Climbing since the early Miocene: the fossil record of Paullinieae (Sapindaceae)

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Abstract

Paullinieae are a diverse group of tropical and subtropical climbing plants that belong to the soapberry family (Sapindaceae). The six genera in this tribe make up approximately one-quarter of the species in the family, but a sparse fossil record limits our understanding of their diversification. Here, we provide the first description of anatomically preserved fossils of Paullinieae and we re-evaluate other macrofossils that have been attributed to the tribe. We identified permineralized fossil roots in collections from the lower Miocene Cucaracha Formation where it was exposed along the Culebra Cut of the Panama Canal. We prepared the fossils using the cellulose acetate peel technique and compared the anatomy with that of extant Paullinieae. The fossil roots preserve a combination of characters found only in Paullinieae, including peripheral secondary vascular strands, vessel dimorphism, alternate intervessel pitting with coalescent apertures, heterocellular rays, and axial parenchyma strands of 2–4 cells, often with prismatic crystals. We also searched the paleontological literature for other occurrences of the tribe. We re-evaluated leaf fossils from western North America that have been assigned to extant genera in the tribe by comparing their morphology to herbarium specimens and cleared leaves. The fossil leaves that were assigned to Cardiospermum and Serjania from the Paleogene of western North America are likely Sapindaceae; however, they lack diagnostic characters necessary for inclusion in Paullinieae and should be excluded from those genera. Therefore, the fossils described here as Ampelorhiza heteroxylon gen. et sp. nov. are the oldest macrofossil evidence of Paullinieae. They provide direct evidence of the development of a vascular cambial variant associated with the climbing habit in Sapindaceae and provide strong evidence of the diversification of crown-group Paullinieae in the tropics by 18.5–19 million years ago.

Introduction

Paullinieae (Sapindaceae) are tropical and subtropical woody vines (i.e., lianas), herbaceous climbers (i.e., vines), and seldom shrubs [1]. The six genera of
Paulinieae—Paulinia L., Serjania L., Cardiospermum Kunth., Urvillea Kunth., Lophostigma Radlk., and Thionia Triana & Planch—form a clade defined by their tendrilate climbing habit and presence of stipules. With approximately 475 species, they comprise nearly one quarter of all species in Sapindaceae. The Paulinieae are one of the four successively nested tribes of the Supertribe Paulinioideae sensu by Acevedo-Rodríguez et al., however the other members—Athyaneae, Bridgesieae, Thouinieae—are all trees and shrubs. Numerous members of Paulinieae undergo developmental re-patterning during the production of secondary xylem (i.e., wood) and secondary phloem (i.e., inner bark), resulting in the formation of “vascular cambial variants,” such as continuous or discontinuous successive cambia, neoformations forming peripheral secondary vascular strands (i.e., corded), compound stems, fissured xylem, divided xylem, lobed xylem, and phloem wedges.

The monophyly of Paulinieae within the subfamily Sapindoideae is supported by morphology and molecular sequence data. Molecular phylogenetic analyses have repeatedly yielded a long branch subtending the Paulinieae, suggesting shifts in nucleotide substitution rates potentially associated with the evolution of the climbing habit. Previous efforts to calibrate the phylogeny of Sapindaceae have yielded Oligocene or Miocene estimates for the age of crown-group Paulinieae; however, critical evaluation of the fossil record is necessary to constrain the timing of diversification and the evolution of morphology and anatomy of Paulinieae.

Although the fossil record of Sapindaceae is rich, macrofossils of Paulinieae are rare and at least some previous identifications are unreliable. Here, we describe the first anatomically preserved macrofossils of Paulinieae. The fossils are roots, but nonetheless provide strong evidence of the climbing habit based on wood anatomy associated with climbing in Sapindaceae. Next, we evaluate fossil leaves that have been attributed to the tribe. Then, we summarize the fossil record of the tribe with a focus on macrofossils and identify occurrences best suited for calibrating time-trees. Finally, we discuss the implications of our findings for future studies of the evolution of Paulinieae.

Materials and methods

Geologic Setting

Two fossil roots were identified in a collection from the Lirio East site in lower part of the Cucaracha Formation along the Culebra Cut (Gaulard Cut) of the Panama Canal (Fig. 1). These collections were made in 2007 by F. Herrera and S.R. Manchester. The lower Cucaracha Formation consists of deltaic and coastal swamp deposits laid down during the early Miocene when the nearby Pedro-Miguel Volcanic Complex was active. At the Lirio East site, fossil fruits as well as woods with bark are preserved as calcareous permineralizations in a poorly sorted, carbonate-cemented sandstone.

So far, remains of Sacoglottis (Humiriaceae), Oreomunnia (Juglandaceae), Parinari (Chrysobalanaceae), Mammea (Calophyllaceae), Rourea (Connaraceae), and Spondias (Anacardiaceae), have been described. Plant macrofossils from elsewhere in the Cucaracha Formation include palm stem fragments, Guazuma-like Malvaceae, legume woods, and Malpighiaceous wood. Fossil pollen from the Cucaracha Formation includes at least 52 pollen types. Together, these records suggest the vegetation was primarily tropical rainforest near the paleoshoreline of central Panama.
Fossil preparation

We cut the fossils in transverse and tangential and radial longitudinal sections using a Microslice 2 annular saw and prepared serial sections using the cellulose acetate peel technique [44]. Peels were mounted on 25 x 75 mm glass slides with Canada Balsam or Eukitt mounting medium and examined using light microscopy. Images of microscopic features were captured with a Canon EOS digital camera mounted on a Nikon compound microscope with transmitted light and processed with Adobe Photoshop (San Jose, California, USA). All specimens, peels, and microscope slides are curated at the Florida Museum of Natural History Paleobotanical Collections, Gainesville, Florida, United States.

Terminology and measurement protocols for the wood anatomy generally follow the IAWA Hardwood List [56] but we adapted our approach for characters particular to Paullinieae [64]. Summary statistics for anatomical characters were calculated from 25 measurements. The fossil exhibits vessel dimorphism; this term has been used for both highly skewed distributions and bimodal distributions [57–59], so we measured all vessels in the central xylem cylinder [14] of a single transverse peel \( n = 162 \) from the holotype (UF 19391-63016) to generate a histogram of the distribution of vessel diameters. Then, we used the densityMclust function in the package mclust [60] in R [61] to identify the modes in the distribution that correspond to the narrow and wide vessel classes. We report “narrow vessel diameter” and “wide vessel diameter” as two separate characters. All measurements were made in ImageJ 1.50a [62].

Fossil leaves

We searched the literature for fossils identified as Paullinieae (Table 1). Of the species we found, we examined specimens and images for those from North America and we re-described their morphology following the format of the Manual of Leaf Architecture [63]. For putative occurrences from South America and Europe, we evaluated images and descriptions from the published literature. We used herbarium collections and online images to survey angiosperm families for leaves with organization, margin type, and venation patterns similar to the fossil leaf taxa re-described here (originally assigned to modern genera within Paullinieae). Then, we compared the morphology of the fossils with leaves from extant genera in Paullinieae and with leaves of selected genera outside Sapindaceae that exhibit similarities in organization, shape, margin, and venation patterns. Cuticle was not preserved on any of the fossil leaves we examined and we did not evaluate cuticle for diagnostic characters. Comparisons are based on dried specimens in the University (UC) and Jepson (JEPS) Herbaria at the University of California – Berkeley, the R. L. McGregor Herbarium (KANU) at the University of Kansas, images available online via JSTOR Global Plants, and cleared and stained leaves in the National Cleared Leaf Collection (NCLC-H; https://collections.peabody.yale.edu/pb/nclc/).

Phylogenetic Analysis

We obtained the concatenated multiple sequence alignments from [21] and [22]. From these datasets, we exclusively selected species within the supertribe Paullionieae as described by Acevedo-Rodríguez et al. [21], which includes Athyaneae, Bridgesieae, Thouinieae, and Paullinieae, totalling 100 ITS and 88 \( \text{trnL intron} \) sequences from [21], and 115 ITS sequences from [22]. We then combined the two ITS datasets and realigned them in Geneious Prime 2021.0.3 (https://www.geneious.com) using the MUSCLE v3.8.425 aligner under default settings; the \( \text{trnL intron} \) sequences were realigned under the same settings.
We then obtained wood anatomy data for 11 terminals from [13] and 33 terminals from [64], and one terminal from [20], now available on morphobank (morphobank.org/permalink/?P3910), and scored the fossil for 22 out of the 27 anatomy characters. Finally, we added the character “habit” (0=self-supporter, 1=climber) and scored it for all extant species. Although the wood anatomy characters scored for extant species were observed in stems and the fossils are roots, available evidence indicates that differences in wood anatomy between stems and roots within individual plants tend to be quantitative rather than qualitative [16,65,66]. The resulting dataset (S1 Appendix) comprises 216 tips and 1517 characters with three partitions: anatomy (1-28), ITS (29-882), and trnL intron (883-1517).

We estimated the phylogenetic position of the fossil taxon using a Bayesian analysis with two runs each of four chains (three hot, one cold, temp=0.02) in MrBayes 3.2.7 [67]. We applied the GTR+G model of nucleotide evolution to the ITS and trnL intron partitions. The Mk model with rates drawn from a lognormal distribution was applied to the anatomy partition. The analysis ran for 12 million generations, sampling trees every 1000th generation. The analysis converged with a standard deviation of split frequencies of 0.007428 and the estimated sample size (ESS) of all parameters exceeded 2108. All trees were generated using the post burnin (25% of initial trees discarded) from the combined MrBayes runs. The allcompat consensus tree (50% majority rule consensus with compatible groups added) was generated with the MrBayes command: contype=allcompat and annotated using iTol v4 [70]. The maximum clade credibility (MCC) tree was generated with Tree Annotator v1.10.4 [68], and the maximum a posteriori tree (MAP) was generated with RevBays v1.10 [69]. The MrBayes input nexus file (data matrix), allcompat consensus, MCC, and MAP trees, and full accession list with associated molecular and anatomical data references are provided in (S1 Appendix).

Nomenclature

The electronic version of this article in Portable Document Format (PDF) in a work with an ISSN or ISBN will represent a published work according to the International Code of Nomenclature for algae, fungi, and plants, and hence the new names contained in the electronic publication of a PLOS ONE article are effectively published under that Code from the electronic edition alone, so there is no longer any need to provide printed copies. The online version of this work is archived and available from the following digital repositories: PubMed Central and LOCKSS.

Results

Fossil roots

Family:
Sapindaceae Jussieu

Subfamily:
Sapindoideae Burnett

Tribe:
Paullinieae (Kunth) DC.
Genus:

*Ampelorhiza* Jud, S.E. Allen, Nelson, Bastos & Chery gen. nov.

Generic diagnosis:

Roots woody with neoformations forming peripheral secondary vascular strands; vessels of two distinct size classes, wide vessels solitary and in tangential multiples, narrow vessels in long radial multiples; intervessel pits alternate with slit-like coalescent apertures on the walls of large vessels; heterocellular rays composed of mixed upright, square, and procumbent cells; axial parenchyma strands 2–4 or more cells tall, often chambered with prismatic crystals.

Type Species:

*Ampelorhiza heteroxylon* Jud, S.E. Allen, Nelson, Bastos & Chery gen. et sp. nov.

Specific diagnosis:

As for genus.

Holotype:

UF 19391-63016 (Fig 2, 3).

Paratype:

UF 19391-63026 (S2 Figure).

Repository:

Florida Museum of Natural History (FLMNH), Gainesville, Florida, U.S.A.

Type Locality:

Panama; Culebra Cut, northeast side of the Panama Canal (N 9.051375°, W 79.649027°, WGS84).

Stratigraphic position and age:

Cucaracha Formation; early Miocene, c. 18.5–19 Ma [30,31].

Etymology:

The genus comes from the Greek *ámpelos*, meaning vine, and *ríza* meaning root. The specific epithet comes from the Greek *héteros* meaning different and *-xylon* meaning wood, referring to the different sizes of the peripheral secondary vascular strands found in Paullinieae.
Description (descriptio generico-specifica):

The holotype is an axis 1 cm wide and 3 cm long; the paratype is an axis 0.5 by 1 cm wide and 2.5 cm long. Each consists of bark with one or two peripheral secondary vascular strands (Fig 2A–C), surrounding a central woody cylinder with a small core of primary vascular parenchyma (Fig 2A–C). The peripheral vascular strands consist of secondary xylem and phloem derived from C-shaped cambia that lack primary vascular parenchyma. In the holotype, the two preserved peripheral strands are of different sizes. One is c. 3.3 mm by c. 2.0 mm in transverse section and the other is 0.7 mm by c. 0.4 mm (Fig 2A lower arrow, Fig 2C). Primary vascular parenchyma in the central cylinder of the holotype is an eccentric collection of parenchyma cells 200 µm tall by 500 µm wide (Fig 2D). Radial files of cells with dark contents also extend away from the center of the central cylinder on one side (Fig 2D). The primary vascular parenchyma cells are tall (c. 150–300 µm), and many have dark contents in the lumen (Fig 2E). Secondary xylem is diffuse porous (Fig 2A & F). Growth rings are indistinct (Fig 2A & F). Vessels are in two distinct size classes: wide vessels 50-270 µm (mean: 104 µm) in tangential diameter, mostly solitary but also in tangential multiples of 2–3; narrow vessels are 11–50 µm in tangential diameter and arranged in radial multiples of 2–9 (Fig 2A & F). Vessel elements are 153–280 µm long (mean: 223 µm, n=14). Mean vessel frequency is 27 per mm². Vessel element end walls are without scalariform bars; perforation plates are simple (Fig 2I). Tyloses and helical thickenings were not observed. Intervessel pits alternate with distinct borders and coalescent apertures on the walls of large vessels (Fig 2F). Vessel-ray parenchyma pits were difficult to observe; we did not find large simple pits different from those on the vessel walls (Fig 3A). Fibers are poorly preserved but appear non-septate with minutely bordered uniseriate pits on the radial walls (Fig 3A). Axial parenchyma is diffuse and scanty paratracheal, with strands at least 2–4 cells tall and often chambered with prismatic crystals (Fig 3D). Rays are 1–2 (rarely three) cells wide, less than 1 mm tall, and heterocellular with rows of procumbent square and upright cells mixed throughout (Fig 3E). Secretory structures were not observed.

Remarks:

Although cambial variants are often associated with the climbing habit, the presence of peripheral vascular strands is not sufficient to identify the fossils as stems or roots. Bastos et al. [16,66] demonstrated that cambial variants can be found in both organs. In stems of Paullinieae, the pith is conspicuously angular (e.g., triangular, pentangular) in transverse section with primary vascular bundles at the corners [19]. By contrast, in roots the primary vascular parenchyma is diarch and this region (i.e., the “medulla”) is oval and smaller than the stem pith in transverse section (Fig 4). In Ampelorhiza heteroxylon, there is an eccentric oval-shaped parenchymatous core c. 200 by 500 µm in diameter (Fig 2D); therefore, our interpretation is that the specimens are roots. We initially recognized that these fossils might be lianas based on the diameter of the largest vessels relative to the width of the axis. To illustrate this approach, we used logistic regression to classify unknown fossil axes from Lirio East as climbers or self-supporters based on maximum vessel diameter and diameter of the central woody cylinder (S3 Figure). The model was trained using a dataset of 71 samples obtained from Ewers et al. [71], and predicted the habit of 22 fossil axes with woody cylinders greater than 5 mm in diameter from the Lirio East fossil collections. Although the model did predict that the Ampelorhiza fossils (and the Rourea fossil described by Jud and Nelson [37]) are climbers, the training dataset is only stem material and therefore may not be suitable for classifying roots, given the patterns found by Ewers et al. [72] when comparing stems and roots in lianas and trees. Further work on the relationship between hydraulic path length, vessel diameter, and root diameter in lianas and...
self-supporters (as has been done for stems [73]) would be useful for identifying lianas in the fossil record.

**Fossil leaves**

We found one fossil species assigned to *Serjania* and two assigned to *Cardiospermum* from North America in the literature (Table 1). All three were described from fossils of isolated leaflets or partially complete compound leaves (Fig 5). MacGinitie [74] described “*Serjania*” rare based on leaves from the Eocene Aycross Formation in northwestern Wyoming. The same species also occurs in the Eocene Bridger Formation in southwestern Wyoming [75]. “*Cardiospermum*” *terminale* (Lesquereux) MacGinitie was first described from the Eocene Florissant Formation in central Colorado by Lesquereux [76] as *Lomatia*. MacGinitie [77] transferred these specimens and others to *Cardiospermum* based on the twice-ternate leaf organization and architecture of lobes, teeth, and major vein framework of the leaflets. This species was later reported from the late Eocene to early Oligocene Climbing Arrow Member of the Renova Formation in southwestern Montana [78,79] as well. Finally, “*Cardiospermum*” *coloradensis* (Knowlton) MacGinitie was first described from fossils of the Eocene Green River Formation as *Phyllites* by Knowlton [80]; and later transferred to *Cardiospermum* by MacGinitie [81]. This species has been reported from throughout the Green River Formation [81,82]. Updated descriptions of these three species are provided in the Supporting information (S4 Appendix).

The extinct genus *Bohlenia* Wolfe & Wehr [85] was established for sapindaceous leaves and fruits from the Eocene Republic flora (Klondike Mountain Formation) in Washington, USA (Table 1). Wolfe and Wehr [85] suggested that *B. americana* (Brown) Wolfe & Wehr may belong to Paullinieae based on the course of the secondary veins and on the assumption that co-occurring samaras belonged to the same species; however, McClain and Manchester [86] transferred the samaras to *Dipteronia brownii* McClain & Manchester and noted that *Bohlenia* foliage is similar to *Koelreuteria elegans* (Seem.) A.C. Sm. Both of these fossil species are members of Sapindaceae, but neither belong to Paullinieae.

We also found three species assigned to *Serjania* from the Cenozoic of Brazil in the literature (Table 1). Fittipaldi et al. [87] described *Serjania lanceolata* Fittipaldi, Simões Giulietti et Pirani and *Serjania itaquaquecetubensis* Fittipaldi, Simões Giulietti et Pirani based on incomplete unlobed, toothed leaf blades from the Oligocene upper Itaquaquecetuba Formation. To our knowledge, the characteristic pollen of Paullinieae has not been recognized in palynological studies of this formation [88]. Finally, *Serjania mezzalire* Duarte et Rezende-Martins was described from fossil leaves in the Miocene Rio Claro Formation [89–90].

Edwards and Wannacot [92] compiled list of all fossil species that had been assigned to Paulliniea based on leaf morphology from Europe. They concluded that a close relationship to extant Paullinieae can be rejected or is doubtful for all of them based on morphology or quality of preservation. We concur, so we did not consider these further.

There is considerable variation in the blade shape, margin type, tertiary venation, and base shape among extant Paullinieae (Fig 6). Leaf margins may be unlobed or lobed, toothed or untoothed. Toothed margins may be serrate, dentate, or crenate. Secondary vein framework may be craspedodromous, semicraspedodromous, brochidodromous, or eucamptodromous. Leaf organization is also variable. Leaves may be simple, once or twice imparipinnate, or up to thrice ternate (most commonly twice ternate). In compound leaves, the rachis may be winged or unwinged. Axillary tendrils may be absent or present. Many of these characters also vary across Sapindaceae. Based on our observations, isolated fossil leaves or leaflets of Paullinieae may be recognizable if
they preserve a combination of the following characters: Axial tendrils, stipules, terno
compound organization, winged rachides, and absence of a marginal vein.

Morphological similarities between “Cardiospermum” coloradensis, “C.” terminale,
“Serjania” rara, and the leaves of some extant Paulliniae include 1. terno-compound
organization, 2. decurrent (Fig 5C, E, F; Fig 6A, B) or complex leaflet bases (Fig 5A,
B), 3. irregular spacing of secondary veins, 4. secondary veins that terminate beyond
the apex of lobes/teeth, 5. secondary veins that terminate in angular (“V-shaped”)
sinuses (Fig 5), and 6. secondary veins that bifurcate around angular sinuses (Fig 5E).

Furthermore, a prominent marginal vein like that present in at least some specimens of
the fossil species (Fig 5D, E) is not present in extant Serjania and Cardiospermum
(Fig 6A, B). The descriptions and images of “Serjania” lanceolata, “S.”
itaquaquecetubensis, and “S.” messalire show the shape of the blade, the presence of a
serrate margin, and craspedodromous secondary vein framework [87,90]. Although these
characters are consistent with Serjania, their combination is not diagnostic of the genus.

Table 1. Summary of pre-Quaternary macrofossils that have been assigned to Paulliniae.

<table>
<thead>
<tr>
<th>Species</th>
<th>Organ</th>
<th>Formation</th>
<th>Age</th>
<th>Country</th>
<th>References</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ampelorhiza heteroxylon</td>
<td>root</td>
<td>Cucaracha</td>
<td>Mi.</td>
<td>Panama</td>
<td>This study</td>
<td>accepted</td>
</tr>
<tr>
<td>Bohlenia spp.</td>
<td>leaf</td>
<td>Klondike Mountain</td>
<td>Eo.</td>
<td>USA</td>
<td>[85,86]</td>
<td>rejected</td>
</tr>
<tr>
<td>“Cardiospermum” coloradensis</td>
<td>leaf</td>
<td>Green River</td>
<td>Eo.</td>
<td>USA</td>
<td>[81]</td>
<td>rejected</td>
</tr>
<tr>
<td>“Cardiospermum” terminale</td>
<td>leaf</td>
<td>Florissant; Renova</td>
<td>Eo.</td>
<td>USA</td>
<td>[77,78,96]</td>
<td>rejected</td>
</tr>
<tr>
<td>“Serjania” rara</td>
<td>leaf</td>
<td>Aycross; Bridger</td>
<td>Eo.</td>
<td>USA</td>
<td>[74,75]</td>
<td>rejected</td>
</tr>
<tr>
<td>Serjania mezzalire</td>
<td>leaf</td>
<td>Rio Claro</td>
<td>Ol.</td>
<td>Brazil</td>
<td>89</td>
<td>uncertain</td>
</tr>
<tr>
<td>Serjania itaquaquecetubensis</td>
<td>leaf</td>
<td>Itaquaquecetuba</td>
<td>Mi.</td>
<td>Brazil</td>
<td>87</td>
<td>uncertain</td>
</tr>
<tr>
<td>Serjania laceolata</td>
<td>leaf</td>
<td>Itaquaquecetuba</td>
<td>Mi.</td>
<td>Brazil</td>
<td>87</td>
<td>uncertain</td>
</tr>
</tbody>
</table>

Each identification is classified as accepted, rejected, or uncertain (material is consistent with Paulliniae, but alternative interpretations have not been ruled out). Mi.: Miocene, Ol.: Oligocene, Eo.: Eocene. See text for further justification of status.

Phylogenetic position of Ampelorhiza

We evaluated the placement of Ampelorhiza by observation of the allcompat consensus,
MCC, and MAP trees sampled from the posterior distribution. Ampelorhiza is always
nested within extant Paulliniae, however its relationship with extant genera differs
based on the method used to generate the tree, reflecting the uncertainty typical of taxa
with a high proportion of missing data. In the allcompat consensus tree (Fig 7)
Ampelorhiza is nested within a clade with Cardiospermum, Paullinia, and Serjania. The
various positions of Ampelorhiza within this clade is represented as a polytomy that
includes several lineages of Serjania and Cardiospermum. In the maximum a posteriori
tree [S1 Appendix], Ampelorhiza is nested within Urvillea, whereas in the maximum
clade credibility tree Ampelorhiza is nested within Serjania. These results further
supports our circumscription of Ampelorhiza as a distinct genus from extant Paulliniae.
The placement of Ampelorhiza within Paulliniae is supported by vessel dimorphism,
heterocellular rays, and axial parenchyma strands typically 2-4 cells long. One
synapomorphy of Paulliniae that we did not observe in the fossil is wide rays (ray
dimorphism); however, we only examined two root fragments and this character is
observed in many, but not all, samples from modern roots [16].
Discussion

Roots

The combination of peripheral vascular strands (Fig. 2A, C; 4A & B), vessel dimorphism (Fig. 2F & I; 4B-D), wide vessels solitary or in tangential multiples of 2-3 (Fig. 2F; 4C), narrow vessels in long radial multiples of 2-21 (Fig. 2F; 4C & D), alternate intervessel pits with slit-like coalescent apertures (Fig. 2G, H; 4E), heterocellular rays, prismatic crystals in axial parenchyma (Fig. 3D; 4F), and dark content (possibly phenolic compounds) in primary vascular parenchyma and ray parenchyma (Fig. 2D, E) support the inclusion of *Ampelorhiza* in Paullinieae. Two wood anatomical characters typical of extant Paullinieae were not observed in the fossils: 1) alternating bands of thin and thick-walled regions in the wood which may either be axial parenchyma alternating with ordinary fibers (e.g., *Serjania* spp.) or parenchyma-like fiber bands alternating with ordinary fibers (e.g., *Paullinia* spp.) and 2) ray dimorphism. Because the bands are clearest in sufficiently thin, stained sections or polished blocks, it may be that the thickness of the peels and the absence of stain obscures this feature.

The cambial configuration in stems and roots is highly variable in Paullinieae. Chery et al. [19] and Cunha Neto et al. [18] together distinguished six ontogenetic pathways in the stems of *Paullinia* alone, and we expect that *Serjania* has the most variation in the tribe based on preliminary observations of images in the Smithsonian Liana databases (Acevedo & Chery, personal observation). Furthermore, Bastos [16, 66] showed that roots may or may not also have cambial variants, and when present they do not necessary mirror the configuration of the stems. An asymmetrical distribution of peripheral secondary vascular strands of different sizes, as in *Ampelorhiza heteroxylon*, occurs in the roots of *Serjania caracasana* (Fig. 4A & B) and the stems of some *Paullinia* [18]. Given the variation among stems and the paucity of data on cambial variants in roots, the configuration of secondary growth in the fossils does not justify assignment to one of the extant genera.

Despite some anatomical differences among the genera of Paullinieae, the fossils of *Ampelorhiza* do not preserve a combination of wood anatomy characters diagnostic of any extant genus either, they are most similar to some *Serjania*. The wood of *Serjania* stems has banded axial parenchyma, no septate fibers, and crystals confined to axial elements, whereas *Paullinia*, *Thinouia*, and *Cardiospermum* have scanty axial parenchyma, abundant septate fibers, and crystals in ray parenchyma. *Thinouia* differs from *Paullinia* and *Cardiospermum* by the absence of crystals in axial elements [13], and some *Paullinia* can be recognized by a herringbone pattern in the wide rays when viewed in transverse section [13]. The fossils do not have banded parenchyma, nor do they have wide rays with a herringbone pattern. They do have crystals in the axial elements but we did not observe them in the rays, nor did we detect septate fibers.

Leaves

We reject the generic assignments of *Cardiospermum* and *Serjania* species described from fossil leaf material. Our search for leaves with organization, margin features, and venation architecture similar to “C.” *coloradensis*, “C.” *terminale*, and “S.” *rara* outside of Sapindaceae led to comparisons with Anacardiaceae (e.g., *Rhus* L.), Fagaceae (e.g., *Quercus* L.), Proteaceae (e.g., *Roupala* Aubl., *Lomatia* R. Br., *Beauveria* Brongn. & Gris), Ranunculaceae (e.g., *Clematis* L.), and Solanaceae (e.g., *Hyoscyamus* L., *Chamaesaracha* (A. Gray) Benth. & Hook. f., *Physalis* L., *Lycopersicum* Hill.). Some *Rhus* (Anacardiaceae) have similar shapes to the fossil material, but secondary venation in *Rhus* varies from craspedodromous to cladodromous. Some Fagaceae have similar...
blade shape, secondary veins, and major veins that project beyond the margin of the blade; however, all Fagaceae have simple leaves and the sinuses are generally rounded rather than angular as in the fossils. Previous authors (e.g., [76,83]) have attributed fossils like these to Proteaceae; however, although secondary veins in the Proteaceae are variable (e.g., brochidodromous to semicraspedodromous to festooned brochidodromous to festooned semicraspedodromous), they are unlike the craspedodromous framework in the fossils and again the sinuses between teeth are generally rounded in Proteaceae rather than angular. The compound leaves of some lobed and toothed Clematis (Ranunculaceae) can be distinguished from the fossils because they usually have festooned secondary venation. Finally, several Solanaceae have asymmetric blades and similarly shaped teeth and lobes; however, again the sinuses tended to be rounded rather than angular as in the fossils.

Leaf architectural characters preserved in “C.” coloradensis, “C.” terminale, and “S.” rara support inclusion in Sapindaceae, yet we consider a close relationship with Paullinieae unlikely based on the presence of a prominent perimarginal vein in the fossils and the absence of co-occurring fossil fruits or pollen despite decades of intensive sampling in the Green River Formation and the Florissant fossil beds. Similarly, in his update of the fossil flora of Florissant, Manchester [96] doubted the generic assignment of “C.” terminale based on the rather coriaceous texture of the fossils compared to extant Cardiospermum and the absence of associated fruits. Other extant Sapindaceae with similar leaf organization, margin type, teeth, and venation include: Thouinia Poit., Koelreuteria Laxm., Dipterodendron Radlk., Dilodendron Radlk., and Athyana (Griseb.) Radlk.

**Evolution of Paullinieae**

To our knowledge, the oldest reliable fossil evidence of Paullinieae is heteropolar hemi-tri-syncolpate pollen from the Gatuncillo Formation in Panama [52]. Some fossil species of the genera Syncolporites and Proteacidites (used for dispersed pollen) may belong to Paullinieae (or Proteaceae or Myrtaceae) [95]; however, a review of those species is beyond the scope of this work. Heteropolar hemi-tri-syncolpate pollen is a synapomorphy of the clade that includes all Paullinieae except Thinouia and Lophostigma [21,97,98]. Therefore, these fossils can be considered evidence of crown-group Paullinieae in the fossil record. Unfortunately, constraining the age of these samples is challenging. Montes et al. [99] reported Late Eocene and Oligocene foraminifera from the Gatuncillo Formation, consistent with the original age estimate from Graham [52]. More recently, Ramírez et al. [100] obtained detrital zircons from two sites that constrain the maximum age of deposition of the Gatuncillo Formation to Late Eocene, c. 41 Ma and c. 36 Ma respectively, but we do not know their position relative to Graham’s [52] pollen sample. Older putative occurrences of Middle Eocene pollen from the Wagon Bed Formation in Wyoming [101] and the Claiborne Group in northern Alabama [102], were not described nor figured, and are not reliable [103].

Pollen from the Kisinger Lakes paleoflora in Wyoming that MacGinitie compared with Serjania [74] was not described; however, one figure shows a single grain 24 µm across in polar view with a 3-(parasyncol)porate structure. It is not possible to determine whether it was heteropolar and pollen grains in Paullinieae are larger than 30 µm across [98,104]. Therefore, we do not consider this a reliable fossil occurrence of Paullinieae based on the available information. Younger occurrences include heteropolar demisyncolpate pollen from the late Miocene Gatum Formation in Panama [43,49] and the Pliocene Paraje Solo Formation, also in Panama [47].

The transition to the liana habit occurred only once in Sapindaceae along the branch leading to crown-group Paullinieae [21]. Accordingly, all members of the tribe share anatomy associated with the climbing habit such as abrupt changes in vessel diameter,
vessel dimorphism, and numerous members have cambial variants \[19,105\]. The combination of wood anatomical characters and the presence of the peripheral vascular strands preserved in the fossils provides strong evidence of the climbing habit in Paullinieae by the early Miocene.

**Paleoecology**

Lianas are a conspicuous element of tropical forests and their fossils contribute to reconstructions of paleoenvironments and paleocommunities. The Lirio East fossil assemblage includes at least 32 plant morphotypes have been distinguished and assigned to family based on fossil fruits, seeds, and woods \[32,34,36,38\]. The discovery of *Ampelorhiza* brings the number of liana species to a minimum of 8, or 25% of the local assemblage. This value is typical of lowland tropical forests \[106\]. Three other potential liana axes were identified using logistic regression \(S3\) Figure, but remain to be described (F. Herrera, pers. comm.). At least 31 additional fruit and seed morphotypes have been distinguished but not yet identified to family \[32\]. In modern tropical forests liana species richness is highest in seasonally dry tropical forests and locally near forest edges or in treefall gaps \[107,109\]. Given the rarity of distinct growth rings in the co-occurring fossil woods and the preference of *Sacoglottis* and *Oreomunnea* for humid tropical forests \[33,34\], we hypothesize that the high proportion of lianas in the Lirio East assemblage is a signal of riparian zone disturbance and/or edge effects in a humid tropical forest on a landscape shaped by nearby volcanic activity \[31\].

**Conclusion**

The discovery of *Ampelorhiza* reported here is the oldest reliable macrofossil evidence of Paullinieae. Fossil leaves from the Eocene of North America previously attributed to *Cardiospermum* and *Serjania* likely belong to Sapindaceae, but are not reliable occurrences of Paullinieae. Our findings support the conclusion that diversification of the tribe was underway by at least 18.5–19 Ma (early Miocene) and that the climbing habit had evolved by that time.

**Supporting information**

**S1 Appendix** Folder containing the accession list, mrbayes infile.nex, mcc, map, allcompat, and accession list.

**S2 Figure** Transverse section of the paratype, UF 19391-63026

**S3 Figure** Plot of lianas and self-supporting woody dicots. Filled points are fossil axes from the Lirio East site classified as either climbers or self-supporters using logistic regression. We applied a conservative decision threshold of 0.95 for classifying lianas.

**S4 Appendix** Revised descriptions of the leaf architecture. Descriptions of *Bohlenia americana*, *Bohlenia insignis*, “*Cardiospermum*” coloradensis, “*Cardiospermum*” terminale, and “*Serjania*” rara.

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Figure 1. Native distribution of Paullinieae and fossil occurrences. Modern occurrence data from the BIEN database [45,46]. Red star indicates the location of the Lirio East fossil site where the fossil roots were collected. Fossil pollen occurrence codes: 1 = Serjania sp., upper Miocene Paraje Solo Formation [47,49]; 2 = Serjania sp. and Paullinia sp., lower-middle Miocene Méndez Formation [50]; 3 = Serjania sp. and Paullinia sp., upper Miocene Gatun Formation [49,51]; 4 = Serjania sp., Paullinia sp., and Cardiospermum sp., upper Eocene Gatuncillo Formation [48,52]. Occurrence data were extracted from BIEN ver. 4.1 database using the RBIEN package [46], supplemented with C. pechuelii data from GBIF [53]. Cardiospermum spp. distribution data follows native ranges determined by [54,55] (excluding controversial range in India).
Figure 2. Cambial variant and vessel characters in *Ampelorrhiza heteroxylon*

(A) XS of the stem showing diffuse-porous wood of the central cylinder (cc) and peripheral vascular strands (ps) in the external tissues. Arrow indicates the position of the smaller of two peripheral vascular cylinders. Specimen UF 19391-63016 XS peel 10. (B) Close up XS of the larger of two peripheral vascular strands. Specimen UF 19391-63016 XS peel 10. (C) XS of the smaller peripheral vascular strands. There is no pith. Specimen UF 19391-63016 XS peel 10. (D) Close up of A showing the primary vascular parenchyma. Specimen UF 19391-63016 XS peel 10. (E) TLS through the tall cells of the primary vascular parenchyma (center right), ray cells (center left) and juvenile wood (far left). UF 19391-63016 LS peel 16. (F) XS showing wide vessels (WV) and narrow vessels in long radial multiples (at arrow). Specimen UF 19391-63026 XS peel 6. (G) TLS showing coalescent pit apertures on the vessel wall. Specimen UF 19391-63016 LS peel 6. (H) TLS showing alternate polygonal pits on the vessel wall (at arrow). Specimen UF 19391-63016 LS peel 7. (I) TLS showing narrow vessels (NV) with oblique end walls, and wide vessels (WV) with simple perforation plates and end walls perpendicular to lateral walls (right arrow). Specimen UF 19391-63026 TLS peel 1. Scale bars: A = 3 mm; B = 1 mm; C, F, I = 200 µm; D, E = 500 µm; G, H = 100 µm.
Figure 3. Wood anatomy in *Ampelorhiza heteroxylon*.

(A) Tangential longitudinal section showing uniseriate pitting on the fiber walls. Specimen UF 19391-63016 LS peel 5. (B) Tangential longitudinal section showing axial elements including narrow vessels and uniseriate rays (at arrow). Specimen UF 19391-63016 LS peel 1. (C) Radial longitudinal section showing ray cells against a vessel. Note the partially preserved vessel-ray parenchyma pitting similar in size to the intervessel pitting (at arrow). Specimen UF 19391-63016 LS peel 7. (D) Tangential longitudinal section showing uniseriate and biseriate rays (left arrow) and axial elements with crystals (right arrow). Specimen UF 19391-63016 LS peel 5. (E) Radial longitudinal section showing upright (at arrow), square, and procumbent ray cells. Specimen UF 19391-63026 LS peel 2. Scale bars: A = 70 µm; B = 150 µm; C = 40 µm; D, E = 100 µm.
Figure 4. Wood anatomy of the roots of extant Paullinieae species.

A–B: Neoformations forming peripheral vascular strands in *Serjania caracasana* (Jacq.) Willd. in transverse section. (A) Root macromorphology presenting a cambial variant. Arrows point to individual peripheral vascular strands. (B) Close up of the juncture of the central cylinder (cc) and a peripheral vascular strand (ps) with a c-shaped “pith” (i.e., primary vascular parenchyma of the root). (C) Secondary xylem of *Thinouia scandens* Triana & Planch. with vessel dimorphism in transverse section. Note the wide vessels (WV) are solitary or in tangential (upper arrow) or radial multiples (lower arrow), while the narrow vessels (NV) are in longer radial chains. (D) Primary vascular parenchyma in the center of the diarch roots (arrows towards protoxylem poles) of *S. caracasana* in transverse section. (E) Alternate intervessel pits (lower arrow) and those with coalescent apertures (upper arrow) in *S. caracasana* in tangential longitudinal section. (F) Prismatic crystals in the axial parenchyma (*) of *S. caracasana* in macerated material. Scale bars: A = 0.5 cm, B = 1 mm, C = 250 µm, D = 100 µm, E = 70 µm, F = 50 µm. *prismatic crystals in axial parenchyma.
Figure 5. Leaf fossils previously assigned to Paullinieae.

(A) “Serjania” rara MacGinitie from the Bridger Formation, Blue Rim site, Sweetwater County, Wyoming, UF 15761S-57786. (B) “Serjania” rara MacGinitie from the Bridger Formation, Blue Rim site, Sweetwater County, Wyoming, UF 15761N-61430. (C) Paratype of “Serjania” rara MacGinitie from the Aycross Formation, Kisinger Lakes site, northwestern Wyoming (Pl 25, Fig 3 in [74]), UCMP PA 108, 5698. (D) Hypotype of “Cardiospermum” coloradensis (Knowlton) MacGinitie from the Green River Formation, west of Wardell Ranch site, Colorado (Pl 22, Fig 3 in [81]), UCMP PA 321, 20593. Arrow indicates marginal vein. (E) “Cardiospermum” coloradensis (Knowlton) MacGinitie from the Green River Formation in Rainbow, UT, UCMP PB02016, 201265. Arrow indicates marginal vein. (F) “Cardiospermum” terminale (Lesquereux) MacGinitie from the Florissant Formation in central Colorado, FLFO 10147. Scale bars = 1 cm.
Figure 6. Modern leaves for comparison with the putative Paullinieae fossils.
Cleared leaves from the National Cleared Leaf Collection (NCLC). (A) *Serjania rhombea* Radlk. (Coll.: W.H. Lewis, J.D. Dwyer, T.S. Elias, and R. Solís #72 (UC 1355158), 1966, Panama]. (B) *Cardiospermum halicacabum* L. [Coll.: R.D.A. Baylis #5080 (UC 1409568), 1972, South Africa]. (C) *Paullinia pinnata* L., NCLC 0012. (D) *Quercus nigra* L., NCLC 0215. (E) *Lycopersicum esculentum* L., NCLC 1640. (F) *Beauprea balansae* Brongn. & Gris, NCLC 6658. Scale bars = 1 cm.
Figure 7. Phylogeny of supertribe Paulliniodae.

(A) Majority rule consensus tree with all compatible groups ("allcompat") of supertribe Paulliniodae sensu Acevedo et al. [21], generated in MrBayes 3.2.7 from an anatomical and molecular combined dataset of 216 tips. Branch colors indicate posterior probabilities. The outermost black line indicates the tribe Paullinieae. Note the position of the fossil taxon *Ampelorrhiza* within Paullinieae indicated by the arrow and the dagger. (B) Summary tree showing the same topology, but pruned to show genera only, assuming all genera are monophyletic. Numbers above branches are posterior probabilities, dashes indicate genera represented by a single species in the "allcompat" consensus tree.