01 (0.16–0.22)	2.81 ± 0.07 (2.60–3.10)	35.29 ± 0.71 (34–39)	0.18 ± 0.01 (0.14–0.22)	1.46 ± 0.05 (1.20–1.60)
4 ppt (11.4% seawater)	30.00 ± 0.79 (26–34)	0.21 ± 0.01 (0.17–0.29)	3.03 ± 0.11 (2.50–3.50)	33.40 ± 0.85 (29–36)	0.17 ± 0.01 (0.12–0.24)	1.38 ± 0.06 (1.10–1.70)
6 ppt (17.2 % seawater)	31.40 ± 1.12 (26–36)	0.18 ± 0.01 (0.14–0.21)	2.59 ± 0.09 (2.20–3.20)	34.70 ± 1.05 (31–41)	0.14 ± 0.01 (0.10–0.18)	1.48 ± 0.12 (1.10–2.50)
8 ppt (22.9% seawater)	66.00	0.13	2.60	70.00	0.15	1.60

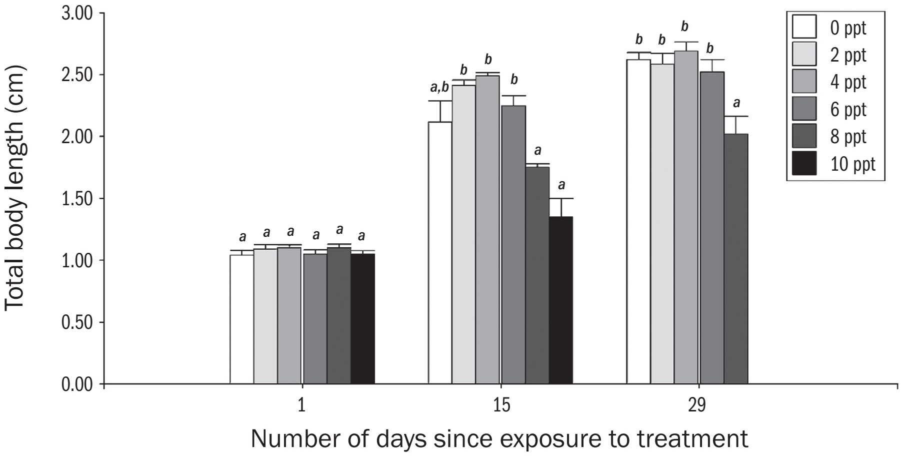


Figure 4. Tadpole total body length (mean ± s.e) on days 1, 15, and 29 in the different salinity treatments. Different letters indicate significant differences (alfa = 0.05; Tukey test) among salinity treatments.

treatment remained alive, but both died by day 29. There was no significant difference in the total body length of tadpoles from treatments 10-ppt, 8-ppt, and control. Similarly, the tadpoles from the control were not different from the 2-ppt, 4-ppt, and 6-ppt treatments. Nonetheless, on day 29, tadpoles from the 8-ppt treatment were the shortest. Mean rank total body length was similar between the control, 2-ppt, 4-ppt, and 6-ppt treatment. Tadpole's total body length on the day of metamorphosis (Gosner stage 42) was not significantly different between the control, 2-ppt, 4-ppt, and 6-ppt treatments (ANOVA: $F_{(3, 28)} = 2.57$, $p = 0.0746$) (Table 1). By the time they reabsorbed their tail (Gosner stage 46), total body length was similar between all treatments ($H = 1.75$, $df = 3$, $p = 0.6143$) (Table 1). Since only one tadpole from the 8-ppt treatment survived until metamorphosis, we did not consider it in this part of the analysis. Tadpole's mean total body length at metamorphosis was 2.78 ± (SE) 0.07 cm, ranging from 2.00 to 3.80 cm. The mean total body length at full tail reabsorption was 1.47 ± (SE) 0.05 cm, ranging from 1.10 to 2.50 cm.

Survival until metamorphosis was significantly different between all the treatments ($\chi^2 = 64.67$, $p < 0.0001$) (Figure 5). All the tadpoles exposed to the highest concentration of water salinity died (10 ppt = 28.6% seawater), eight of them within five days of exposure. Eight tadpoles of the 8-ppt treatment survived up to 74 days without metamorphosing before dying on October 4, 2009, due to a husbandry-related error. Only one tadpole from the 8-ppt treatment metamorphosed. Survival probability was similar between tadpoles of the 4-ppt and 6-ppt treatments ($\chi^2 = -2.53$, $p = 1.00$) and similar between the control, 2-ppt and 8-ppt treatments ($\chi^2 = 2.11$, $p = 0.35$). Additionally, reduced activity (swimming and feeding) was noted among tadpoles in the 8-ppt treatment. However, we found no physical abnormalities (e.g., kinked tails, deformed limbs, etc.), besides tadpoles being very small and thin from the 8-ppt and 10-ppt treatments.

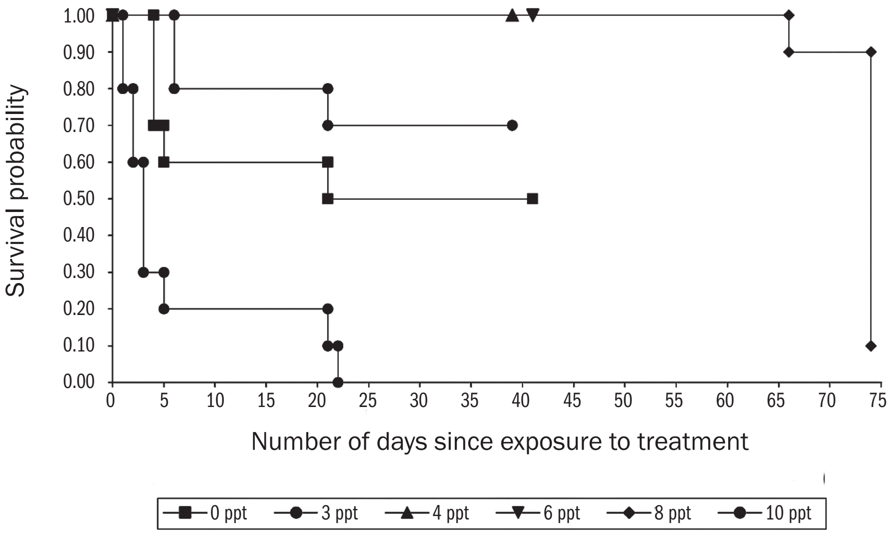


Figure 5. Tadpole survival after exposure to different salinity treatments until metamorphosis.

Field surveys

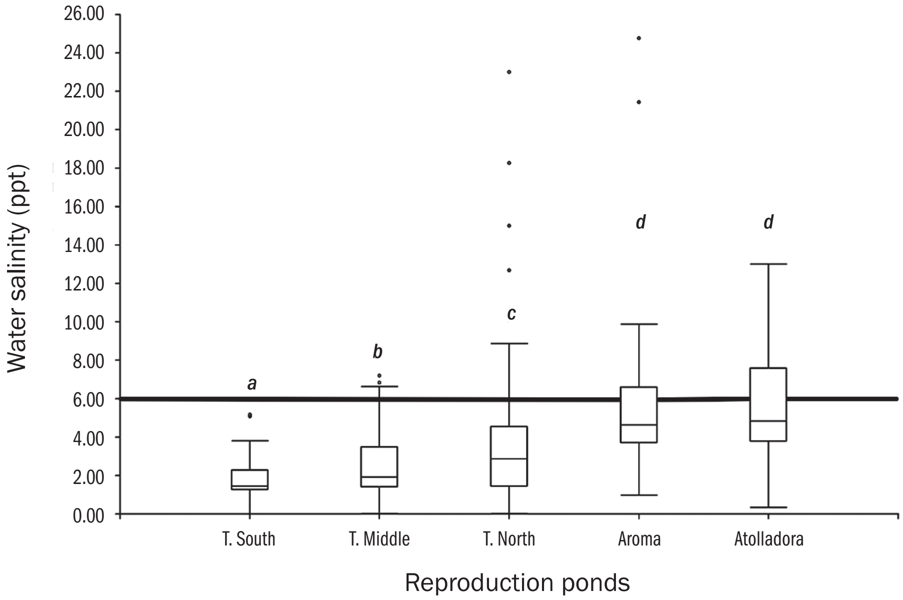


Figure 6. Variability in the water salinity among reproduction ponds. Open circles represent extreme values; the straight line at 6-ppt treatment represents *P. lemur*'s upper limit of water salinity tolerance.

For the years sampled (2008–2014), the five breeding ponds in GCF had different mean water salinity concentrations (Kruskal-Wallis: H = 265.04, df = 4, $p < 0.0001$) (Figure 6). Aroma and Atolladora had similar water salinity concentrations and had the highest mean water salinity concentration compared to all the Tamarindo pond sections. The mean water salinity concentration of Aroma and Atolladora ponds was 5.79 ± (SD) 4.18 and 5.98 ± (SD) 3.35 ppt, respectively. Tamarindo North had the second highest mean salinity concentration, 3.28 ± (SD) 2.57 ppt, followed by Tamarindo Middle with a mean salinity concentration of 2.51 ± (SD) 1.43 ppt. Tamarindo South had the lowest mean salinity concentration of all the ponds, 1.90 ± (SD) 1.05 ppt.

There was a significant difference between ponds on mean water salinity after controlling for years (ANCOVA: $F_{[4,\ 1377]} = 90.63$, $p < 0.0001$) (Figure 6). High variability in water salinity measurements was observed in Aroma and Atolladora. Nevertheless, 92.7 % of all water salinity measurements for all ponds were below 6-ppt water salinity. Extreme water salinity concentration was recorded from Aroma in 2010, 24.76 ppt (70.7 % seawater), and from Tamarindo North in 2013, with a salinity concentration of 23 ppt (65.7 % seawater). The mean water salinity has remained below 6 ppt in most of te Tamarindo pond. Aroma and Atolladora had the highest mean salinity concentration. Tamarindo South had the lowest water salinity of all years sampled. In addition, there was a significant difference between years on mean water salinity after controlling for the pond (ANCOVA: $F_{[6,\ 1375]} = 57.08$, $p < 0.0001$) (Figure 7). The year 2008 had the lowest mean water salinity concentration was 1.96 ± (SD) 0.09 ppt. The

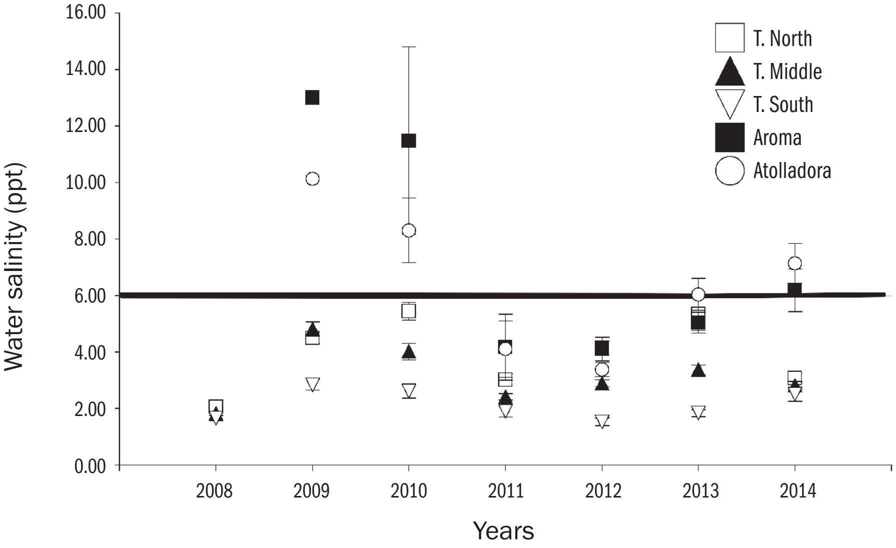


Figure 7. Water salinity (mean ± s.e.) of the reproduction ponds compared by years. The straight line at 6-ppt treatment represents *P. lemur*'s level of water salinity tolerance.

highest mean water salinity measured was in the year 2010 (5.04 ± 0.19 ppt).

We found a negative relationship between water salinity and pond depth at the Tamarindo North section (the main breeding location for *P. lemur*) (Figure 8). Here, the deeper the pond, the lower the concentration of water salinity ($y = -0.08x + 7.03$, $r^2 = 0.39$; $F_{[1, 488]} = 308.27$, $p < 0.0001$). This pattern was also observed in all but one pond: Aroma ($y = -0.16x + 8.23$, $r^2 = 0.27$; $F_{[1, 77]} = 28.44$, $p < 0.0001$), Atolladora ($y = -0.08x + 10.02$, $r^2 = 0.26$; $F_{[1, 82]} = 28.25$, $p < 0.0001$), Tamarindo Middle ($y = -0.05x + 4.15$, $r^2 = 0.38$; $F_{[1, 469]} = 284.81$, $p < 0.0001$), and Tamarind South ($y = -0.02x + 2.49$, $r^2 = 0.11$; $F_{[1, 245]} = 29.94$, $p < 0.0001$). In Tamarindo North pond, however, salinity at a water depth between 30 cm and 59 cm is somewhat variable but remains below the 6-ppt water salinity. Specifically, mean water salinity at a depth of 29 cm and below was 6.06 ± (SE) 0.40 ppt, between 30 cm and 59 cm was 3.24 ± (SE) 0.11 ppt, and above 60 cm was 1.36 ± (SE) 0.04 ppt. Overall, there was a significant difference in water salinity at different water depths (Kruskal-Wallis: H = 230.85, df = 2, $p < 0.0001$) (Figure 8), and a pond deeper than 60 cm provides enough water for dilution of water salinity.

DISCUSSION

Peltophryne lemur breeds in a temporary pond adjacent to the Caribbean Sea. For more than 30 years, *P. lemur* has been under the protection and management of the Department of Natural and Environmental Resources (DNER), the US Fish and Wildlife Service, and the Association of Zoos and Aquariums' Puerto Rican Crested Toad Species Survival Plan. Through research and oversight of the natural breeding population located in GCF, biologists have documented salinity-related mortalities of eggs and tadpoles, presenting concerns over the future persistence of the population. The proximity of the ocean and a history of salt intrusion into the ponds have increasingly affected breeding events, which prompted intensive monitoring of water salinity in the area and our tadpole salinity tolerance research. Some of the negative effects of increased salinity for tadpoles include reduced growth rate, delayed metamorphosis, physical abnormalities, and increased mortality (Chinathamby et al. 2006; Rios-López 2008; Alexander et al. 2012).

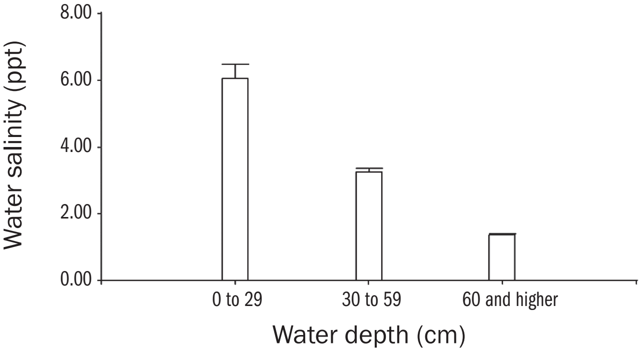


Figure 8. Relationship between water depth and salinity in Tamarindo North between 2008 and 2014. The straight line at 6-ppt treatment represents *P. lemur*'s level of water salinity tolerance.

Results from our laboratory experiment show that *P. lemur* tadpole survival and growth depend on water salinity concentration. Tadpoles of *P. lemur* can tolerate up to 6 ppt (17.1 % seawater) without adverse effects to time to metamorphosis and can survive at 8-ppt salinity concentration even though only one reached metamorphosis and it took twice as long to metamorphose. Although 6-ppt salinity affected tadpoles' body mass and total body length, we suggest that 8-ppt salinity represents the threshold above which the growth rate is reduced significantly to the detriment of their survival.

Salinity affects the process of osmoregulation in which amphibians keep their internal ionic balance by drinking water from the environment and by excreting salts through urine (Uchiyama and Yoshizawa 1992; Ultsch et al. 1999). Osmoregulation requires a significant energetic investment from organisms during the active take up of ions from the water to compensate for ion loss and during the recovery of ions from urine before it is excreted (Wells 2007). When exposed to osmotically stressful environments, tadpoles may invest more energy in osmoregulation; therefore, feeding and growth may be suppressed (Rios-López 2008; Bernabò et al. 2013; Gomez-Mestre et al. 2004). These energetic costs affect size and growth rate. In our experiment, tadpole body mass and total length during the tadpole stage were affected by salinity treatments, specifically in the 8-ppt and 10-ppt treatments, and to a lesser degree in the tadpoles of the control and 6-ppt treatments. Tadpoles exposed to high salinities were shorter and smaller, which is consistent with other salinity studies (Christy and Dickman 2002; Chinathamby et al. 2006; Rios-López 2008; Alexander et al. 2012; Bernabò et al. 2013). After exposure to high concentrations of water salinity, there is a possibility that *P. lemur* tadpoles could recuperate, like tadpoles of *Litoria ewingii,* in a similar study, whose osmotically stressed tadpoles accelerated growth rate, surpassing that of freshwater tadpoles and metamorphosing at a similar size (Squires et al. 2010). Compensatory growth would be beneficial in the natural breeding pond of *P. lemur* where an intense or frequent event of precipitation could further dilute water salinity and prolong favorable conditions for eggs and tadpoles. For instance, in 2014, there were three distinct ponding events in Tamarindo (August, September, and November). By October, the pond was very shallow, and salinity concentration was increasing, but when it was refilled in November, salinity concentrations decreased once again until the ponding period ended.

The salinity treatments affected tadpole body mass. Eight days after exposure to salinity treatments, tadpole body mass was variable between all treatments. The two tadpoles from the 10-ppt treatment that survived 20 days were severely small and underdeveloped. Tadpoles exposed to 8-ppt water salinity also experienced reduced body mass and were underdeveloped (no visible hind limb buds for at least 36 days after exposure). Reduced body mass at 8-ppt salinity has also been observed in another native Puerto Rican species *Leptodactylus albilabris* (Rios-López 2008). ANCOVA results also showed that tadpoles from the control and 6-ppt treatments had a decreased body mass compared to those in the 2-ppt and 4-ppt treatments. This indicates that some salinity, between 2-ppt and 4-ppt salinity (5.7 to 11.4 % seawater), is tolerable in terms of tadpole body mass and that by 6-ppt salinity (17.1% seawater), body mass during the tadpole stage becomes affected. However, there was no difference in average body mass at metamorphosis among treatments. These salinities are consistent with the range of salinities during ponding events in the natural breeding ponds at GCF (Figure 6). In captivity, tadpoles are reared with reconstituted reversed-osmosis water, and tadpole development has not been affected by "freshwater" conditions in the zoos nor the tadpole reintroduction ponds located around the island. However, in one study, wild-caught *R. marina* from Australia showed decreased survival when reared in captivity at a water salinity of 0.035 ppt (~ 0.1% seawater) (Wijethunga et al. 2016). Another native Australian species, *L. aurea*, has also shown reduced survival in freshwater at ~ 0.14 ppt, which was explained by locally adapted populations to higher salinities (Kearney et al. 2012). Water temperature, other abiotic factors, and crowding are thought to play a major role in tadpole development in some reintroduction ponds. For example, the low temperatures in which our experiment was held (average 23.9 °C) may have contributed to increased time to metamorphosis (Alvarez and Nicieza 2002; Maciel and Juncá 2009), which contrasted with suggested temperatures between 26 and 30 °C (Lentini 2006) for caring and maintaining *P. lemur* in captivity. Also, the average time to the metamorphosis of *P. lemur* in the wild is 21 days (between 14 and 25 days) (Moreno and Canals-Mora 1985; Canals-Mora 1990), but in captivity at lower temperatures compared to the wild, can range between 20 and 35 days (Miller 1985), which may be an additional 10 to 14 days (Lentini 2006).

Tadpole survival was dependent on the salinity treatment. Eight out of 10 tadpoles raised at a 10-ppt salinity died within the first five days of exposure. In a similar experiment, tadpoles of *R. marina* and *L. albilabris* did not survive 3 hours of exposure to 12 ppt (Rios-López

2008). *Peltophryne lemur* tadpoles raised at 8 ppt lived for 74 days without metamorphosing, 44 days longer than tadpoles raised at control, 2-ppt, 4-ppt, and 6-ppt salinity treatments. All tadpoles exposed to 4 ppt and 6 ppt survived until metamorphosis. The average time to reach metamorphosis (forelimb emergence) was 30 days, and full tail reabsorption was 34 days for all treatments except the 8-ppt. Tadpoles exposed to water salinity in the wild can survive in 8 ppt but will probably not reach metamorphosis. During the salt intrusion event in 2007, the metamorphosis was possible for *P. lemur* tadpoles when salinity in the pond was reduced to 5 ppt by adding 30,000 gallons of freshwater into Tamarindo pond (M. Canals-Mora, pers. comm.; see Introduction). This was also documented in tadpoles of *L. aurea*, which could survive at a 3.4 ppt ~ 10 % seawater but would only metamorphose at a salinity lower than 1.87 ppt ~ 5.5 % seawater (Christy and Dickman 2002). Prolonged exposure to increased salinity further constrains a tadpole's ability to osmoregulate. As gills play a major role in tadpole osmoregulation, increasing salinity severely degenerates gill integrity by altering its morphology and function (Bernabò et al. 2013). In addition, salinity can hinder metamorphosis by affecting the mitochondrial-rich cells that make salinity tolerable during the tadpole stage but that are lost when the internal gills degenerate right before metamorphosis (Uchiyama and Yoshizawa 1992). Salinity has also been shown to reduce growth rates and the rate of differentiation, therefore, increasing the time to metamorphosis (Christy and Dickman 2002; Chinathamby et al. 2006; Bernabò et al. 2013). As a tadpole develops, there are significant changes in its body water and ion content, which causes it to lose or gain water, and consequently decrease or increase in body mass or size (Ultsch et al. 1999). A reduction in a tadpole's mass gain or size can increase its chance of being eaten by a larger predator and affect the metamorph's fitness (Ultsch et al. 1999; Gomez-Mestre and Tejedo 2003; Wijethunga et al. 2016).

The time to development of tadpoles until metamorphosis can be significantly decreased under accumulated dissolved salts in drying and warmer temporary ponds (Chinathamby et al. 2006; Gomez-Mestre and Tejedo 2003). However, accelerating development time at the cost of metamorphosing at a smaller size could reduce metamorph fitness (Alexander et al. 2012; Bernabò et al. 2013; Kearney et al. 2012). Amphibians exhibit plasticity in growth rate until metamorphosis, trying to weigh the consequences of staying in a vulnerable habitat or metamorphosing at a smaller size. We have documented metamorphosis at a smaller size in tadpoles of *P. lemur* from the Tamarindo pond during August 2010, after the pond started to evaporate quickly and salinity increased (R. Cáceres-Charneco, unpublished data) (Figure 2A). Staying in the pond for prolonged periods, exposed to increasing water salinity, can also increase the chances of predation. For example, tadpoles of *L. ewingii*, after being exposed to high concentrations of water salinity (5.25 ppt ~ 15 % seawater), were more susceptible to predation by dragonfly nymphs (Squires et al. 2008). Decreased activity levels and sluggish behavior may also decrease a tadpole's ability to avoid predators and search for food (Squires et al. 2008; Rios-López 2008; Chinathamby et al. 2006). Repetitive failures of tadpole survivorship for a species such as *P. lemur*, with limited distribution and a small number of individuals, could rapidly impact their population since fewer metamorphs would survive to adulthood and return for future breeding events.

A recent review of the occurrence of amphibians in saline habitats identified a total of 21 bufonids found in a wide range of habitats with varying salinities (Hopkins and Brodie 2015). These habitats can include marshes, swamps, and tidal ponds, sometimes directly exposed to the ocean or sea spray. Monitoring the environmental salinity of these habitats was highlighted as an essential part of understanding salinity tolerance in amphibians. Our study reviews the salinity concentration of the natural breeding ponds used by *Peltophryne lemur* in a tropical dry forest. Water salinity in these temporary coastal ponds experienced yearly variation. However, the average water salinity was below 6 ppt during our seven years of sampling. The Aroma and Atolladora ponds have a higher water salinity concentration on average and experience high variability in salt concentration, making these ponds unpredictable regarding reproduction events. The high variability in salt concentration in Aroma and Atolladora could explain why these ponds are used less frequently for breeding than Tamarindo sub-ponds. In Tamarindo pond, water salinity concentration increases from Tamarindo South towards Tamarindo North.

Nevertheless, in Tamarindo North pond, an accumulation of more than 30 cm of water will provide suitable conditions for tadpole growth and survival. A generalized dynamic shared among all ponds was that the more water accumulated in the pond, the lower the salinity concentration, and at the end of the ponding period, salinity concentrations increased again. Not all the extreme salinity values observed occurred during a ponding event that coincided with a breeding event. However, these measurements suggest the dynamic hydrologic conditions of these ponds and their ecological importance in a tropical dry forest. Furthermore, *P. lemur* tadpole's tolerance to different salinity concentrations suggests possible local adaptation or tolerance to changing salinity concentrations, as seen in other amphibians even after exposure to salt intrusion into the habitat after a hurricane (Gunzburger et al. 2010).

The ephemeral nature of the breeding ponds utilized by *P. lemur* makes them challenging to the developing tadpoles. For example, the distance between Atolladora, Aroma, and all Tamarindo sub-ponds to the shoreline is very small and subjected to frequent saltwater intrusion through upwelling and storm surges (Blanco et al. unpublished data). Other contributing factors include sea breeze and the growth of vegetation adapted to drought and high salinity, such as mangroves that deposit salt, mostly from leave and gland exudates, from subsurface and groundwater. Although we did not test *P. lemur* egg survival under high salinity concentrations, we have documented breeding event failures due to salinity. *P. lemur* tends to select Tamarindo North and Tamarindo Middle for oviposition. *Rhinella marina* usually prefers Tamarindo South but has been known to use Tamarindo Middle and is seen in Tamarindo North on occasion (R. Cáceres-Charneco, unpublished data). *Rhinella marina* also seems to prefer the Tamarindo South and Middle sections judging by oviposition events, presumably because of lower water salinity (e.g., Wijethunga et al. 2016). As for *P. lemur*, oviposition selection of Tamarindo North, Aroma, or Atolladora could mean that *P. lemur* adults are selecting ponds that have salinities that the tadpoles can tolerate (Hopkins and Brodie 2015).

Peltophryne lemur tadpoles can tolerate up to 6-ppt salinity and survive at 8-ppt salinity without reaching metamorphosis. However, this salinity tolerance may not be enough due to the vulnerability of its habitat, specifically to sea level rise and variability in precipitation expected for the Caribbean. Although the sea level is expected to rise 1.4 mm/year (PRCCC 2013), precipitation is already a limiting factor for the accumulation of water for pond formation in the GCF, and precipitation is expected to become more sparse with drought becoming more prevalent (Govender et al. 2013). Additionally, increasing water salinity may benefit introduced species like *R. marina* (Rios-López 2008; Wijethunga et al. 2016) and the Cuban Treefrog, *Osteopilus septentrionalis* (Brown and Walls 2013). Both introduced species have been documented in the historical and current distribution of *P. lemur*, and due to their higher tolerance to water salinity, as adults (Liggins and Grigg 1985) and tadpoles (Rios-López 2008; Wijethunga et al. 2016), they may be able to withstand changes in coastal environments, as well as disturbed sites. However, the development of *P. lemur* in low-land habitats that exhibit high salinity may protect them from chytridiomycosis infection, a fungal infection affecting amphibians, as proposed for coastal breeding populations of *R. marina* in Australia (Wijethunga et al. 2016).

Peltophryne lemur mainly uses reproduction ponds in GCF despite its long land-use history that includes modification from non-anthropogenic and anthropogenic phenomena (e.g., shifts in vegetation composition, seawater intrusion/upwelling, salt mining, removal of dunes, roads, parking, and other infrastructure). Due to our inability to completely stop saltwater intrusion in these areas, management strategies have switched from short-term practices of maintaining the integrity of the current ponds to more long-term goals. Two management projects have already taken place:

1) An elevated boardwalk was built in 2016 to reduce pedestrian interference with emerging metamorphs and facilitate a passage towards the beach.

2) In 2017 new ponds were built at a higher elevation for tadpole translocation and to provide additional breeding ponds if the Tamarindo pond eventually becomes too saline to sustain *P. lemur* tadpole development.

The results from our laboratory experiment confirm that *P. lemur* tadpoles can tolerate salinity up to 6 ppt, and showed that all tadpoles exposed to 8 ppt can survive but may not metamorphose before the pond dries up or at all. Furthermore, tadpoles at salinities of 10 ppt or higher will die, which has profound consequences for conservation efforts. Consequently, our results also highlight the importance of monitoring salt concentrations in GCF breeding ponds to promote the success of the breeding events of a threatened amphibian species in a vulnerable habitat. Moreover, our work illustrates the importance of monitoring and conserving coastal breeding habitats for *P. lemur* in the immediate future, considering that it may already be living near its physiological limit at our study site (and presumably elsewhere).

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PUERTO RICO NO YACE SOBRE UN PRECIPICIO AL ATLÁNTICO Y EL CARIBE COMO A MENUDO ILUSTRAN IMÁGENES PUBLICADAS POR AGENCIAS GUBERNAMENTALES Y OCEANÓGRAFOS

Ferdinand Quiñones Márquez[1,*]

[1] PO Box 3387, Brentwood, TN 37024.
* Correo-e: FQUINON@msn.com

Por décadas, la Administración Federal Oceánica y Atmosférica (NOAA, por sus siglas en inglés) ha publicado mapas y dibujos ilustrando la ubicación de Puerto Rico (incluyendo a la Santo Domingo en la República Dominicana hacia el oeste y parte de las Islas Vírgenes hacia el este) relativa a los cañones submarino que nos rodean. Desafortunadamente, esas imágenes frecuentemente exhiben una exageración extrema de la inclinación ("pendiente") del Atlántico, el Canal de Mona y el Caribe en general. El resultado de esta representación visual es la apariencia de que Puerto Rico yace en una loma con un precipicio casi vertical hacia las fosas submarinas en el Océano Atlántico (Fosa de Puerto Rico), así como hacia el Canal de Mona y el Mar Caribe (Paseo de Mona) (Figura 1). Así, se ha generalizado ampliamente la percepción que Puerto Rico yace en una loma extrema con un precipicio casi vertical hacia las fosas marinas indicadas. No obstante, a continuación explico las razones para (1) exagerar visualmente las pendientes submarinas en la vecindad de PR y las Antillas y (2) cómo esta percepción – producto de la selección de escala en estas ilustraciones – no es correcta en la realidad.

La razón principal – en mi opinión – para estas imágenes donde se exagera la pendiente submarina en nuestra vecindad es la limitación de los formatos y exigencias – unas de "estilo" y presumiblemente por consideraciones económicas – del "espacio impreso" en publicaciones técnicas y profesionales en tiempos recientes. Todos los científicos aspiramos a que nuestros escritos ("artículos") se publiquen en revistas profesionales revisadas por pares ("journals") como la revista de oceanografía ECO, medios generados por el "Smithsonian Institute", la "Academia Nacional de Ciencias", en medios para el público general como "National Geography" (entre otras) o incluso en medios generados por agencias gubernamentales como la National Oceanic and Atmospheric Administration (NOAA) y el US Geological Survey (USGS por sus siglas en inglés o "Servicio Geológico de los Estados Unidos" en español), entre otras. En general, son estos último dos – la NOAA y el USGS – quienes publican la mayoría de los estudios submarinos en la vecindad de Puerto Rico y tanto los "formatos" de publicación impresos y electrónicos, como la amplitud del área de investigaciones, limitan el tamaño de las imágenes que se incluyen en sus artículos (particularmente el "ancho" de las páginas).

El "estándar" moderno es que las figuras no excedan el ancho básico del papel tamaño carta (8.5 pulgadas o ~21.6 centímetros); generalmente se limita el ancho de las imágenes a las 8 pulgadas independientemente la publicación sea en formato electrónico o impreso en papel. No obstante, tanto NOAA como el USGS, también publicaban mapas de estudios terrestres y marinos de hasta 3 pies de ancho (~91.4 centímetros), que se "doblaban" para ajustarse al tamaño de los textos impresos. Los "Atlas" son una de las pocas excepciones donde se excede este tamaño "estándar" e incluyen mapas de hasta 30 pulgadas de ancho (~76.2 centímetros) en apoyo al texto. Entonces, ¿cuál es la consecuencia de estas limitaciones de ancho de las ilustraciones? Antes de contestar esta pregunta, brevemente describiré un caso real a continuación.

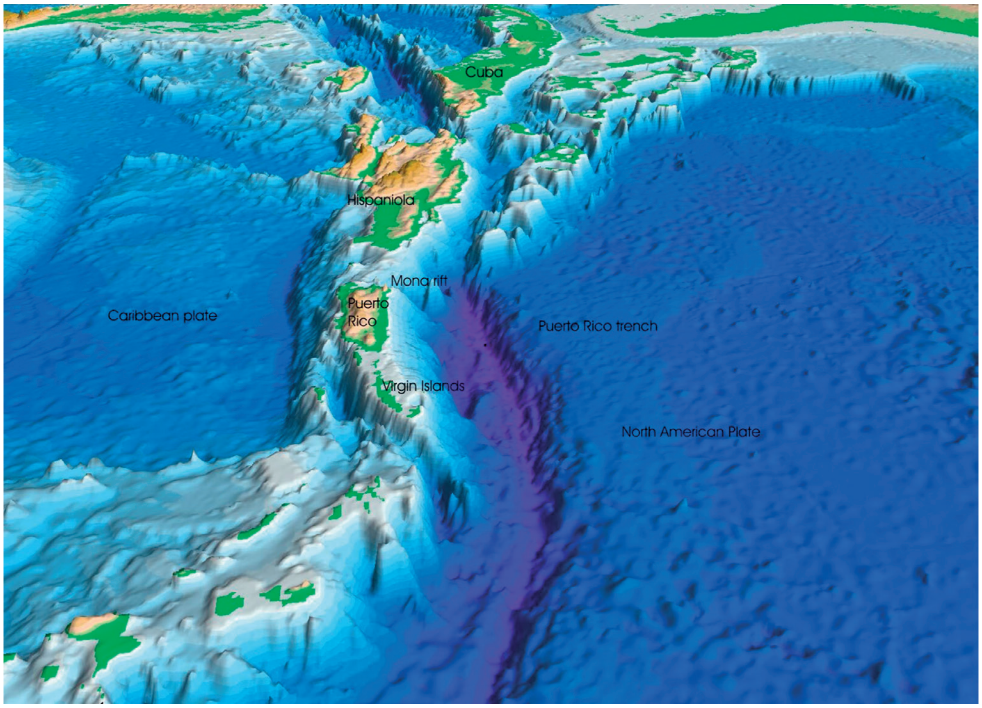

Figura 1. Vista de la Fosa de Puerto Rico relativa al fondo marino del Océano Atlántico y el Mar Caribe (vista de este a oeste). Las Antillas Menores están en el lado inferior izquierdo de la imagen mientras que Las Bahamas y Florida (EE. UU.) están en el lado superior derecho. El fondo marino en color púrpura en el centro de la imagen destaca la parte más profunda, la Fosa de Puerto Rico en el Océano Atlántico. Tomado de (título del archivo) 'Atlantic-trench.JPG' (https://commons.wikimedia.org/wiki/File:Atlantic-trench.JPG). Autor: USGS. Creada: 24 febrero 2005. Imagen de Dominio Público en los Estados Unidos de América porque solo contiene materiales que provienen originalmente del Servicio Geológico de los Estados Unidos, una agencia del Departamento del Interior de los Estados Unidos. Fuente: "Project PROBE Leg II - Final Report and Archive of Swath Bathymetric Sonar, CTD/XBT and GPS Navigation Data Collected During USGS Cruise 03008 (NOAA Cruise RB0303) Puerto Rico Trench 18 February - 7 March, 2003. USGS Open-File Report 2004-1400. 2005".

El paisaje terrestre y marino natural se representa en general por las distancias (escala horizontal) y las elevaciones (escala vertical) del terreno y profundidades del mar. Pero, si quisiéramos ilustrar las profundidades en el Atlántico – desde la costa norte hasta la Fosa de Puerto Rico – y en relación a la elevación de la superficie terrestre de la isla y solamente utilizando la escala natural sin exageraciones en la escala vertical, terminaríamos con un mapa extraordinariamente largo y ancho imposible de publicar excepto en "Atlas" de enormes dimensiones. Esto es así debido a que la elevación máxima en Puerto Rico es de unos 4,390 pies sobre el nivel del mar (psnm; ~ 1338 metros snm), mientras que la profundidad máxima de la Fosa de Puerto Rico es de unos 27,470 pies bajo el nivel del mar (pbnm; ~8373 metros bnm), y ubica a unas 100 millas (528 000 pies; ~161 kilómetros) al norte de Puerto Rico. Entonces, la razón de la distancia a la Fosa con la elevación máxima de Puerto Rico es de 528 000:4390 pies (o ~161 000:1338 metros), lo que equivale a 120 unidades de profundidad por cada unidad de elevación como escala original.

Lo descrito en el párrafo anterior, en términos simples, quiere decir (1) que para crear un mapa que refleje la escala original de elevación y profundidad del Atlántico hacia al Fosa de Puerto Rico y (2) que dicho mapa quede del alto de un papel tamaño carta (11 pulgadas o ~28 centímetros) de manera que el lector pudiera apreciarlo en detalle, requeriríamos 1320 hojas de este papel, arregladas en formato "portrait", en un rollo que casi se extendería tres veces la distancia que se cubre en una carrera de 100 metros en el atletismo; 1020 páginas si fuera en formato "landscape". Visto de una manera práctica, requeriríamos unas 14 páginas tamaño carta en formato "portrait" para ilustrar el mapa a base de su relación 120 (unidad de distancia):1 (unidad de elevación) pero apenas la escala vertical sería equivalente a una pulgada (2.54 centímetros) de espacio impreso, lo que eliminaría la apreciación de la topografía tanto terrestre como marina (Figura 2). Incluso en lo "práctico", jamás sería deseable publicar un mapa como este último (~10 pies o 3 metros de ancho) por todo el desperdicio de espacio (tanto en papel como en formato digital si fuera el caso), excepto si la intención fuera recrear "rollos" de jeroglíficos egipcios y mapas de los romanos hace 2000 años.

¿Cuál es la consecuencia de estas limitaciones de ancho de las ilustraciones con la que inicié este ensayo? La

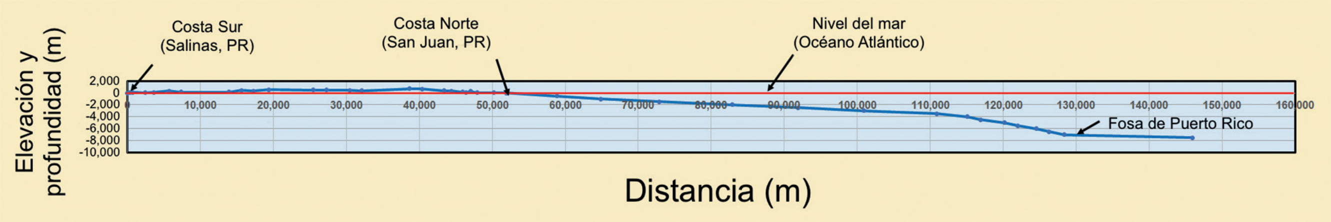

Figura 2. Perfil de elevación natural – **con exageración 4:1 vertical a horizontal** – de sur a norte desde la costa sur cerca de Salinas hasta San Juan, y luego de la costa en San Juan hacia la Fosa de Puerto Rico en el Atlántico. Datos de profundidad obtenidos de los mapas de NOAA y de navegación marina.

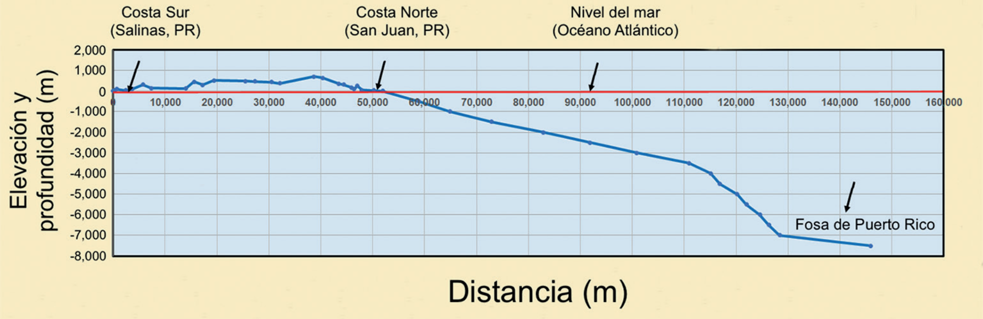

Figura 3. Perfil de elevación natural – **con exageración 10:1 vertical a horizontal** – de sur a norte desde la costa sur cerca de Salinas hasta San Juan, y luego de la costa en San Juan hacia la Fosa de Puerto Rico en el Atlántico. Datos de profundidad obtenidos de los mapas de NOAA y de navegación marina.

consecuencia de estas limitaciones es la aplicación de "exageraciones de escala", principalmente en la vertical, de las imágenes publicadas en la mayor parte de los revistas científicas e informes técnicos; así, se presenta la información dentro de los límites espaciales para su representación gráfica de manera páctica aunque sacrificando fidelidad a la realidad espacial. Por lo tanto, una convención adoptada como norma por la mayor parte de las casas editoras es la exageración máxima vertical de 2.5 unidades por cada unidad horizontal. Esto quiere decir que las pendientes de elevación del fondo del mar desde la costa norte de Puerto Rico hasta la Fosa serían 2.5 veces la declinación real. Pero como indiqué, esta no ha sido la exageración generalmente adoptada por NOAA y otras entidades científicas, usando frecuentemente exageraciones de entre 8 y 12 veces la real. Estas exageraciones resultan en ilustraciones con pendientes desde nuestras costas que son un abismo casi vertical (Figuras 3 y 4).

Sin dudas, Puerto Rico asienta sobre una plataforma que a 100 millas (161 kilómetros) tiene la profundidad de 27 470 pbnm (~8373 mbnm) pero no es un abismo casi vertical como ilustran las imágenes en fuentes mencionadas; es un descenso paulatino (Figura 2), no un barranco vertical, a medida que recorremos la distancia submarina desde la costa norte hasta la Fosa de Puerto Rico en el Océano Atlántico.

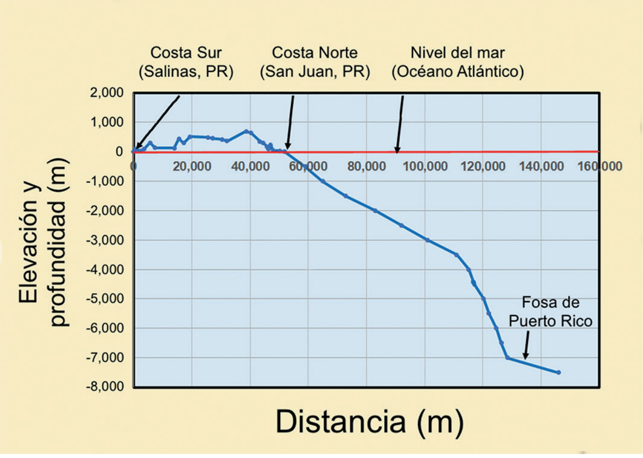

Figura 4. Perfil de elevación natural – **sin exageración vertical a horizontal** – de sur a norte desde la costa sur cerca de Salinas hasta San Juan, y luego de la costa en San Juan hacia la Fosa de Puerto Rico en el Atlántico. Datos de profundidad obtenidos de los mapas de NOAA y de navegación marina.

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PLIGHT OF THE GOLDEN LION TAMARIN: OPINION

Francisco Watlington-Linares*

* e-mail: francisco.watlington@gmail.com

A consortium of American zoos devoted to saving from extinction the Golden Lion Tamarin (*Leontopithecus rosalia*; Figure 1), threatened in its shrinking native Brazilian habitat, is faced with an intractable problem. Successful breeding has produced a surfeit of zoological populations with nowhere to go. Relocating to the still available habitat within its original distribution would overcrowd extant populations. Moreover, establishing new colonies elsewhere on the same coastal range would impinge on related species of *Leontopithecus* and likely lead to hybridization and loss of identity (e.g., hybridization with the Golden Headed Lion Tamarin, *L. chrysomelas*; Ruiz-Miranda et al. 2021).

There are four disjunct species of lion tamarins of the genus *Leontopithecus* aligned south to north along the coastal mountain rainforest known as the Mata Atlântica (Kleiman and Rylands 2002). The "flagship" Golden (*L. rosalia*) is mid-range, with scattered relict populations in Rio de Janeiro and south of the Rio Tietê

Figure 1. Golden lion tamarin (*Leontopithecus rosalia*) vocalizing. From (title) 'Golden lion tamarina vocalization.jpg' (https://commons.wikimedia.org/wiki/File:Golden_lion_tamarina_vocalization.jpg). Author: ©Jeroen Kransen (https://www.flickr.com/photos/48503061@N00/2954013271. It was reviewed on 7 February 2013 by FlickreviewR and was confirmed to be licensed under the terms of the cc-by-sa-2.0) – Own work. Created 18 October 2008. Licensed under Attribution-ShareAlike 2.0 Generic (CC-BY-SA-2.0; https://creativecommons.org/licenses/by-sa/2.0/deed.en).

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in São Paulo. Both areas comprise the most densely populated region of Brasil. *Leontopithecus chrysomelas* is farthest north and occupies the southernmost corner of Bahia, touching the border of Minas Gerais. Other *Leontopithecus* are the Black-Faced Lion Tamarin (*L. chrysopigus*), formerly occupying the south of São Paulo state to the border of Paraná state, and the Black Lion Tamarin (*L. caissara*), which has the southernmost distribution among species of the genus and survives on the coastal island of Superagui of the state of Paraná.

Given the abundant population of Golden Lion Tamarins in American zoos and the problems inherent in relocation to Brasil, I proposed to establish a foster home colony on a U.S. territory with environmental attributes similar to those of the Mata Atlântica forest of Brasil and readily accessible from the eastern states; the proposed site is the El Yunque National Forest of Puerto Rico, a mountainous rainforest massif of over 11,000 hectares, and average elevation between 700 and 1,000 meters above sea level. Under federal control, the forest periphery is much better protected from unwanted incursion than the tamarin refuges in its natural distribution. Moreover, the most widespread forest tree species is the Tabonuco (*Dacryodes excelsa*) which produces a gummy exudate, a favorite tamarin treat. The second most common tree is the Palo Colorado (*Cyrilla racemiflora*) which hollows as it ages, thus providing tamarins with protected bedrooms (sleep and retreat sites). Consequently, the botanical diversity of tamarin foods is similar to that of the Mata Atlântica, and since most native sites in Brasil are already at carrying capacity, serious consideration should be given to a foster home colony in Puerto Rico.

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- ○ cuando una unidad es expresada en denominador, se debe utilizar el sólido (p. ej., g/m^2); para dos o más unidades en un denominador, use el sólido y un decimal (p. ej., $g/m^2 \cdot d$).
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      Clark, C. M., and D. Tilman. 2010. Recovery of plant diversity following N cessation: effects of recruitment, litter, and elevated N cycling. Ecology 91:3620–3630.
    - ○ **de un libro**:

      Sokal, R. R., and F. J. Rohlf. 1995. Biometry: the principle and practice of statistics in biological research. Third edition. W. H. Freeman and Co., New York, New York, USA.
    - ○ **del capítulo de un libro**:

      Hartshorn, G. S., and B. E. Hammel. 1994. Vegetation types and floristic patterns. Pages 73–89 in L. A. McDade, K. S. Bawa, H. A. Hespenheide, and G. S. Hartshorn, editors. La Selva: ecology and natural history of a neotropical rain forest. University of Chicago Press, Chicago, Illinois, USA.
    - ○ **de un reporte gubernamental**:

      Pardo, L. H., M. J. Robin-Abbott, and C. T. Driscoll. 2011. Assessment of Nitrogen deposition effects and empirical critical loads of Nitrogen for ecoregions of the United States. General Technical Report NRS-80. USDA Forest Service, Northern Research Station, South Burlington, Vermont, USA.
    - ○ **de una disertación**:

      Foster, S. E. 2007. The co-occurrence and interactions of large invertebrate predators in relation to the Bythotrephes invasion. Dissertation. University of Toronto at Mississauga, Mississauga, Ontario, Canada.
    - ○ **de una página web**:

      Keeland, B. D., and P. J. Young. 2004. Construction and installation of dendrometer bands for periodic tree-growth measurements. U.S. Geological Survey, National Wetlands Research Center, Lafayette, Louisiana, USA. http://www.nwrc.usgs.gov/Dendrometer/index.htm
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      SAS Institute. 2009. JMP version 8.0. SAS Institute, Cary, North Carolina, USA

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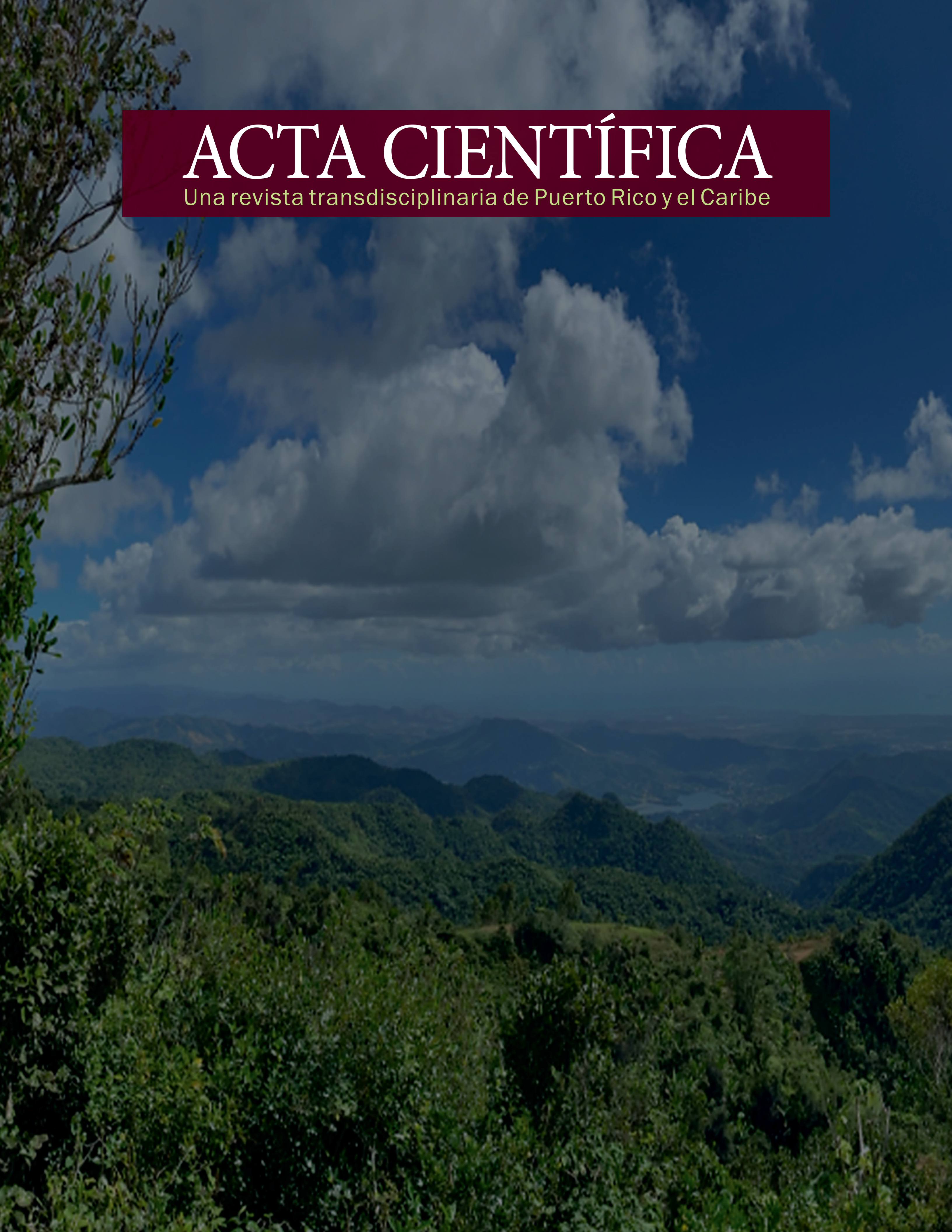

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