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Description of two new *Quadrastichus* (Hymenoptera: Eulophidae) reared from *Litchiomyia chinensis* (Diptera: Cecidomyiidae) on commercial lychee (*Litchi chinensis*; Sapindaceae) in Taiwan

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ABSTRACT

The lychee gall midge, *Litchiomyia chinensis* Yang and Luo (Diptera: Cecidomyiidae), invaded Taiwan in 2008. This fly induces blister-galls on the leaves of lychee, *Litchi chinensis* Sonn (Sapindaceae), and causes significant yield losses. At present, its natural enemy complex is largely undocumented; thus, the overall aim of ongoing research is to investigate the natural enemies on *L. chinensis* in different areas and seasons in Taiwan. We describe two species that parasitise this gall midge: *Quadrastichus lasallei*, **sp. n.** and *Quadrastichus johnlasallei*, **sp. n.** that demonstrate biocontrol potential of this pest.

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Introduction

The lychee gall midge (*Litchiomyia chinensis*; Diptera: Cecidomyiidae), originally described from Canton (currently Guangzhou), China, was recorded from Chiayi, Taiwan in 2008 (Hung et al. 2008). It now occurs in lychee (*Litchi chinensis* Sonn (Sapindaceae)) orchards throughout Taiwan as well as Australia (Yeh et al. 2012a). The adult female lays eggs in young shoots, and newly hatched larvae induce blister-galls on leaves of lychee, an evergreen, subtropical fruit tree. In 2018, lychee production was 78,668 tonnes with a value of 139.5 million USD (Zeng 2012; Council of Agriculture 2018, 2019). Hereinafter, the abbreviation *L. chinensis* will refer only to *Litchiomyia chinensis* while *Litchi chinensis* will be spelled fully. Galls can lead to decreased photosynthesis, and provide a pathway for pathogen infection (Hung et al. 2008). The infestation of *L. chinensis* can decrease lychee production by more than 60% (Yeh et al. 2012b).

Pesticides are used to control the population of *L. chinensis* in Taiwan, but overlapping generations and asynchronous development of *L. chinensis* decrease their

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efficacy. Therefore, the use of biological control agents as a potential alternative to pesticides could prove efficacious, as demonstrated for other gall-inducing pests (Aebi et al. 2006; Protasov et al. 2007).

In this paper we treat two new species of *Quadrastichus* (Hymenoptera: Eulophidae) reared from *L. chinensis: lasallei*, **sp. n.** and *johnlasallei*, **sp. n.** *Quadrastichus* (Girault (1913 [1967]) contains many species associated with galls induced by gall midges (Diptera: Cecidomyiidae), gall wasps (Hymenoptera: Cynipidae), and even other *Quadrastichus* (Hymenoptera: Eulophidae). Species associated with gall inducers are usually endoparasitoids, but one European species *Q. sajoi* (Szelényi) is a predator of eriophyid mites within galls (Graham 1991; La Salle 1994), and another phytophagous on young mango stems (Narendran 2007). *Quadrastichus erythrinae* Kim is an invasive pest which induces galls on coral bean trees (*Erythrina* spp.: Fabaceae) (Kim et al. 2004). In addition to being associated with galls, species of *Quadrastichus* have various hosts: Curculionidae and Buprestidae (Coleoptera: Graham 1991; La Salle 1994; Noyes 2019), and leaf-mining Agromyzidae or Gracillariidae (Reina and La Salle 2003, 2004). The nomenclatural history of *Quadrastichus* is somewhat convoluted (Graham 1987; Bouček 1988; Graham & La Salle 1991, LaSalle 1994) and will continue to pose challenges until a global revision of the group is completed.

Much of the recent interest in species of *Quadrastichus* globally has been driven by the emergence of invasive gall-inducing species. The primary example is *Q. erythrinae* Kim which induces galls on coral bean trees (*Erythrina* spp.: Fabaceae) (Kim et al. 2004) and has spread from its hypothesised native range in Africa (Messing et al. 2009) into many tropical regions (detailed by Jansen-Gonázlez et al. 2019). Most recently, Jansen-Gonázlez et al. (2019) reported on a second *Erythrina*-galling species detected in Costa Rica that keys to *Q. bardus* in the key of Prinsloo and Kelly (2009) but differs biologically in galling stems rather than leaves. The second example is the beneficial *Q. mendeli* Kim & LaSalle that was reared from galls of *Leptocybe invasa* Fisher & LaSalle in Australia. The latter is an invasive gall inducer on *Eucalyptus* that has spread notably throughout the Mediterranean and Middle East regions, into SE Asia and Brazil (Kim et al. 2008).

Quadrastichus species are recognised by a single dorsal seta on the submarginal vein (SMV), one adnotaular seta on midlobe of mesoscutum in posterior half (less commonly 2–3), propodeum lacking Y-shaped paraspiracular carina, cercal setae unequal in length, with one distinctly longer and sinuate, antenna with all funicular segments longer than broad, scutellum with submedian lines, propodeal spiracles close to metanotum with rims exposed, ovipositor sheaths not, or only slightly, projecting beyond epipygium (Graham 1991).

Anysis-group species, to which the new species described herein belong (see species treatments below), are characterised by being mostly black with yellow markings (sometimes only base of gaster), to entirely yellow, non-metallic; frons with a median area instead of median longitudinal carina; lines delimiting scrobes slightly laterally convergent dorsally; malar sulcus distinctly curved, not foveate; scutellum without offset border along its hind edge (Graham 1991; Reina and La Salle 2004).

Species known from China include *anysis* (Walker), *citrella* Reina and LaSalle, *erythrinae* Kim, *pteridis* Graham, and *sajoi* (Szelenyi). Taiwan includes *citrella* Reina and LaSalle, *erythrinae* Kim, *liriomyzae* Hansson & LaSalle (Noyes 2019). However, described species

in related genera (*Aprostocetus*: 42 species, *Tetrastichus*: 34 species) which may contain misplaced *Quadrastichus* must be examined in order to obtain a better understanding of SE Asian diversity for the genus.

Materials and methods

Ethanol-preserved specimens were dehydrated through increasing concentrations of ethanol, and transferred to hexamethyldisilazane (HMDS) (Heraty and Hawks 1998) before point-mounting. MWG identified parasitoids using a Leica M205 C stereomicroscope with 10X oculars and a Leica LED ring light source for point-mounted specimen observation. All specimens were determined to genus by sight identification or using Graham (1991). We used several species keys to determine whether our material belonged to any described species (Graham 1991; Reina & La Salle 2004; Narendran 2007) with details below under each specific treatment. Where possible, all species identifications were corroborated by comparison with authoritatively identified specimens in the Smithsonian National Museum of Natural History. Habitus images were captured using a Macropod Pro 3D system (Canon 6D Mark II body) with a Canon EF 70–200 mm telephoto with a 10x objective lens (Macroscopic Solutions, LLC). Our image series was merged into a single in-focus, composite image with the program Zerene Stacker (ver. 1.04). Post-imaging processing was completed with the editing tools in Zerene Stacker. Image editing to both the SEM and the habitus photos was done in Adobe Photoshop CS6 with a Wacom Intuos Pro tablet on a MacBook Pro. Plate layout was done in Adobe Illustrator CS6. In the diagnosis and recognition sections, comparative features of previously described taxa precede those for the newly described species, which are in parentheses.

Terminology used in this paper follows Gibson (1997) and Graham (1987). OOL, ocellar–ocular distance; OD, ocellar diameter; POL, post-ocellar distance; F, funicle segment; CC, costal cell; SMV, submarginal vein; MV, marginal vein; STV, stigmal vein; PMV, postmarginal vein; F1–4, funicular segment 1–4. Abbreviations for museums are CNCI, Canadian National Collection of Insects, Ottawa, Ontario, Canada; NCHU, National Chun Hsing University Collection, Taichung, Taiwan; NHMUK, Natural History Museum, London, UK; USNM, United States National Museum of Natural History, Washington, D.C., USA.

Results and discussion

Quadrastichus lasallei, sp. n. (Figs 1, 2)

Female holotype

Length: 3.0 mm. Colour: Head, body, and legs pale yellow, flagellomeres light brown with pale yellow, especially apically (Figure 1(b)). Fore wing hyaline, venation yellow.

Head, in frontal view (Figure 2(a)), 1.4 X as broad as high, 1.5 X as broad as frontovertex at its narrowest; malar space 0.8 X as long as an eye, the sulcus curved, without a triangular fovea beneath the eye; POL 1.1 X OOL, OOL 2.8 X OD; mandible bidentate with a truncation; head finely setose, eyes sparsely setose, setae short, ~1 ommatidial diameter (Figure 2(a)); lower margins of toruli approximately one torulus diameter below lower eye margins; clypeus shallowly emarginate (Figure 2(a)).



Figure 1. (a) *Quadrastichus johnlasallei*, lateral habitus, female. (b) *Quadrastichus lasallei*, lateral habitus, female.

Antenna (Figure 2(d–h)) with scape 5.2 X as long as broad, a little shorter than the height of eye, almost reaching vertex; pedicel approximately 2.5 X as long as broad, 1.5 X as long as basal funicle segment; one transverse anellus present; funicle three-segmented, segments about equal in size, or progressively decreasing a little in size, F1 3.3 X, F2 3.8 X, F3 3.8 X as long as broad; clava 5.0 X as long as broad; apical spine short, distinctly shorter than apical segment (Figure 2(h)); sensilla sparse, flagellum rather sparsely setose (Figure 2(g–h)).

Mesosoma (Figure 2(b–c)) 1.7 X as long as broad; mesoscutum in profile gently convex dorsally, in dorsal view gently rounded laterally; mesoscutal midlobe just longer than broad, with trace of median line posteromedially (difficult to see without high magnification), with 1 adnotaular seta at each side in posterior third; mesoscutum with very fine lineate sculpture; scutellum convex in profile, 1.5 X broader than long with sublateral and submedian lines (difficult to see without high magnification); sculpture much as in mesoscutum; scutellum with 2 pairs of setae; dorsellum convex, smooth, medially about as long as propodeum; propodeum with median carina indistinct, with curved spiracular sulcus mesad reminiscent of paraspiracular carina, with very fine reticulate sculpture; spiracles less than their own diameter from anterior propodeal margin (Figure 2(c)); calli each with 2 setae.

Fore wing (Figure 1(b)) 2.2 X as long as broad; costal cell 16 X as long as broad, 0.8 X length marginal vein, asetose; submarginal vein with 1 dorsal seta; marginal vein 5.7 X as long as stigmal vein, the postmarginal vein not apparent; subcubital line of setae extending basally as far as basal setal line, closing speculum posteriorly; longest marginal cilia (at the apex of marginal vein) about 0.6 X as long as longest setae on marginal.

Metasoma 1.2 X longer than mesosoma, somewhat circular in dorsal view, just longer than broad, broadly rounded apically; epipygium 1.6 X as long as broad; hypopygium reaching to about half the length of gaster; ovipositor sheaths short hardly protruding apically; one cercal seta twice length others and kinked.

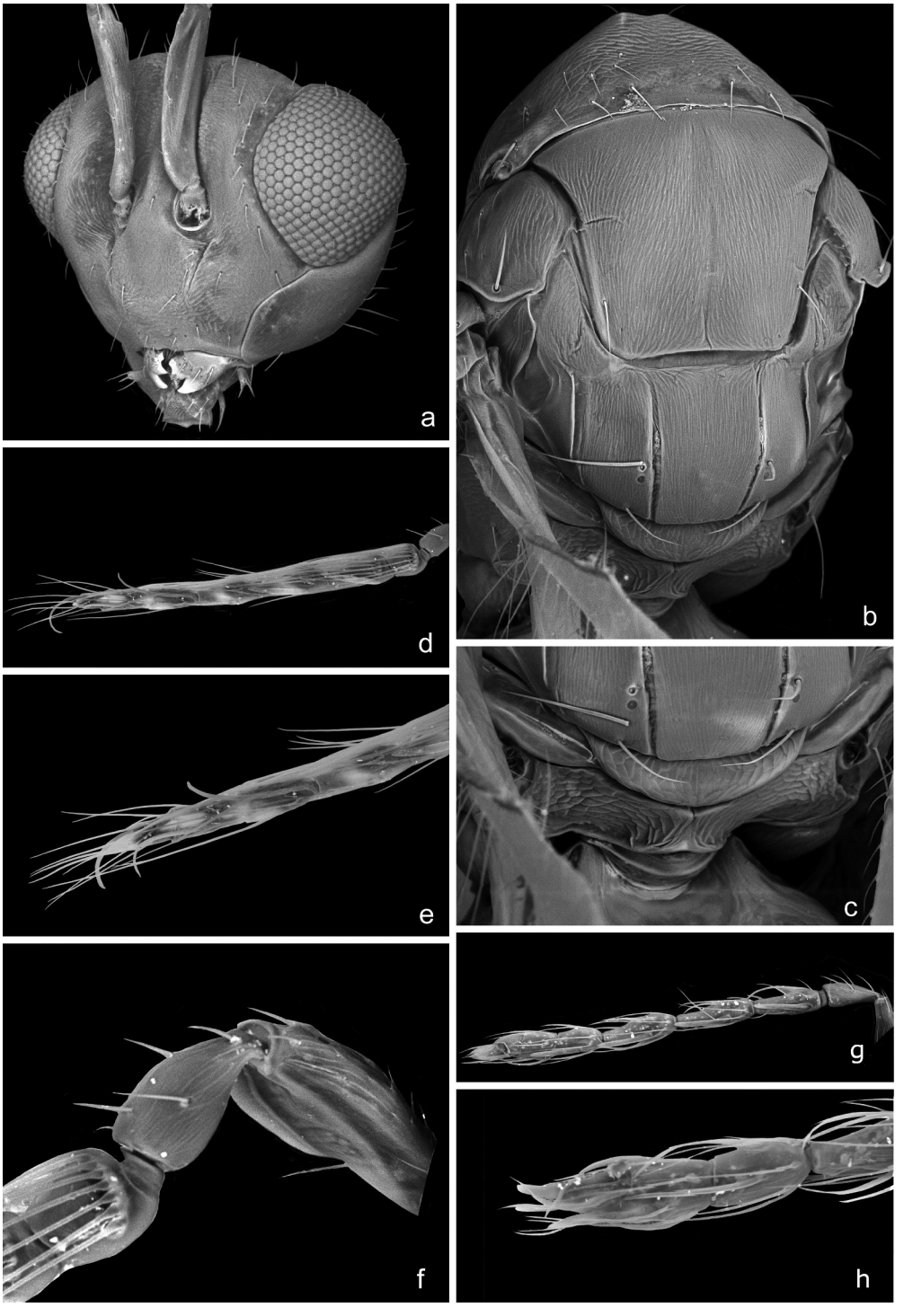


Figure 2. *Quadrastichus lasallei*, female: a, anterolateral head; b, dorsal mesosoma; c, propodeum; g, lateral flagellum; h, lateral clava. *Q. lasallei*, male: d, lateral flagellum; e, lateral clava; f, lateral scape.

Male

Length: 1.9 mm. Colour: much as in female except following brown: vertex; pronotum dorsally, mesoscutum in anterior half, except along notauli; dorsellum, propodeum, metapleuron, gastral terga 3–8. Differing structurally from the female mainly in the antenna (Figure 2(d–f)): scape with a linear ventral plaque, placed in apical half and extending from near apex to beyond mid length of scape (Figure 2(f)); a single anellus present; funicle four-segmented, F1 1.0 X F2 2.0 X, F3 2.7 X, F4 2.8X as long as broad, each broadest basally and narrowing apically; clava 5.0 X as long as broad; flagellum sparsely setose, the setae on funicle segments fairly long, slightly curved, basal dorsal whorls on F1–4 reaching beyond following segment. Some clava sensilla strongly recurved (Figure 2 (d–e)).

Variation

One male has additional brown colouration anteriorly on gastral tergum 1, encircling petiole base.

Etymology

Named in honour of our friend and colleague, Dr John La Salle, for his good humour and love of Chalcidoidea. He will be missed.

Biology

Larva is a koinobiont endoparasitoid of mature larva of lychee gall midge, *Litchiomyia chinensis*.

Diagnosis and recognition. This species is recognised by female completely yellow, clypeus slightly emarginate (both sexes), and male with strongly recurved sensilla on clava.

This species keys to the *anysis*-group to a large extent, ultimately to couplet 20 in Graham 1991 where it splits the diagnostic features with three of five characters leading to *Q. anysis*. However, *Q. lasallei* differs from *Q. anysis* in completely pale yellow colouration in female (areas of brown/black on head and metasoma, mesosoma mostly black), scape reaching the level of vertex (not reaching vertex), clypeus notched (not subtruncate), and recurved sensilla on male clava (straight). Biologically, *Q. anysis* is known from *Monarthropalpus buxi* Laboulbène (Diptera: Cecidomyiidae) that mines the leaves of *Buxus* spp. (box; Buxaceae) throughout Europe and North America. In the key of Narendran (2007), this species runs to *Q. longiclavatus* Narendran, but differs in claval spine 0.2 X the length of clava (0.52 X) and female completely yellow (largely black). The biology and male are unknown for *Q. longiclavatus*. Finally, in the Reina and La Salle (2004) key to Old World species of the *anysis*-group, *Q. lasallei* runs to *Q. citrella* Reina & LaSalle, as both share F1 shorter than F2, and speculum extending ~0.2–0.3 X length marginal vein, but all gastral terga yellow (dark brown band on gastral terga 3–4) and propodeum distinctly reticulate (sculpture much smoother). Further, *Q. citrella* is an idiobiont ectoparasitoid of the leafminer *Phyllocnistis citrella* Stainton (Lepidoptera: Gracillariidae) whereas *Q. lasallei* is a koinobiont endoparasitoid of *L. chinensis*.

Type material examined

Female holotype, 1 female: TAIWAN: Changhua Co.: Fenyuan Township, No. 139 Fongshan Rd., 24°00′9.2″N 120°37′32.3″E, 19.IX.2018, Heyieh, Coll. Yi-Min Chao; sp. 2, female #6; USNMENT01525925 (NCHUC). 2 female, 3 male paratypes, same data as holotype (NCHU). 2 female, 3 male paratypes, same data as holotype, except secondary labels are sp. 2, female #5, USNMENT01525926 (1 f, USNM); sp. 2 female #6, USNMENT01525927 (1 f, NHMUK); sp. 2 male #7, USNMENT01525928 (1 m, USNM); sp. 2 male #7, USNMENT01525929 (1 m, NHMUK); sp. 2 male #7, USNMENT01525924 (1 m, CNCI). 1 female paratype, same locality and collector as holotype, except date 13. XI.2018 (1 f, NCHU). 1 female paratype: Nantou Co.: Caotun Township, Jianxing Rd., 23°59′39.7″N 120°46′18.1″E, 6.IX.2018, Coll. Yi-Min Chao; sp. 1 male #4, USNMENT01525920 (1 f, CNCI). 1 female, 4 male paratypes: TAIWAN: Taichung City: Taiping Dist., Guangxing Rd., No.60 2140th S. Ln., 24°07′42.4″N 120°44′17.1″E, 21. XI.2018, em. 29.XI.2018, Coll. Yi-Min Chao (1 f, 2 m, NCHU); same collected date except em. 27.XI.2018 (2 f, NCHU).

Quadrastichus johnlasallei, sp. n. (Figs 1, 3)

Female Holotype. Length: 4.0 mm. Colour: Head, mesosoma, fore coxa, ovipositor sheaths, and gaster dorsally dark brown (except as noted beyond); antenna, middle and hind legs, gaster (anterodorsal quarter, anterolateral two-thirds, anteroventral two-thirds, dorsolaterally on gastral tergum 5) pale yellow (Figure 1(a)). Fore wing hyaline, venation yellow.

Head, in frontal view (Figure 3(a)), 1.5 X as broad as high, 1.7 X as broad as frontovertex at its narrowest; malar space 0.6 X as long as an eye, the sulcus slightly curved, without a triangular fovea beneath the eye; POL 3.2 X OOL, OOL 1.3 X OD; mandible tridentate; head finely setose, eyes very sparsely setose, setae short, <1 ommatidial diameter (Figure 3(a)); lower margins of toruli approximately two torulus diameter above lower eye margins; clypeus bilobate (Figure 3(a)).

Antenna (Figure 3(d–h)) with scape 3.6 X as long as broad, longer than the length of an eye, just exceeding vertex; pedicel approximately 2.5 X as long as broad, 1.5 X as long as basal funicle segment; one transverse anellus present; funicle three-segmented, F1 just shorter than the subequal F2–F3, F1 2.6 X, F2 3.8 X, F3 3.8 X as long as broad; clava 5.0 X as long as broad; apical spine ~0.8 X length apical segment; sensilla sparse, flagellum rather sparsely setose (Figure 3(d–e)).

Mesosoma (Figure 3(b–c)) 1.3 X as long as broad; mesoscutum in profile gently convex dorsally, in dorsal view gently rounded laterally; mesoscutal midlobe approximately as long as broad, with fine median line; with 2 adnotaular setae at each side, in posterior half; mesoscutum with very fine lineate sculpture; scutellum convex in profile, 1.2 X broader than long with submedian lines; sculpture as in mesoscutum; scutellum with 2 pairs of setae; dorsellum convex, smooth, medially about as long as propodeum; propodeum without median carina, with curved spiracular sulcus mesad reminiscent of paraspiracular carina, with very fine reticulate sculpture; spiracles ~1x their own diameter from anterior propodeal margin; cali each with 2 setae.

Fore wing (Figure 1(a)) 2.2 X as long as broad; costal cell 15.0 X as long as broad, 0.7 X length of marginal vein, asetose; submarginal vein with 1 dorsal seta; marginal vein 3.0

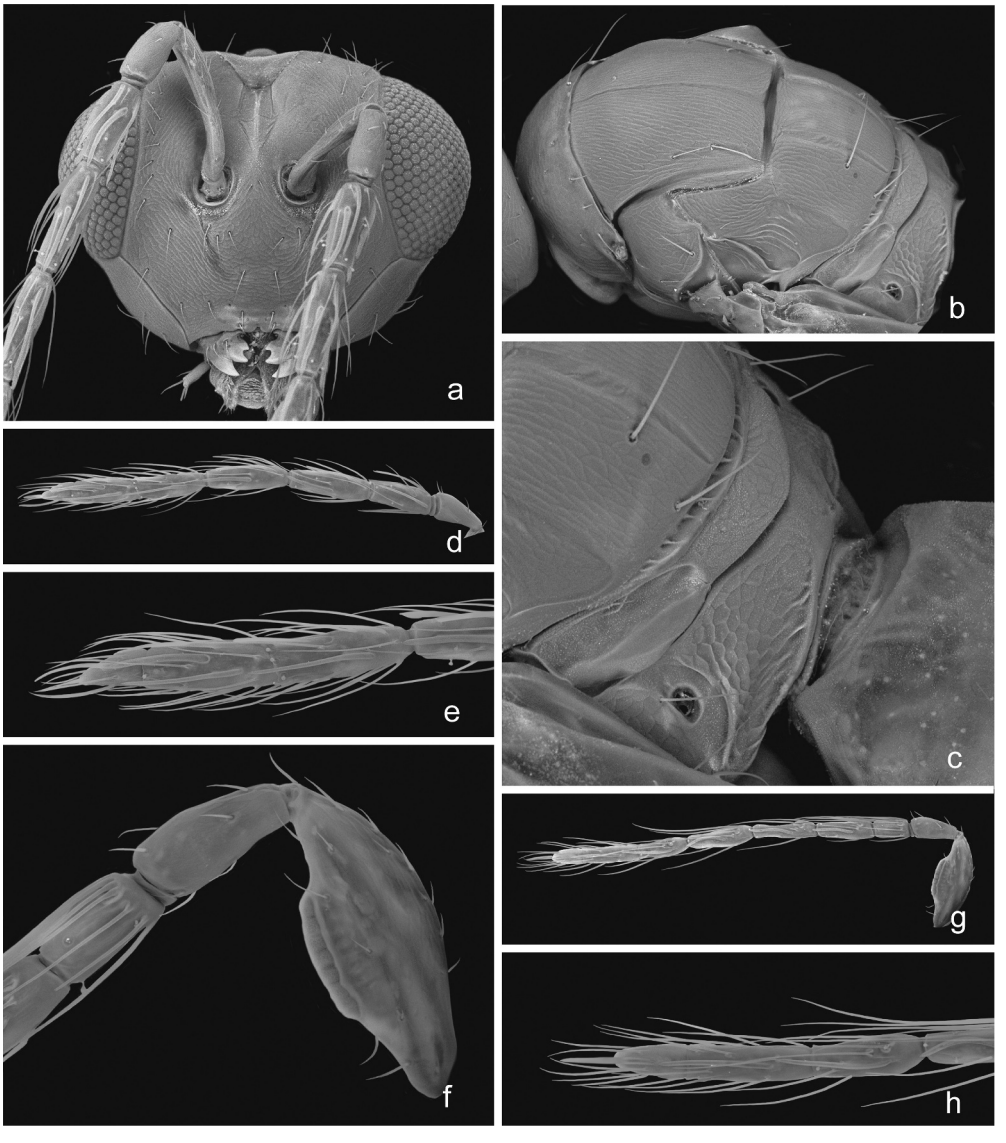


Figure 3. *Quadrastichus johnlasallei*, female: (a) anterior head; (b) dorsolateral mesosoma; (c) dorsolateral propodeum; (d) lateral flagellum; (e) lateral clava. *Q. johnlasallei*, male: (f) lateral scape; (g) lateral antenna; (h) lateral clava.

X as long as stigmal vein, the postmarginal vein 0.3 X stigmal; subcubital line of setae extending basally as far as basal setal line, closing speculum posteriorly; longest marginal cilia ~1.4 X as long as longest setae on marginal vein.

Metasoma elongate, 2.6 X longer than mesosoma, 2.0 X longer than broad, tapered apically; epipygium 2.3 X longer than broad; hypopygium reaching to about 0.3 X the length of gaster; ovipositor sheaths short, hardly protruding apically; one cercal seta twice length others and curved.

Male

Length: 3.1 mm. Colour: much as in female except following lacking anterodorsal yellow patches on gastral tergum 5 and all coxae brown. Differing structurally from the female mainly in the antenna (Figure 3(f–h)): scape with a linear ventral plaque, placed in middle half (Figure 3(f)); a single transverse anellus present; funicle four-segmented, F1 2.0 X, F2 2.5 X, F3 2.5 X, F4 2.8 X, as long as broad, all broadest basally and narrowing apically, clava 8.3 X as long as broad; flagellum sparsely setose, the setae on funicle segments fairly long, slightly curved, basal dorsal whorls on F1–4 reaching beyond following segment; clava sensilla not recurved (Figure 3(g–h)).

Variation

One female has the dorsoapical margin of gastral tergum 6 yellow and basal ¼ hind coxa brown.

Diagnosis and recognition. This species keys to the *anysis*-group to a large extent, ultimately to couplet 21 where it roughly matches diagnostic features of *Q. xanthosoma*, namely the elongate metasoma and epipygium. However, *Q. johnlasallei* differs from *Q. xanthosoma* in having brown head and mesosoma, partially brown metasoma (head and body mostly to wholly yellow), female clava 5.0 X as long as broad (3.0 X), clypeus bilobate (straight). *Quadrastichus xanthosoma* is known from Europe and USSR where it attacks *Massalongia* spp. (Diptera: Cecidomyiidae) on *Betula* spp. (Noyes 2019). In the key of Narendran (2007), ours runs to *Q. suhderi* Narendran and roughly matches in overall colouration, 2 adnotaular setae and hypopygium not extending to middle of gaster, but differs in lacking characteristic banding patterns on the middle and hind femur and tibia (legs wholly yellow). Biologically, *Q. sudheri* is phytophagous in tender shoots of mango, *Mangifera indica* L. (Anacardiaceae), causing desiccation of the branches in India. Finally, in the Reina and La Salle (2004) key to Old World species of the *anysis*-group, Q. *johnlasallei* runs to *Q. anysis* Reina & LaSalle as both share mesoscutum dark brown and male ventral plaque ~0.5 X scape length, but differ in speculum ~0.5 X length MV (0.2 X), but dark brown band on gastral terga 3–4 (most gastral terga brown) and propodeum distinctly reticulate (sculpture effaced reticulate). Further, *Q. citrella* is an idiobiont ectoparasitoid of the leafminer *P. citrella* in SE Asia and parts of Europe whereas *Q. anysis* is known from *M. buxi* that mines the leaves of *Buxus* spp. throughout Europe and North America.

Etymology

Named in honour of our friend and colleague, Dr John La Salle, for his numerous contributions to our knowledge of Eulophidae.

Biology

This species was reared from leaf blister galls of *Litchiomyia chinensis*. Its specific biology within the gall remains unknown.

Type material examined

Female holotype, 1 female: TAIWAN: Nantou Co.: Caotun Township, Jianxing Rd., 23° 59'39.7"N 120°46'18.1"E, 15.VIII.2018, em 15.VIII.2018, Coll. Yi-Min Chao; sp. 3 female #9;

USNMENT01525920 (NCHUC). 2 female paratypes, same data as holotype, except dates are 27.VII.18, em. 14.VIII.2018; secondary label reads: sp. 3, female #8, USNMENT01525921 (NHMUK); USNMENT01525922 (CNCI). 2 females, same data as holotype, except dates are 25.VII.2018, em. 20.VIII.2018; secondary label reads: sp. 1, male #3, USNMENT01525919 (NCHUC); USNMENT01525918 (NHMUK). 1 female paratype, same data as holotype, except dates are 18.V.2018, em. 15.VII.2018 (1 f, NCHU). 3 females, 3 male paratypes: TAIWAN: Changhua Co.: Fenyuan Township, No. 139 Zhongshan Rd., 24°00′9.2″N 120° 37′32.3″E, 19.IX.2018, Heyieh, Coll. Yi-Min Chao; sp. 2 female #6, USNMENT01525917 (1 f, USNM); same locality, dates and secondary labels as follows: 15.VIII.18, em. 9.IX.2018, sp. 3 male #11,USNMENT01525916 (1 m, USNM); 25.V.18, em. 21.IX.2018, sp. 3 female #10, USNMENT01525915 (1 f, NCHUC); 16.VIII.18, em. 15.IX.2018, sp. 3 male #12, USNMENT01525912 (1 m NHMUK); 13.IX.18, em. 21.IX.2018, sp. 1 female #1, USNMENT01525914 (1 f, USNM); 19.IX.18, em. 22.IX.2018, sp. 2 female #11, USNMENT01525913 (1 f, CNCI); same locality and collector, 12.III.2018 (1 f, NCHU). 3 female paratypes: TAIWAN: Chiayi Co.: East Dist., No. 2 Minquan Rd., 23°29′07.7″N 120°28′13.5″E, 14.VIII.2018 Coll. Yi-Min Chao, em.3.IX.2018 (2 f, NCHU); em.6.IX.2018 (1 f, NCUH).

We hope that this work will stimulate research on *Quadrastichus* worldwide, especially larger regional treatments. However, the necessity of recent work to date on various pestiferous/beneficial *Quadrastichus* (Kim et al., 2004; Kim et al. 2008; Prinsloo and Kelly 2009; Jansen-Gonázlez et al. 2019) is undeniable and underscores the need for further research.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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