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Taxonomy and nomenclature of some mainland SE-Asian *Coeliccia* species (Odonata, Platycnemididae) using micro-CT analysis

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Abstract

The taxonomic status of some mainland Southeast Asian *Coeliccia* species is evaluated. The following synonymies are presented: *C. acco* is a junior synonym of *C. pyriformis*; *C. tomokunii* that of *C. scutellum*; *C.onoi* that of *C. cyanomelas. C. scutellum hainanense* is promoted to species level, *C. hainanense*. Redescriptions of the holotype of *C. pyriformis* and of the lectotypes of *C. scutellum* and *C. hainanense* are presented with illustrations. The male genital ligulae were examined by means of non-destructive X-ray micro-computed tomography (micro-CT) and subsequent 3D-reconstruction. The advantage of virtual types generated by micro-CT analysis, particularly for the examination of internal structures, is discussed.

Key words: *Coeliccia scutellum, hainanense, tomokunii, acco, pyriformis, cyanomelas, onoi*, new synonymy, new status, Micro-Computed Tomography Analysis, micro-CT, cybertype

Introduction

The genus *Coeliccia* Kirby, 1890, is the largest within the family Platycnemididae, comprising over 60 known species (Schorr & Paulson 2013). Species of the genus occur from Japan in the east to India in the west and southwards to Java. Since the last revision of the genus (Laidlaw 1932), which considered 27 species and one subspecies, more than 30 species have been described (e.g. Lieftinck 1940, Asahina 1984, 1997, Xu 2006, Do 2007, 2009). Among those are some synonyms, e.g. *Coeliccia megumii* Asahina, 1984, was recently placed in synonymy with *Coeliccia kazukoae* Asahina, 1984 (Kosterin 2011, see supplementary table 1 for a list of actual and potential synonyms). Recently Dow (2010) revised the *Coeliccia borneensis*-group of species from Borneo, and Steinhoff & Do (2013) reviewed four Vietnamese *Coeliccia* species. However, the status of many other species in the genus still remains unclear, particularly since some descriptions and drawings of *Coeliccia* species are of inadequate quality for reliable identification (cf. Asahina 1997). Recent morphological and genetic analyses suggest a paraphyly of the genus *Coeliccia* (Gassmann 2004, Dijkstra *et al.* 2014). Consequently, detailed redescription and illustration of the species are a prerequisite of a future comprehensive revision.

Here, we review the taxonomic status of some *Coeliccia* species that occur in mainland Southeast Asia and that have been described from Vietnam and southern China. Since the type specimens of the species described by Asahina (1997) from Vietnam are not accessible and may be lost, our re-evaluation is based on the original descriptions and on the investigation of specimens collected later at the type localities or at nearby sites. For those cases for which type specimens are available, we applied X-ray micro-computed tomography (micro-CT) to inspect and illustrate the shape of the male genital ligulae. This approach pays tribute to the uniqueness of the holotype and the often very small number of paratypes by avoiding the extraction of the ligulae from the abdomens (cf. Orr and Hämäläinen 2013). Micro-CT has enhanced research on insect anatomy considerably since it offers a non-destructive way of scrutinizing and visualizing internal morphological characters (e.g. Beutel & Friedrich 2008, Friedrich *et al.* 2013). Micro-CT has been used for anatomical and phylogenetic research on Odonata (e.g. Blanke *et al.* 2012, 2013, 2015 Büsse *et al.* 2013, 2015, Büsse & Hörnschemeyer 2013, McPeek *et al.* 2010,

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Willkommen *et al.* 2015). Although micro-CT requires access to high end imaging facilities and is costly, the usefulness of tomographic "cybertypes" is widely acknowledged (Faulwetter *et al.* 2013, Michalik *et al.* 2013, Simonsen & Kitching 2014). Here, we assess the practicability of micro-CT as a tool for taxonomic research on Odonata.

Methods

All specimens were examined and documented using a Zeiss Discovery V20 stereo microscope with a Zeiss MCr camera and Axiovision 4.8 software. Editing of images and assembly of figure plates was performed using Gimp 2.8.2, Adobe Photoshop CS3 and Adobe Illustrator CS3 (Adobe Systems Inc., San José, USA).

Morphological investigations of male genital ligulae were performed using X-ray micro-computed tomography (micro-CT). In particular, we used an optical laboratory-scaled X-ray microscope (Zeiss XradiaXCT-200), which entails a two-stage magnification (geometric and optical magnification). (Technical Note on Resolution of a 3D X-ray Microscope, Carl Zeiss Microscopy GmbH 2013). Scans were performed with a 10x objective lens unit and with the following settings: 40 kV voltage / 4 W power, 360° rotation and exposure times between 10 and 17s, resulting in scan times of about 5 h and a 1.8–1.9µm pixel size. Tomography projections were reconstructed using XMReconstructor (Carl Zeiss Microscopy GmbH), resulting in image stacks (TIFF format). The image stacks of the investigated type material are stored at the BMNH (http://dx.doi.org/10.5519/0006955). All scans were performed using Binning 2 for noise reduction (summarizing 4 pixels) and subsequently reconstructed with full resolution (using Binning 1). The 3D-visualization of image stacks was performed using the software AMIRA 5.4.5 and AMIRA 5.6.0 (Visualization Science Group, FEI, www.vsg3d.com).

In order to achieve a high quality of the scans the detector should be as close as possible to the rotating sample. The needle of the pinned specimens was fixed in a piece of polystyrene that was clamped in a sample holder (Fig. 1A). Unpinned specimens were glued (super glue "Ultra Gel", Pattex) by the apical part of the mesepisternum onto a plastic Q-tip (Fig. 1B). After the scan, the glue can be removed with no damage to the specimen, although a shiny mark might remain. See Supplementary Figures 1–5 for interactive 3D visualizations of the genital ligulae. Interative 3D PDF's were created using Adobe Acrobat 9.0.

The terminology used follows Fraser (1956) and Garrison *et al.* (2010); terminology for wing venation follows Riek and Kukalová-Peck (1984).

Abbreviations in the text used as follows:

S1–10	abdominal segments 1–10
Abd	abdomen
Fw	forewing
Hw	hindwing
Px	postnodal cross vein
Pt	pterostigma
BMNH	Natural History Museum, London, UK
RMNH	Naturalis Biodiversity Center, Leiden Netherlands (Rijksmuseum van Natuurlijke Histoire).

Taxonomy

Coeliccia scutellum Laidlaw, 1932

Coeliccia tomokunii Asahina, 1997 has been considered a junior synonym of *C. scutellum* Laidlaw, 1932 (Wilson & Reels 2001). Asahina (1997: 24) indicated this possibility in his original description of *C. tomokunii* and suggested that "...a careful comparison of the type specimen is needed between the two species." In order to test this possible synonymy we compared the lectotype of *C. scutellum* with specimens that were collected near the type locality of *C. tomokunii,* since the type specimens of *C. tomokunii* are not accessible and may be lost.

Descriptions and illustrations of specimens are provided and compared with the original descriptions by Laidlaw (1932) and Asahina (1997). Laidlaw (1932) gave only a short description and a rough sketch of the thoracic markings of *C. scutellum*, whereas Asahina's (1997) description includes illustrations of the head, thorax and anal appendages of *C. tomokunii*.

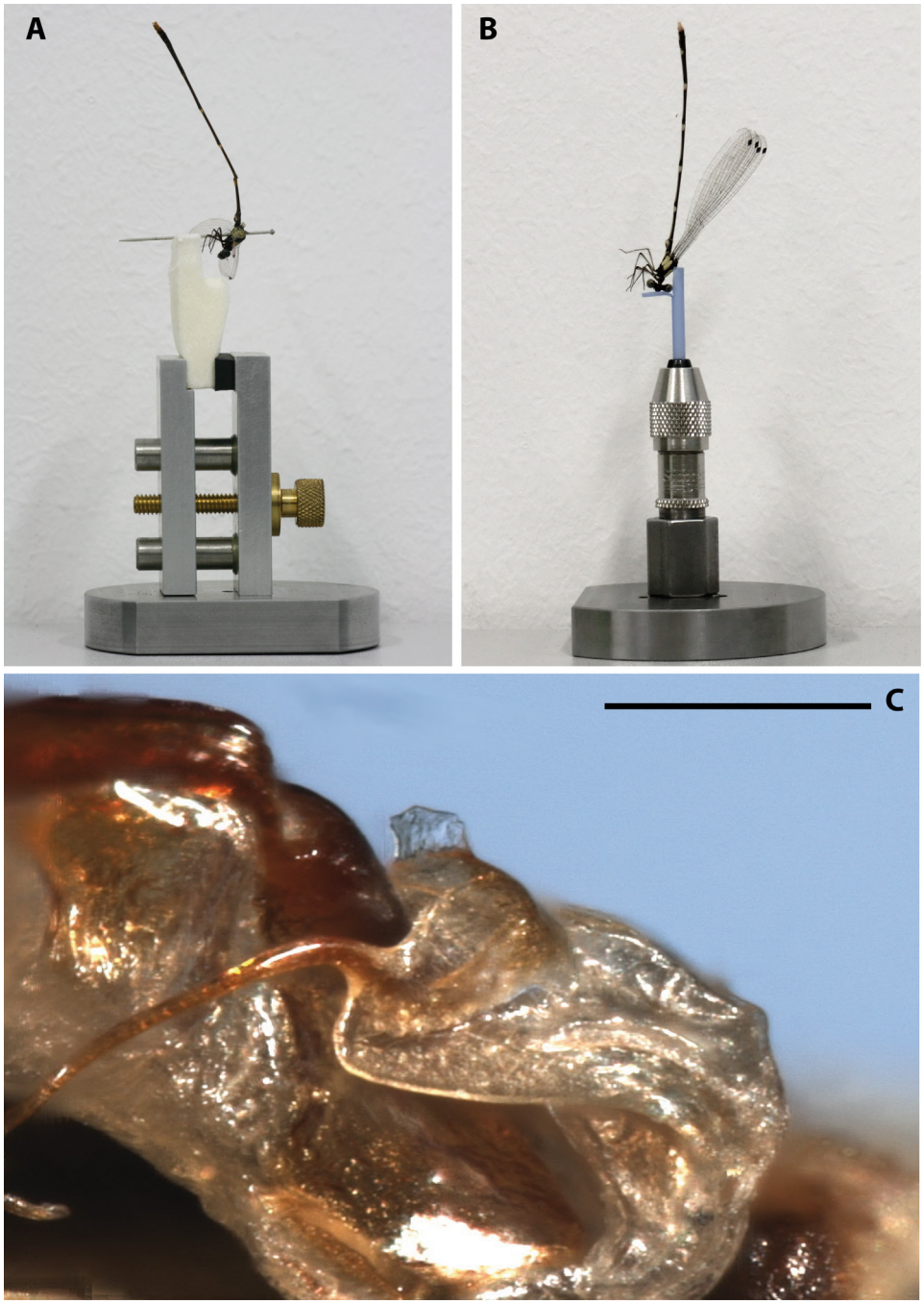

FIGURE 1. Mounting methods and detail of genital ligula. **A** Pinned specimen (*Coeliccia scutellum*) mounted for micro-CT scan, **B** papered specimen (*Coeliccia scutellum*) mounted for micro-CT scan, **C** macro-photograph (Zeiss MCr Camera) of *C. scutellum* genital ligula, showing thinness of flaps. *Scale bar:* 250µm.

Material examined. Type material: 1♂ Lectotype: Bao Ha, Tonkin (Vietnam), 20.04.1924, leg. H. Stevens [BMNH, NHMUK 010266912].

Other material: Total 6♂: 1♂ Mt. Tam Dao, Vinh Phu Province, northern Vietnam, 1994, leg. M. Hämäläinen [RMNH]. 1♂ "Stream below Thac Bac" Tam Dao, Vinh Phu Province, northern Vietnam, 26.06.2008, leg. M. Hämäläinen [RMNH]. 1♂ same locality, 28.06.2008, leg. M. Hämäläinen [RMNH]. 3♂ "Rhododendron & Five-lakes trail" Bach Ma National Park, Thua Tien Hue Province, central Vietnam, 15–18.06.2008, leg. M. Hämäläinen [RMNH].

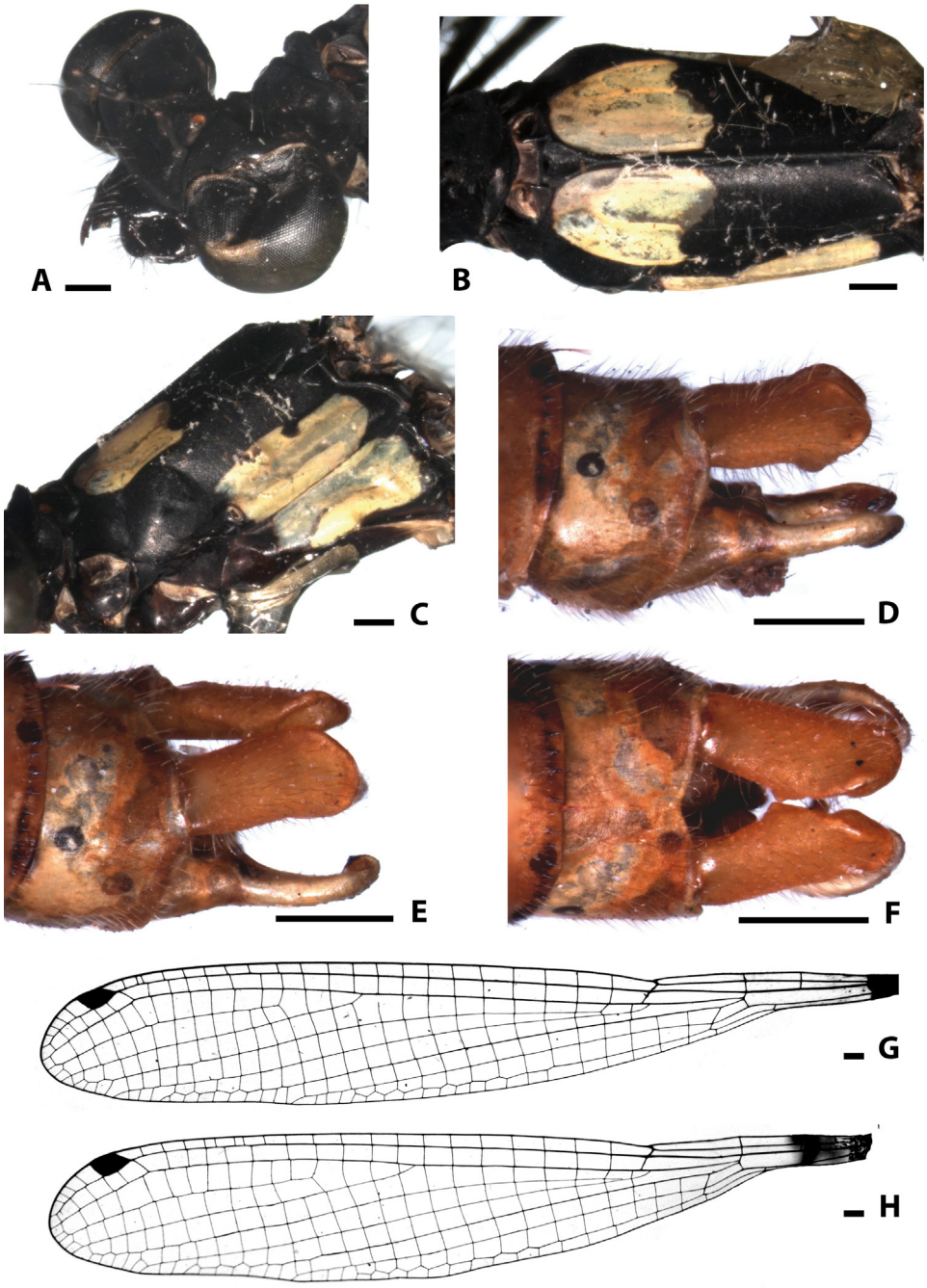

FIGURE 2. *Coeliccia scutellum* Lectotype. **A** head dorsolateral, **B** prothorax and thorax dorsal, **C** prothorax and thorax lateral, **D** anal appendages lateral, **E** anal appendages dorsolateral, **F** anal appendages dorsal, **G** left Fw, **H** left Hw. *Scale bars:* 500µm.

Description of the lectotype. Head (Fig. 2 A): Completely black except for diffuse greyish patches reaching out apically from the ocelli; typical postocular spots only just visible, the coloration faded away almost entirely. Prothorax (Fig. 2 B–C): All black, posterior lobe slightly raised.

Synthorax (Fig. 2 B–C): Black dorsally, with two big yellow markings (Fig. 2B). Synthorax laterally black with two big yellow markings, the lower one covering most of the metepimeron, the upper one covering the posterior part of the metepisternum up to the metathoracic spiracle, dorsally reaching slightly onto the mesepisternum. A small but distinct black spot near the upper margin of the metepisternal yellow marking; mesepisternum black.

Wings (Fig. 2 G–H): Hyaline with black Pt, covering nearly two cells in Fw and Hw. 21 Px in Fw, 20 Px in Hw. RP2 arising slightly proximal to Px 10 in Fw, between Px 7 and Px 8 in Hw. IR1 arises at Px 13 in Fw, and at Px 11 in Hw. IR2 arises slightly distal to subnodus in all wings.

Abdomen: Slender, black with whitish lateral spots on S3–6.

Anal appendages (Fig. 2 D–F): Paraprocts slightly overtopping cerci in length. Cerci with small, medially directed spine on upper inner border; followed dorsoapically by a rounded elevation, and with distinct ventromedial tooth arising subapically. This tooth is difficult to see in the lectotype, as the cerci are turned so that the tooth is rather directed inwards.

Genital ligula (Fig. 5 A–B, Supplementary Fig. 1): First segment simple with distal bend; second segment curved with well-developed inner fold, without terminal fold; third segment flat, median part distinctly raised, with two recurved flagella arising medially from raised part, bordering first segment.

Measurements (mm): Lectotype: Total length: 49, Abd.: 42, Fw/Hw (left): 21.

Measurement ranges of the six studied specimen collected near the type locality: Total length: 55–61, Abd.: 47–52, Fw (left): 29–34, Hw (left): 29–34.

Variation. Head (Fig. 3 A): Specimens from near the type locality show more extensive whitish coloration reaching out from the lateral ocelli towards the antennal bases, which have a whitish base; postocular spots distinct, yellowish white.

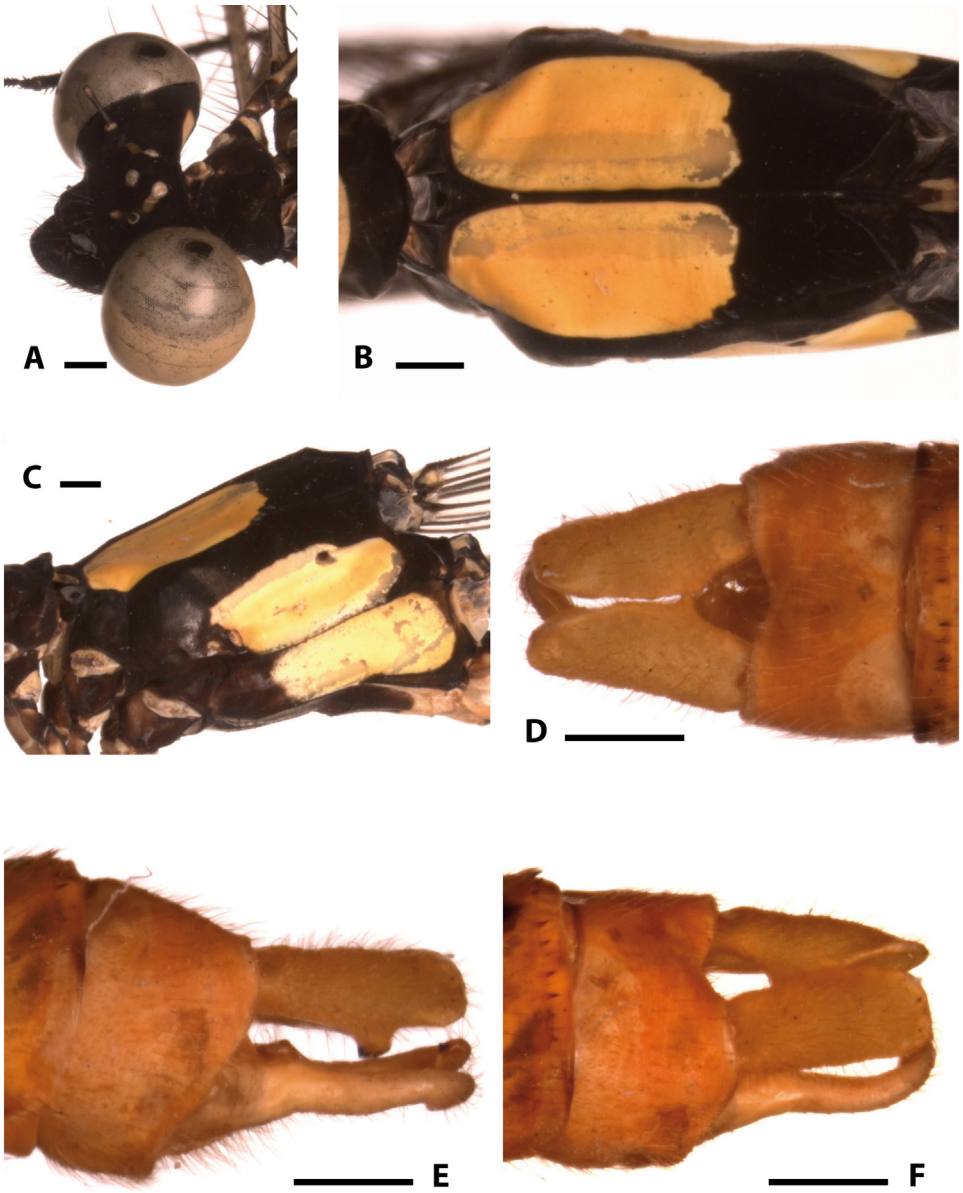

FIGURE 3. *Coeliccia scutellum* Tam Đảo, Vietnam. **A** head dorsolateral, **B** thorax dorsal, **C** thorax lateral, **D** anal appendages dorsal, **E** anal appendages lateral, **F** anal appendages dorsolateral. *Scale bars:* 500µm.

Synthorax (Fig. 3 B–C): Lateral yellow markings of the specimens from near the type locality agree well with the lectotype, but there is great variation in the extent of the two dorsal, escutcheon-shaped spots. In some specimens they cover about one third of the dorsal part of the synthorax as in the lectotype; in other specimens the spots cover up to two thirds of the dorsal synthorax (Fig. 3 B–C). The coloration, described by Laidlaw (1932: 22) as "…citron or sulphur-yellow…" also varies in the specimen from the type locality; some specimen have citron markings as in the lectotype, while in others the markings are of a rather deep golden yellow color (Fig. 3 B–C).

Anal appendages (Fig. 3 D–F): In some of the other specimens examined, the anal appendages dried in another position than in the lectotype, so that the ventromedial tooth is directed straight downward and the small spine is directed rather obliquely inward (Fig. 3 D–F). Asahina (1997: 23) did not describe the anal appendages for *C. tomokunii* but mentioned that the superior appendages are "provided with inflated head…". Depending on the position of these appendages, this impression may arise from the rounded dorsoapical elevation.

Genital ligula (Fig. 5 C–D, Supplementary Fig. 2): All specimens from near the type locality with two small thin flaps arising laterally from raised median part of segment three, posterior of origin of flagella (Fig. 1 C, 5 C–D). Flaps missing in the lectotype.

Remarks. The specimens of *Coeliccia scutellum* studied show rather strong variation in coloration, size and shape of dorsal markings. In order to visualize this variability, we illustrate a specimen that is most different from the lectotype in all mentioned characters (Fig. 3). The genital ligula of all examined specimens, differs from the genital ligula of the lectotype in having two thin lateral flaps on segment three (Fig. 1 C, 5 C–D). The lectotype is the only specimen without flaps on the genital ligula, although the shape of the ligula is otherwise consistent with that found in the other specimens. Since there are no other structural differences between the lectotype and the other examined specimens, it seems possible that the flaps have eroded in the lectotype. Alternatively, within the 70 years that passed between the collection of the lectotype and the collection of the other specimens examined the genital ligula might have changed due to sexual selection or genetic drift. It seems also possible that there is variation in the shape of the genital ligula, with the lectotype without flaps representing the extreme end of the variability.

As the somatic and genital variability is strong between lectotype and all other examined specimens, we suggest that *C. tomokunii* is synonymous with *C. scutellum*. Investigating the variability in a long series of *C. scutellum*, in particular the assessment of whether there is continuous variation in flap size or bimodal distribution, would help to clarify the taxonomic status. We propose the following synonymy:

Coeliccia scutellum Laidlaw, 1932

Syn. *Coeliccia tomokunii* Asahina, 1997, **syn. nov.**

Coeliccia hainanense Laidlaw, 1932, stat. nov.

Laidlaw (1932) gave a short, unillustrated description of 4 specimens which were collected in Hainan and which he considered to represent a subspecies of *C. scutellum.* Here, we redescribe the lectotype of *C. hainanense* including photos of head, thorax, anal appendages and micro-CT reconstructions of the genital ligula. Distinguishing characters of the lectotypes of *C. hainanense* and *C. scutellum* are discussed.

Material examined. 1♂, *Coeliccia scutellum hainanense*, Lectotype: Mt. Wouchi, Hainan, 19.5.03, 1911–288 [BMNH, NHMUK 010266913].

Description. Head (Fig. 4 A): Black; genae, mandible bases, distal ends of first antenna segments and small spots between lateral ocelli and antenna bases whitish.

Prothorax (Fig. 4 B–D): All black, but with two small, lateral yellow spots on posterior lobe.

Synthorax (Fig. 4 B–D): Dorsum with two big yellow spots (Fig. 4 D). Yellow lateral markings extend over nearly all of metepisternum and metepimeron (Fig. 4 B).

Wings (Fig. 4 G–H): Hyaline with black Pt, covering nearly two cells in Fw and about 1½ cells in Hw. 17 Px in both Fw, 18 Px in left, 16 in right Hw. RP2 arising slightly proximal to Px 8 in both Fw, at Px 7 in left Hw and between Px 6 and Px 7 in right Hw. IR1 arises at Px 12 in left Fw, slightly distal to Px 11 in right Fw, at Px 9 in left and at Px 10 in right Hw. IR2 arises slightly distal to subnodus in all wings.

Abdomen: Long and slender; black with cream white ventral part and lateral white spots at the end of S3–6. Sides of S1–2 cream white.

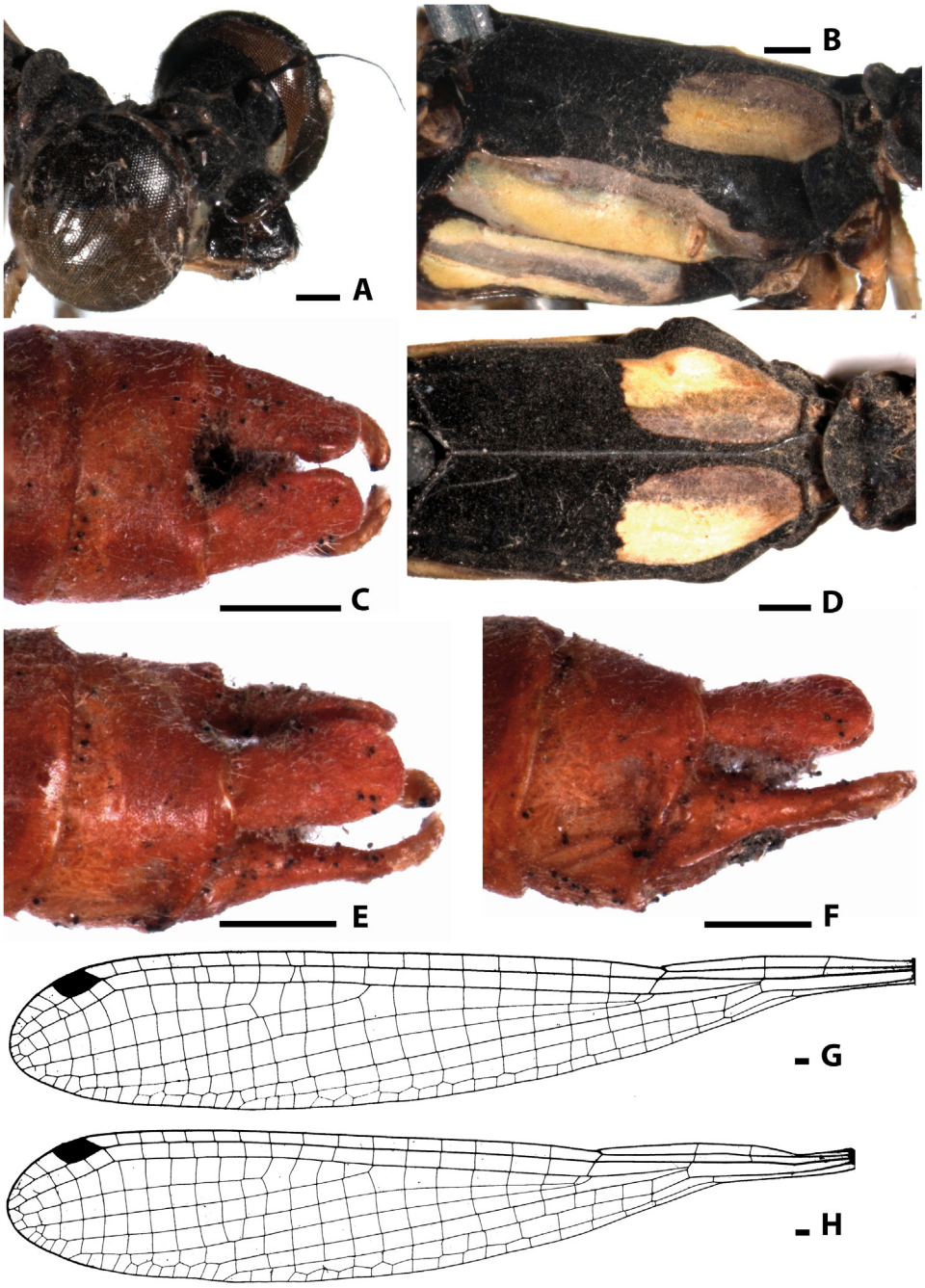

FIGURE 4. *Coeliccia hainanense* Lectotype. **A** head dorsolateral, **B** prothorax and thorax dorsolateral, **C** anal appendages dorsal, **D** prothorax and thorax dorsal, **E** anal appendages dorsolateral, **F** appendages lateral, **G** left Fw, **H** left Hw. *Scale bars:* 500μm.

Anal appendages (Fig. 4 D–F): Golden yellow. Cerci rather stout and club-shaped; paraprocts longer than cerci, slender and curved.

Genital ligula (Fig. 5 E–F, Supplementary Fig. 3): First segment simple, distally slightly curved in lateral view. Second segment broad and curved, nearly concealing spine-like internal fold from lateral view, without terminal fold; third segment with prominent apical fold and two curved, laterally arising flagella at apex.

Measurements (mm): Total length: 56, Abd.: 48, Wingspan: 60, Fw (right): 28, Hw (right): 29

Remarks. The structural differences in the genital ligula suggest that the *C. hainanese* specimen represents a distinct species rather than subspecies of *C. scutellum*. However, these two species may be closely allied.

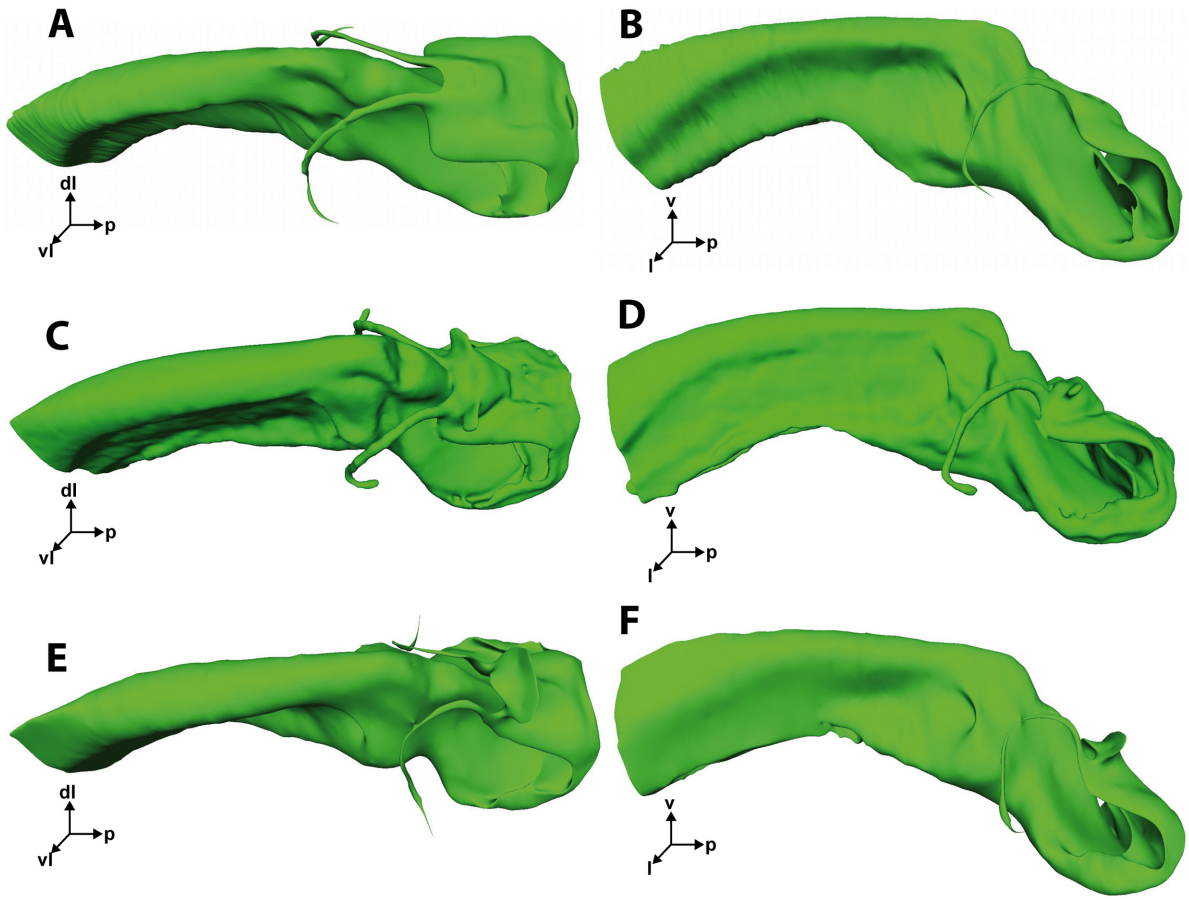

FIGURE 5. Genital ligulae as reconstructed from micro-CT (*orientation bars:* dl dorsolateral, l lateral, p posterior, v ventral, vl ventrolateral). **A**–**B** Genital ligula of *C. scutellum* lectotype **C**–**D** genital ligula of *C. scutellum* from Tam Đảo, Vietnam **E**–**F** genital ligula of *C. hainanense* lectotype.

In addition to several photos taken by the first author (Phong Nha-Kẻ Bàng National Park, Quảng Bình, Vietnam and Sơn Trà, Đà Nẵng, Vietnam), we have seen photos of different individuals of *C. scutellum* from various locations in Vietnam taken by Do Manh Cuong (Hòn Bà, Bà Rịa-Vũng Tàu) Sébastien Delonglée and Tom Kompier (both Tam Đảo, Vĩnh Phúc). Furthermore, we examined photos of some individuals of *C. hainanense* taken by Graham Reels and Shanlian Mo from Yinggelin Nature Reserve, Nanlin Nature Reserve, Hui Shan and Mount Wuzhishan in Hainan (Fig. 6 A–H). This additional material shows that the extent of synthoracic markings varies within both *C. scutellum* and *C. hainanense*. The synthoracic markings of some individuals of *C. scutellum* look almost exactly like those of the lectotype *C. hainanense*; in one specimen the dorsal spots cover about two thirds of the synthorax, more than in any specimen of *C. hainanense* that we have examined. The coloration of the distal abdominal segments in all individuals of *C. scutellum* examined is restricted to S9 and S10 or often only to S10. Thus, the coloration of S8–10 and the considerable larger size seem to be the only characters to distinguish *C. hainanense* from *C. scutellum* in the field. One of the photographs from Hainan shows an immature male that differs from the adults by having four dorsal spots on the synthorax (Fig. 6 C). This interesting difference in the colour pattern between individuals of different age has been shown earlier in other *Coeliccia* species (e.g. Laidlaw 1932, Kosterin & Vikhrev 2009, Kosterin 2011, Steinhoff & Do 2013). More specimens of *C. hainanense* need to be examined for a better understanding of age-dependent variation within the species.

Due to differences in the genital ligula, body size and coloration we propose to promote *C. hainanense* to species level.

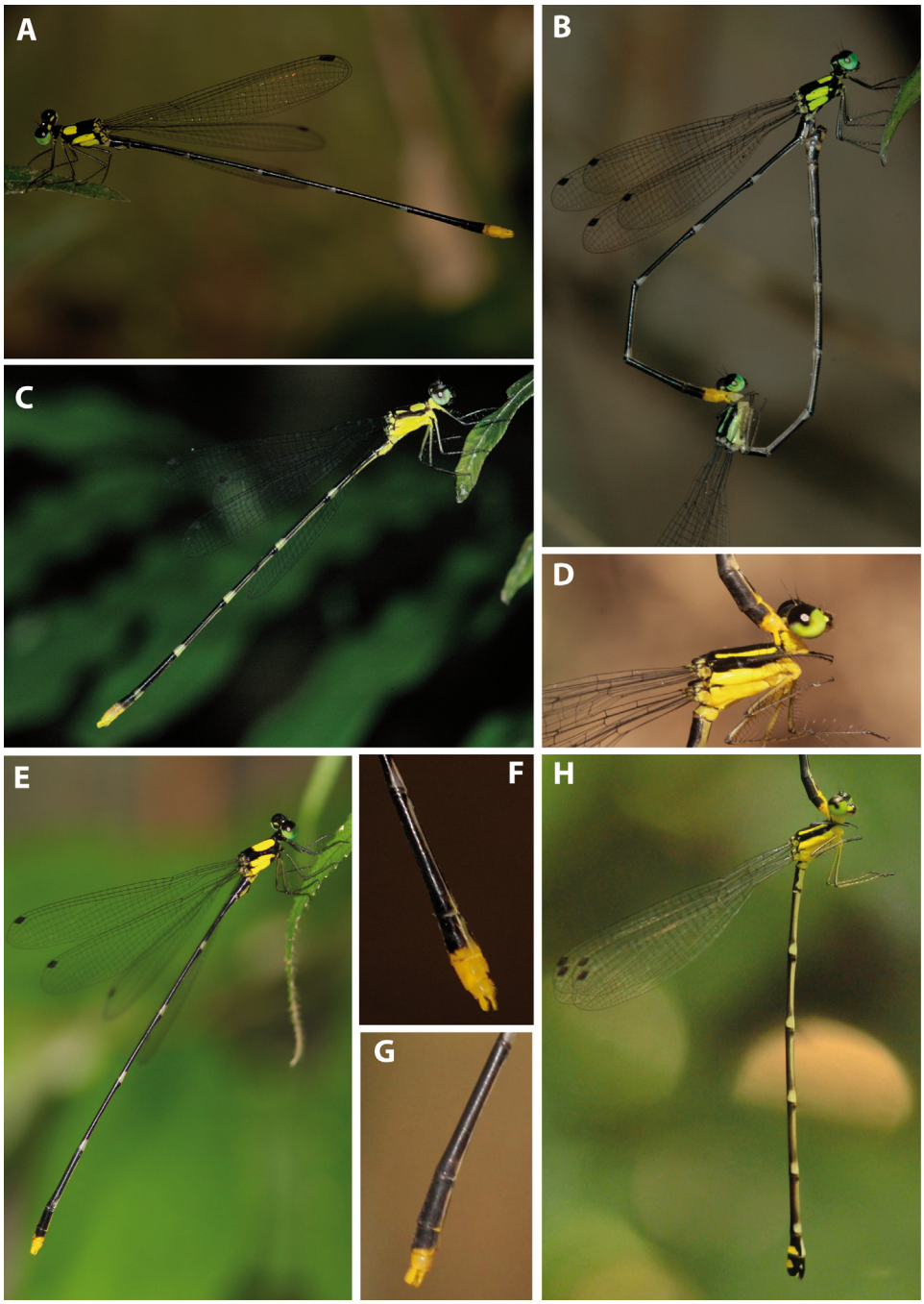

FIGURE 6. Photos in life of *Coeliccia hainanense* and *Coeliccia scutellum*. **A** *Coeliccia hainanense,* male, Mount Wuzhishan, Hainan, China. Photo by Shanlian Mo). **B** *Coeliccia hainanense,* copula, Hui Shan, near Wanning, southeastern Hainan, China. Photo by Graham Reels. **C** *Coeliccia hainanense,* immature male, Nanlin Nature Reserve, near Wanning, southeastern Hainan, China. Photo by Graham Reels. **D** *Coeliccia scutellum,* female in tandem, Tam Đảo, northern Vietnam. Photo by Tom Kompier. **E** *Coeliccia scutellum,* male, Tam Đảo, northern Vietnam. Photo by Tom Kompier. **F** *Coeliccia hainanense,* male S7–10 and anal appendages, Mount Wuzhishan, Hainan, China. Photo by Schanlian Mo. **G** *Coeliccia scutellum,* male S7–10 and anal appendages, Tam Đảo, northern Vietnam. Photo by Tom Kompier. **H** *Coeliccia scutellum,* female in tandem, Tam Đảo, northern Vietnam. Photo by Sebastién Delonglee.

Coeliccia pyriformis Laidlaw, 1932

As pointed out by Dow (2011a), the original description of *Coeliccia pyriformis* by Laidlaw (1932) lacks drawings as well as a sufficiently detailed description. Here, we redescribe the holotype and discuss inaccuracies in the original description. The potential synonymy of *C. pyriformis* and *C. acco* Asahina, 1997, is discussed.

Material examined. 1♂ Holotype: "Bao Ha, Tonkin", 21. July 1924, leg. H. Stevens [BMNH, NHMUK 010266914].

Description. Head and prothorax (Fig. 7 A): Head black, anteclypeus, antefrons and genae cream white; two pale spots between lateral ocelli and base of antennae. Prothorax entirely black, hindlobe slightly raised.

Synthorax (Fig. 7 B–C): Black with grey-purplish markings that are nearly faded away. Dorsally with two inward curved stripes (Fig 7 C); mesepimeron mostly black, metepisternum and metepimeron covered by large markings.

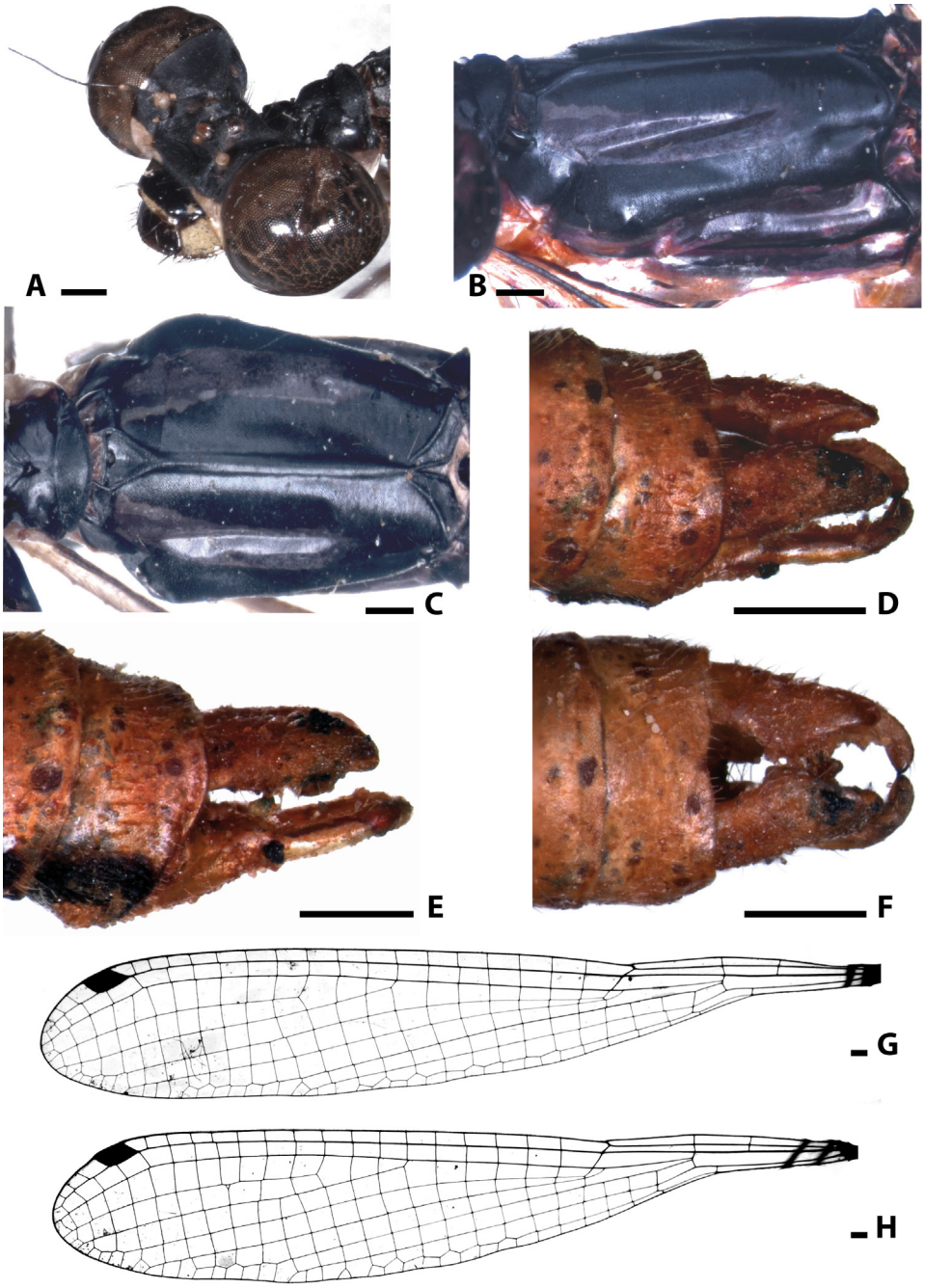

FIGURE 7. *Coeliccia pyriformis* Holotype. **A** head dorsolateral, **B** prothorax and thorax dorsolateral, **C** prothorax and thorax dorsal, **D** anal appendages dorsolateral, **E** anal appendages lateral, **F** anal appendages dorsal, **G** left Fw, **H** left Hw. *Scale bars:* 500µm.

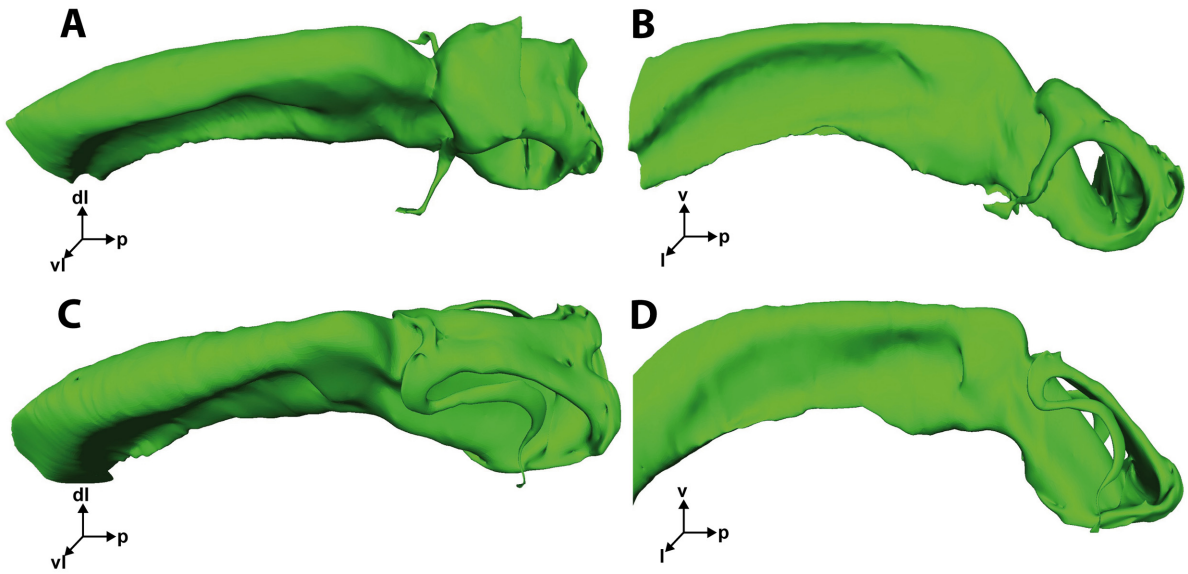

FIGURE 8. Genital ligulae as reconstructed from micro-CT (*orientation bars:* dl dorsolateral, l lateral, p posterior, v ventral, vl ventrolateral). **A**–**B** Genital ligula of *C. pyriformis* holotype, **B**–**C** genital ligula of *C. cyanomelas.*

Wings (Fig. 7 G–H): Hyaline, with black Pt, covering about 1¼ cells. 16 Px in both Hw, 17 Px in left Fw and 18 Px in right Fw. RP2 arising at Px 6 in both Hw, at Px 7 in left Fw and at Px 8 in right Fw. IR1 arises slightly distal to Px 10 in both Fw and slightly distal to Px 9 in both Hw. IR2 arises distal to subnodus and is inserted at subnodal vein.

Abdomen: Black, long and slender; ventral part of the abdomen cream white, the white extending upwards at the end of the segments, forming lateral spots that are visible from S3–7, the spot at S7 being notably smaller (and not visible dorsally) than those on S3–6. Segments 9 and 10 ochre.

Anal appendages (Fig. 7 D–F): Ochreous, cerci slightly shorter than paraprocts. Cerci with ventromedial tooth that is rather difficult to see from lateral view, obvious from dorsolateral and dorsal views.

Genital ligula (Fig. 8 A–B, Supplementary Fig. 4): First segment simple, distally curved; second segment with internal, but without terminal fold; third segment with two laterally placed flagella. Ends of the flagella turned inwards and thickened in lateral view.

Measurements (mm): Total length: 42, Abd.: 36, Wingspan: 43, Fw/Hw (right): 21.

Remarks. The original description of the holotype of *C. pyriformis* (Laidlaw 1932) does not mention the pale spots between lateral ocelli and base of antennae. Additionally, Laidlaw (1932: 26) described two "...pyriform marks of pale blue…" dorsally on each side of the synthorax. He noted that these markings "...faded...the whole dorsum being uniformly black..." (Laidlaw 1932: 26) after a while. However, during the examination of the holotype, we noted that the markings are still clearly visible, when the specimen is viewed under good lighting. Furthermore, the markings on the synthorax do not have a pyriform shape but are rather simple inwardly curved stripes (cf. Fig. 11 A–C for photographs in life of *C. pyriformis*).

Laidlaw (1932: 26) declared that the superior appendages did not have any "...marked projection...". This is, however, not the case. There is a ventromedial tooth that is rather difficult to see from lateral view, but obvious from dorsolateral and dorsal view.

Comparison of the holotype of *C. pyriformis* with the original description of *C. acco* by Asahina (1997) and the recent redescription of this species, based on new material, by Steinhoff & Do (2013), shows that *C. acco* agrees with *C. pyriformis* in all diagnostic characters. Only the number of Px given for *C. acco* by Steinhoff & Do (2013) differ from the holotype *C. pyriformis*, which has 3 Px less in all wings. Therefore we propose the following synonymy:

Coeliccia pyriformis Laidlaw, 1932
Syn. *Coeliccia acco* Asahina, 1997, **syn. nov.**

***Coeliccia cyanomelas* Ris, 1912**

It has been suggested that *Coeliccia onoi* Asahina, 1997 might be a junior synonym of *Coeliccia cyanomelas* Ris, 1912 (Dow 2011b). To test the taxonomic status of these taxa, we present descriptions and illustrations of one *C. cyanomelas* specimen from Taiwan and one *C. onoi* specimen from its type locality in Vietnam (Fig. 10 A–F). In Taiwan, only two species of *Coeliccia* occur, namely *C. cyanomelas* and *C. flavicauda* Ris, 1912 (Wang 2000). A description of the specimen from Taiwan is provided, and differences from the original descriptions by Ris (1912) and Asahina (1997), and the specimen from Vietnam are pointed out. Ris (1912) gave only a very rough sketch of the anal appendages of *C. cyanomelas*, and Asahina (1997) provided rough sketches of head, thorax and anal appendages of *C. onoi*.

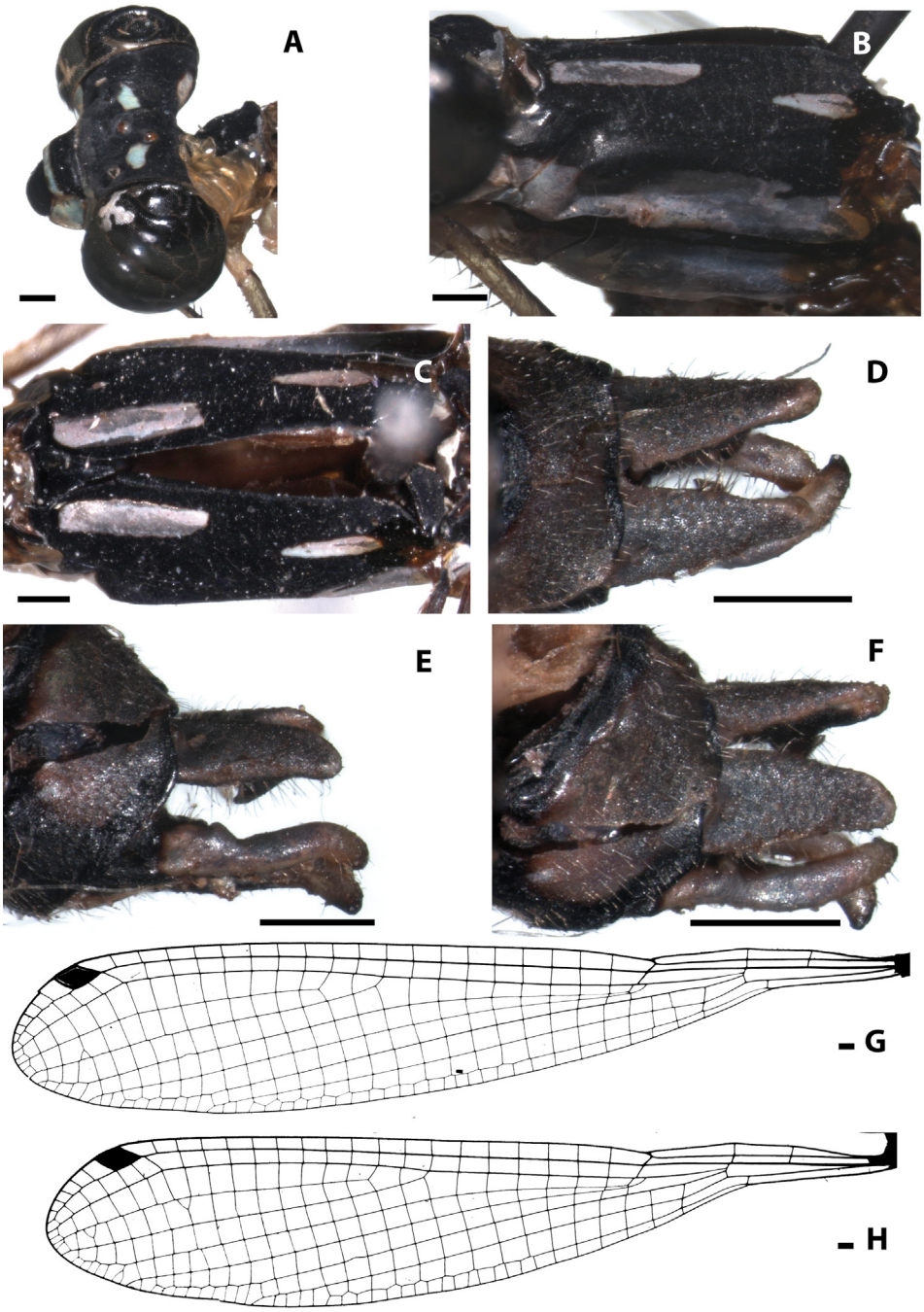

FIGURE 9. *Coeliccia cyanomelas* Taihanroku, Taiwan. **A** head dorsolateral, **B** prothorax and thorax dorsolateral, **C** prothorax and thorax dorsal, **D** anal appendages dorsal, **E** anal appendages lateral, **F** anal appendages dorsolateral, **G** left Fw, **H** left Hw. *Scale bars:* 500µm.

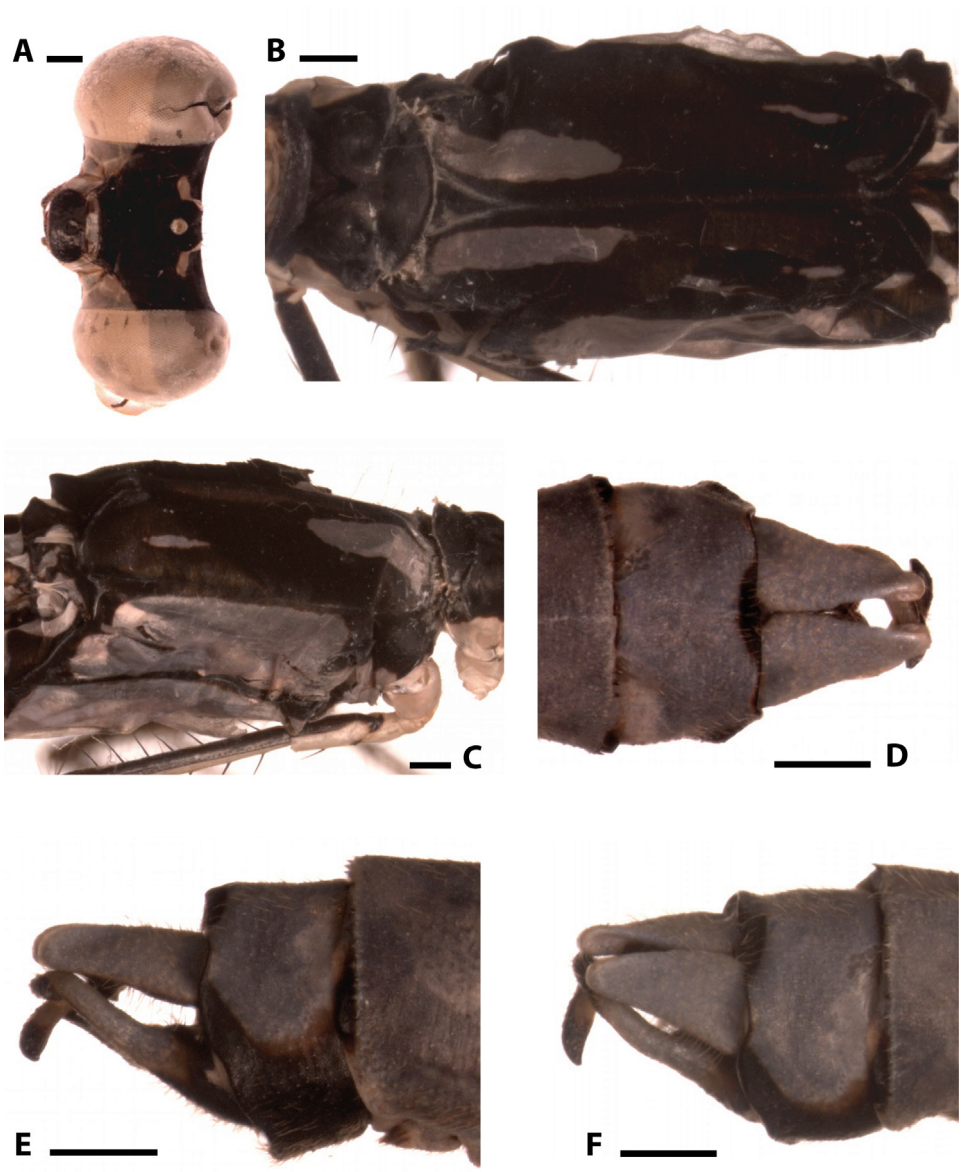

FIGURE 10. *Coeliccia cyanomelas* Tam Đảo, Vietnam. **A** head dorsal, **B** thorax dorsal, **C** thorax dorsolateral, **D** anal appendages dorsal, **E** anal appendages lateral, **F** anal appendages dorsolateral. *Scale bars:* 500μm.

Material examined. Total 2♂: 1♂ "Taihanroku, Formosa", 1968–70, leg. J. Cowley [BMNH, NHMUK 010266915]. 1♂ "small rocky streamlets on roadside to Tam Dao 2" Tam Dao, Vinh Phu Province, northern Vietnam, 27.06.2008, leg. M. Hämäläinen [RMNH].

Description. Head (Fig. 9A): Black with two distinct bluish white spots between lateral ocelli and antennal bases. Anteclypeus, antefrons and genae bluish white.

Prothorax (Fig. 9 A–C): Black, lobes procumbent; sides of prothorax bluish white.

Synthorax (Fig. 9 B–C): Dorsally black with two pairs of bluish grey marks, anterior ones larger and more oriented medially than posterior ones. Big bluish grey marking on metepisternum and metepimeron interrupted by thick black line on interpleural suture. Lower part of mesepimeron bluish grey, upper part black.

Wings (Fig. 9 G–H): Hyaline with blackish Pt. 20 px in Fw, 19 px in Hw. RP2 arising at px 9 in Fw and at px 7 in Hw. IR1 arises slightly distal to Px 11 in Fw and Px 9 in Hw. IR2 arises somewhat distal to subnodus in all wings.

Abdomen: Long and slender; black with lateral white spots at the ends of S3–7. Caudal third of S8, all of S9 and dorsal part and half of sides of S10 blue. Ventral and lower lateral parts of S10 black.

Anal appendages (Fig. 9 D–F): Cerci and paraprocts bluish grey, only base of paraprocts black. Paraprocts slightly overtop cerci in length. Cerci simple and straight with strong ventromedially directed tooth.

Genital ligula (Fig. 8 C–D, Supplementary Fig. 5): First segment simple, distally slightly curved; second segment with slight terminal fold and small internal fold; third segment narrow, resembling two broad coalesced flagella. Third segment with small apical fold and two thick flagella that arise at apex but are strongly recurved, positioned ventrolateral of third segment. Genital ligula of same shape in both examined specimens.

Measurements (mm): BMNH specimen: Total length: 49, Abd.: 41, Wingspan: 56, Fw/Hw (right): 26.

RMNH specimen: Total length: 50, Abd.: 44, Fw (right): 29, Hw (right): 28.

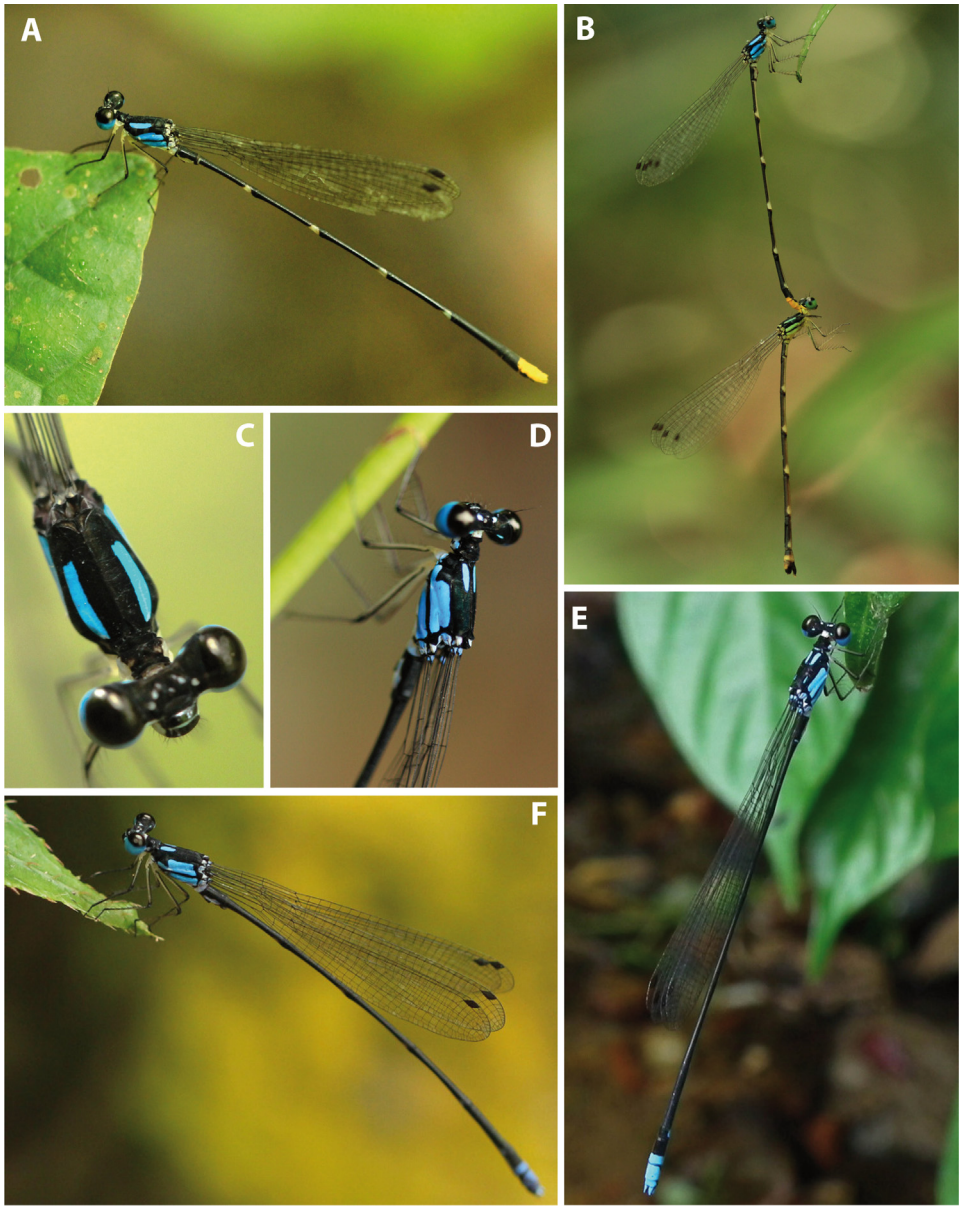

FIGURE 11. Photos in life of *Coeliccia pyriformis* and *Coeliccia cyanomelas*. **A** *Coeliccia pyriformis,* male, Tam Đảo, northern Vietnam. **B** *Coeliccia pyriformis,* tandem, Tam Đảo, northern Vietnam. **C** *Coeliccia pyriformis,* male thorax and head dorsal, Tam Đảo, northern Vietnam. **D** *Coeliccia cyanomelas,* male head and thorax dorsolateral, Tam Đảo, northern Vietnam. **E** *Coeliccia cyanomelas,* male with four dorsal synthorax markings, Tam Đảo, northern Vietnam. **F** *Coeliccia cyanomelas,* male with two dorsal synthorax markings, Tam Đảo, northern Vietnam. All photos by Sebastién Delonglee.

Remarks. There are only two differences between the specimens in the descriptions of *C. cyanomelas* by Ris (1912) and *C. onoi* by Asahina (1997). One is the coloration of the dorsal synthorax, which has two pairs of markings in the specimens examined by Ris (1912) but only one pair in the specimen examined by Asahina. The other difference is the hook-shaped margin of the black dorsal coloration on the anterior mesepimeron and mesepisternum, which is visible in Asahina's (1997) drawings and our specimen from Vietnam but less prominent in our specimen from Taiwan and the specimen examined by Ris (1912). Ris (1912: 66) described the black

coloration on the mesepimeron as "… buchtig begrenzt …" (indented); Asahina (1997: 26) found an abrupt widening of the mesepimeral black coloration "… at its lower 1/4 …" in his specimen. In our specimen from Vietnam and the drawing by Asahina (1997), this widening is hook-shaped and reaches well onto the metepisternum (Fig. 10 C). However, the specimen from Taiwan shows only a slight widening of the black coloration, which is not hook-shaped (Fig. 9 B).

We have seen several photos by Sébastien Delonglée, Do Manh Cuong and Tom Kompier of different *C. cyanomelas* individuals from northern Vietnam, which show a great variation in size and presence of the posterior spots on the dorsal synthorax. The individuals show: i) distinct spots, ii) small spots, or iii) no spots (cf. Fig. 11 D–F). Asahina (1997) only examined one male specimen, thus he could not be aware of the variability of the thoracic markings. Ris (1912) examined 3 males from Taiwan and 8 males from Guangdong province in southern China and does not mention any variation in the thoracic markings; thus the individuals from Vietnam with only one pair of spots and black hook-shaped markings on the mesepimeron and mesepisternum may represent a local variation of *C. cyanomelas*.

We examined one specimen from Vietnam and one from Taiwan, and most characters, including the genital ligula, strongly agree. We therefore propose the following synonymy:

Coeliccia cyanomelas Ris, 1912

Syn. *Coeliccia onoi* Asahina, 1997, **syn. nov.**

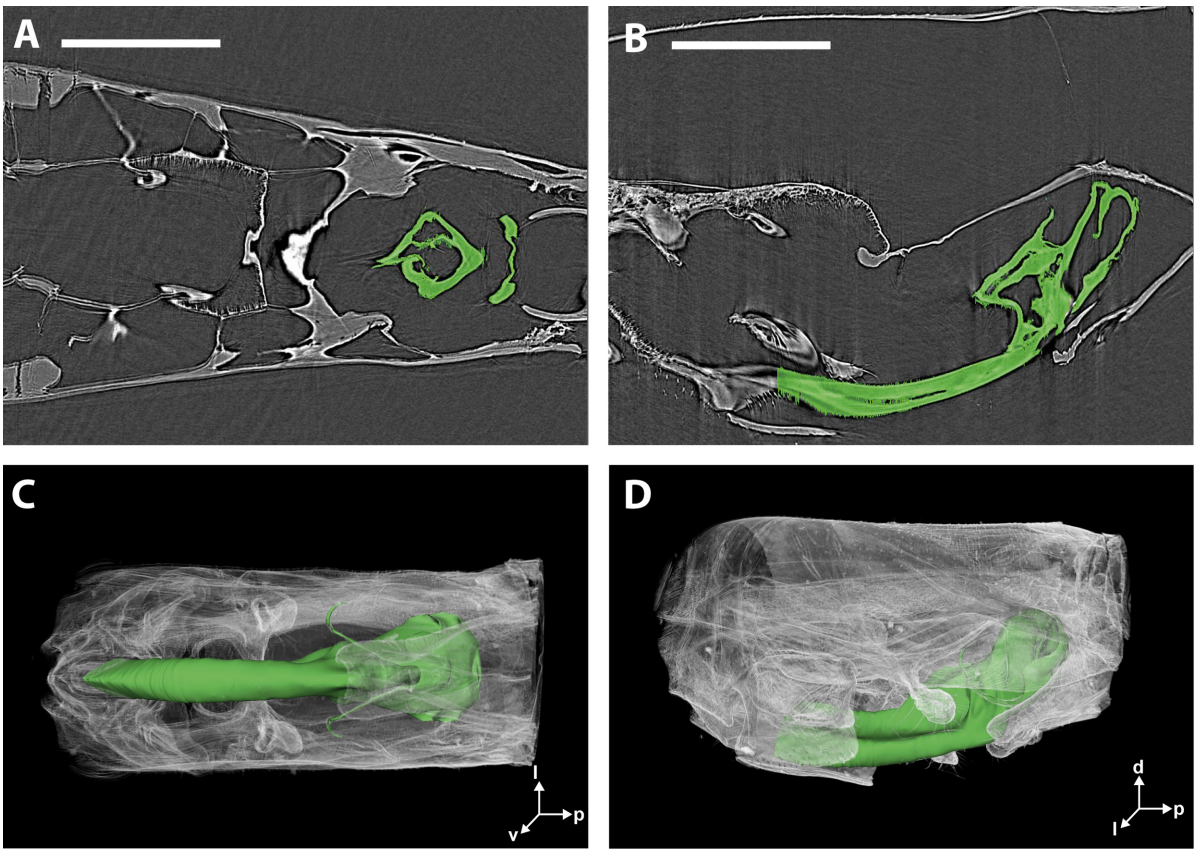

FIGURE 12. Virtual sections and volume rendering with micro-CT reconstruction of the genital ligula of *Coeliccia scutellum* (*orientation bars:* d dorsal, l lateral, p posterior, v ventral). **A** Virtual dorsal section from original image stack with genital ligula labeled in green, **B** Virtual sagittal section from original image stack with genital ligula labeled in green, **C** Transparent volume rendering of cuticle shows positioning of genital ligula within abdominal segment 2, ventral view, **D** Transparent volume rendering of cuticle shows positioning of genital ligula within abdominal segment 2, lateral view. *Scale bars:* 500µm.

Discussion

We confirm two synonyms, reveal a third and upgrade one subspecies to species level as a further step to clarify the

taxonomy of the genus *Coeliccia*. We like to emphasize the need to examine several specimens of a species to reveal the degree of variability in somatic and genital characters.

For the identification of species in many odonate groups it is a prerequisite to examine the secondary copulatory organ (genital ligula) of the males, which often is species specific. In old type material, however, the genital ligula often has never been examined or depicted (e.g. Laidlaw 1932, Asahina 1997). Since dissection is risky with old and precious specimens (Faulwetter *et al.* 2013), micro-CT Analysis represents a highly suitable approach for investigating type material. The risk of damage during mounting is negligible. The diagnostic morphological structures can be visualized with high quality and resolution (cf. Fig. 12), making conventional, potentially destructive dissections unnecessary. Furthermore, once a virtual type is available, including a stack of tomography images for delineation of additional characters, the type does not need to be re-examined for most taxonomic purposes.

It should be noted here that we explicitly do not argue in favor of an automated taxonomy as has been proposed by, e.g., Godfrey (2007), who claimed that taxonomy will become redundant once all information is available on the internet. Instead, we follow the arguments of Carvalho *et al.* (2007) and Faulwetter *et al.* (2013) in that we consider virtual type material important to enhance taxonomy. Taxonomy is the base of all systematic, evolutionary and phylogenetic research and thus a necessary and important discipline that will profit from the new technique. Furthermore, as pointed out by Simonsen & Kitching (2014), micro-CT scans cannot completely replace manual genitalia dissections, as they are needed to learn to know the internal structures and to validate the micro-CT reconstructions. Under these premises, we think that the quality and speed of taxonomic research in Odonata could be improved significantly by using micro-CT. This is especially true for dried museum specimens, in which only cuticular structures are preserved and micro-CT reconstructions can thus be done comparatively fast (cf. Fig. 12). Particularly, providing CT images of type specimens would help to protect the precious material and should become part of curatorial duties.

Acknowledgements

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TABLE S1. List of *Coeliccia* synonyms with notes on the current state of knowledge.

Species	Synonym(s)	Synonymized by	Remarks
C. didyma (Sélys, 1863)	*C. simillima* Laidlaw, 1917	Laidlaw (1931)	Laidlaw himself had some doubts; synonym also questioned by Lieftinck (1954 in footnote)
	C. loringae Laidlaw, 1932	Asahina (1985)	There are differences between *C. didyma* from Peninsular Malaysia and northern Thailand; *C. didyma* in the broad sense might be a composite (pers. comm. R. Dow)
C. renifera (Sélys, 1886)	*C. kuamaoensis* Singh & Baijal, 1964	Hämäläinen (1989)	
	Calicnemis [sic] *maheshi* Sahni, 1964	Hämäläinen (1989)	
	C. dierli St Quentin, 1970	Asahina (1985)	
C. flavostriata Laidlaw, 1918	*C. coomansi* Lieftinck, 1940	Dow (2010)	
C. membranipes Rambur, 1842	*Coeliccia silenta* (Hagen & Sélys, 1863)	Unclear origin of synonymy. Synonym mentioned in e.g. Lieftinck 1954	Close inspection of *C. membranipes* across Java and Sumatra, may lead to the reinstation of *C. silenta* (pers. comm. R. Dow)
C. kazukoae Asahina, 1984	*C. megumii* Asahina, 1984	Kosterin, 2011	
C. pyriformis Laidlaw, 1932	*C. acco* Asahina, 1997	This paper	
C. cyanomelas Ris, 1912	*C. onoi* Asahina, 1997	This paper	
C. scutellum Laidlaw, 1932	*C. tomokunii* Asahina, 1997	This paper	

FIGURE S1. Interactive 3D PDF of the genital ligula of the lectotype *Coeliccia scutellum* as reconstructed from micro-CT.

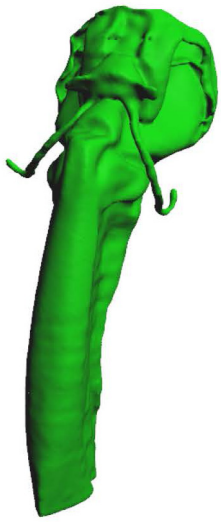

FIGURE S2. Interactive 3D PDF of the genital ligula of the *Coeliccia scutellum* from Tam Dao as reconstructed from micro-CT.

FIGURE S3. Interactive 3D PDF of the genital ligula of the lectotype *Coeliccia hainanense* as reconstructed from micro-CT.

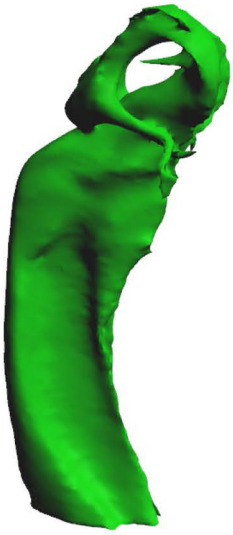

FIGURE S4. Interactive 3D PDF of the genital ligula of the holotype *Coeliccia pyriformis* as reconstructed from micro-CT.

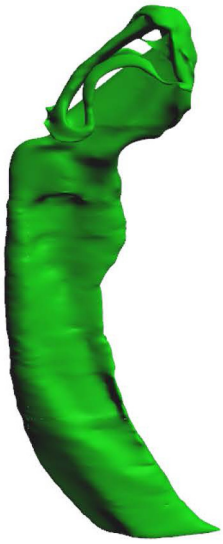

FIGURE S5. Interactive 3D PDF of the genital ligula of *Coeliccia cyanomelas* from Taiwan as reconstructed from micro-CT.