Putting *Parasemia* in its phylogenetic place: a molecular analysis of the subtribe Arctiina (Lepidoptera)

KATJA RÖNKÄ, JOHANNA MAPPES, LAURI KAILA and NIKLAS WAHLBERG

1Department of Biological and Environmental Science, University of Jyväskylä, Jyväskylä, Finland, 2Zoology Unit, University of Helsinki, Helsinki, Finland, 3Department of Biology, University of Turku, Turku, Finland and 4Department of Biology, Lund University, Lund, Sweden

Abstract. Despite being popular among amateur and professional lepidopterologists and posing great opportunities for evolutionary research, the phylogenetic relationships of tiger moths (Erebidae: Arctiinae) are not well resolved. Here we provide the first phylogenetic hypothesis for the subtribe Arctiina with the basic aim of clarifying the phylogenetic position of the Wood Tiger Moth *Parasemia plantaginis* Hübner, a model species in evolutionary ecology. We sampled 89 species in 52 genera within Arctiina s.l., 11 species of Callimorphina and two outgroup species. We sequenced up to seven nuclear genes (CAD, GAPDH, IDH, MDH, Ef1α, RpS5, Wingless) and one mitochondrial gene (COI) including the barcode region (a total of 5915 bp). Both maximum likelihood and Bayesian inference resulted in a well-resolved phylogenetic hypothesis, consisting of four clades within Arctiina s.s. and a clade comprising spilosomine species in addition to Callimorphina and outgroups. Based on our results, we present a new classification, where we consider the *Diacrisia* clade, *Chelis* clade, *Apantesis* clade, *Micrarctia* Seitz and *Arctia* clade as valid genera within Arctiina s.s., whereas *Rhyparia* Hübner syn.n. and *Rhyparioides* Butler syn.n. are synonymized with *Diacrisia* Hübner; *Neoarctia* Neumöegen & Dyar syn.n., *Tancrea* Püngeler syn.n., *Hyperborea* Grum-Grshimailo syn.n., *Palearctia* Ferguson syn.n., *Holoarctia* Ferguson syn.n., *Sibirarctia* Dubatolov syn.n. and *Centrarctia* Dubatolov syn.n. are synonymized with *Chelis* Rambur; *Grammia* Rambur syn.n., *Orodemnias* Wallengren syn.n., *Mimarctia* Neumöegen & Dyar syn.n., *Notarctia* Smith syn.n. and *Holarcia* Smith syn.n. are synonymized with *Apantesis* Walker; and *Epipallica* Hübner syn.n., *Eucharica* Hübner syn.n., *Hyphoraia* Hübner syn.n., *Parasemia* Hübner syn.n., *Pericalia* Hübner syn.n., *Nemeophila* Stephens syn.n., *Ammobiota* Wallengren syn.n., *Platarctia* Packard syn.n., *Chionophila* Guenée syn.n., *Eupsychoma* Grote syn.n., *Gonerda* Moore syn.n., *Platypropia* Dyar syn.n., *Preparctia* Hampson syn.n., *Oroncus* Seitz syn.n., *Acercia* Sotavalta syn.n., *Pararctia* Sotavalta syn.n., *Borearctia* Dubatolov syn.n., *Sinoarctia* Dubatolov syn.n. and *Atlantarctia* Dubatolov syn.n. are synonymized with *Arctia* Schrank, leading to 33 new genus-level synonymies. Our focal species *Arctia plantaginis* comb.n. is placed as sister to *Arctia festiva* comb.n., another widespread aposematic species showing wing pattern variation. Our molecular hypothesis can be used as a basis when adding more species to the tree and tackling interesting evolutionary questions, such as the evolution of warning signalling and mimicry in tiger moths.

Correspondence: Katja Rönkä, University of Jyväskylä, Department of Biological and Environmental Science, Centre of Excellence in Biological Interactions Research, P.O. Box 35, FI-40014, Finland. E-mail: katja.h.ronka@jyu.fi

© 2016 The Authors. Systematic Entomology published by John Wiley & Sons Ltd on behalf of Royal Entomological Society. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
Introduction

Tiger moths are a highly diverse group consisting of about 11 000 species worldwide. Of these, approximately 4000 species in 113 genera belong to the subtribe Arctiina (Erebidae: Arctiinae: Arctiini: Arctiina s.l.) (see Weller et al., 2009 and references therein). Their visual appearance and diverse ecology have made them popular among amateur lepidopterists and some species are studied intensively (e.g. the Ornate Moth Utetheisa ornatrix (Linnaeus), Garden Tiger Moth Arcta caja (Linnaeus) and the Wood Tiger Moth Parasemia plantaginis (Linnaeus)), but in general our knowledge of their diversity and phylogenetic relationships is surprisingly limited (Bendib & Minet, 1998; Conner, 2009). New species are still found, perhaps because many are relatively rare, difficult to observe, or may occur in small numbers in remote places (e.g. Micracricia kauniti Saldaïtis & Pekarsky, 2015). The present classification of Arctiina s.l. is based mainly on detailed studies based on morphological characters (Dubatolov & de Vos, 2010; Lafontaine & Schmidt, 2010; Fibiger et al., 2011; Vincent & Laguerre, 2014). However, these data have not been subjected to rigorous phylogenetic analyses.

Most tiger moths are chemically defended, advertise their unpalatability with spectacular warning colours and take part in several Müllerian mimicry rings (Conner, 2009). High morphological variability in Arctiinae means that it is difficult to determine unequivocal synapomorphies [shared derived characters that support monophyletic groups (clades)], which makes it challenging to trace the evolutionary relationships within the group (Schmidt, 2007; Weller et al., 2009). As mimicry is very likely to occur within Arctiinae, another phenomenon that can potentially obscure our understanding of the systematics of this group is incomplete lineage sorting. This is likely to be common in many systems, such as mimetic butterflies, resulting from rapid radiation or adaptive introgression facilitated by strong selection on adaptive loci (Kozak et al., 2015). In addition, the tendency of researchers to describe each colourful and uniquely patterned species in its own genus has led to a less informative classification, in which many tiger moth genera are species-poor, monotypic and, in some cases, probably paraphyletic (Weller et al., 2009).

Parasemia plantaginis is the only species in its nominal genus Parasemia Hübner. The species occurs in the Holarctic, forming two distinct clades, one of which corresponds to P. plantaginis ssp. caucasica (Ménétriers), with both male and female moths expressing ‘interrupted’ forewing pattern (Hegna & Mapes, 2014; Honma et al., 2015) and hindwing coloration varying from yellow to red (Fig. 1D). The other clade comprises all other forms of P. plantaginis with various patterns and polymorphic hindwing coloration (Fig. 1A–C; Hegna et al., 2015). The effects of variation in both larval and adult coloration of P. plantaginis on their predation risk and other fitness measures, as well as population genetics, have been intensively studied (e.g. Ojala et al., 2005, 2007; Lindstedt et al., 2011; Nokelainen et al., 2011; Hegna et al., 2013 & Galarza et al., 2014) and the species has great potential for becoming a model system in the study of the evolution of warning coloration (Stevens & Ruxton, 2012) and colour polymorphism.

Thus, to further investigate interesting evolutionary questions in this system, such as the evolution of warning signal polymorphism or convergent evolution in mimicry rings, a well-resolved phylogeny of Arctiina is crucially needed (Simmons, 2009; Hegna et al., 2015). With a phylogenetic hypothesis available, it will be possible to determine when colour polymorphisms have evolved in the group and to study the occurrence of mimetic patterns in detail (Simmons, 2009).

The higher classification of tiger moths (Lepidoptera: Erebidae: Arctiinae) was recently studied with molecular methods by Zaspel et al. (2014), but this study had sparse sampling of the species-rich subtribe Arctiina. Zaspel et al. (2014) sampled only Arctia caja from the diverse Arctia group and did not include Parasemia. Parasemia is thought to be closely related to Arctia, with some evidence that it may, in fact, be within the genus (Fibiger et al., 2011). Schmidt’s (2007) tree, with combined evidence from barcode and morphology, placed Parasemia in the same clade with Arctia, Platyspreia, Platarctia and Pararctica. With the broadest sampling of related genera so far, Dubatolov (2008) placed Parasemia closest to Hyphoracia, which consists of three species [Hyphoracia aulica (Linnaeus), H. dejanei (Godart) and H. testudinaria (Geoffroy)], and Epi callia (=Arctia) villica (Linnaeus), a monotypic genus, based on morphological characters.

In this study, we infer a molecular hypothesis of the phylogenetic relationships of species in the subtribe Arctiina, aiming to clarify the position of Parasemia within the subtribe. Based on our results, we revise the classification of Arctiina s.s. By doing this we contribute to establishing the relationships among many monotypic genera, stated by Weller et al. (2009) as the next big challenge in arcticine systematics.

Material and methods

Sampling

Many Palearctic Arctiina species are rare and/or occur in areas that are not easily accessible to collectors. However, with the aid of several amateur lepidopterologists and fellow scientists (see the Acknowledgements) we were able to sample many of the species in the subtribe putatively related to Parasemia. The selection of taxa was based on previous studies (Jacobson & Weller, 2002; Schmidt, 2007; Dubatolov, 2008, 2009; Zaspel et al., 2014) and available checklists relevant to our taxon sampling (Dubatolov & de Vos, 2010; Lafontaine & Schmidt, 2010; Fibiger et al., 2011; Vincent & Laguerre, 2014). Within the tribe Arctiini we sampled 11 species representing nine genera of the subtribe Callimorphina and 89 species representing 52 genera of the subtribe Arctiina, but excluded the mostly tropical subtribes Pericopina, Ctenuchina, Euchromiina and Phaegopterina. As outgroups we used Setina sp. (Erebidae: Arctiinae: Lithosiini) and Amata sp. (Arctiinae: Syntomini), which are closely related to Arctiini according to Zaspel et al. (2014).

Our focal study species, P. plantaginis, is placed in Arctiini: Arctiina. To our knowledge, Parasemia together with other genera putatively related to Arctia belong to Arctiina s.s., and,
within that, to a lineage that has a Holarctic distribution (Weller et al., 2009). Sampling within Arctiini was thus limited to the Holarctic region, with most species having a Palaearctic distribution, although eight species occurring only in the Nearctic were also included. For species with a wide distribution, range we aimed to sample at least two individuals representing different populations to avoid possible bias caused by local adaptive evolution. As we focused our sampling to Arctiina s.s. in the hope of finding the closest relatives of *Parasemia*, the so-called spilosomine genera and other mainly tropical lineages of Arctiini were left more sparsely sampled. However, including the sequences of Arctiina used by Zaspel et al. (2014) in our analysis broadened our coverage to tropical regions for the spilosomine genera.

We used samples that were as fresh as possible, with the oldest ones sampled successfully being up to 10 years old, stored dry, in alcohol or frozen at −20°C. For DNA extraction we used either one to two legs of adult specimen or a small piece of tissue (e.g. anal prolegs) from larvae. The barcode (COI) sequences of our samples were cross-checked in the Barcode of Life Data System (Ratnasingham & Hebert, 2007) for those species that already had a reference barcode provided. All our sampled taxa, genes and GenBank accession numbers are provided in Appendix S1.

**DNA markers and laboratory protocols**

The eight genetic markers used in this study have proven useful in resolving evolutionary relationships between species above and below the family level (e.g. Wahlberg & Wheat, 2008; Zahiri et al., 2011, 2012; Zaspel et al., 2014). We amplified the mitochondrial cytochrome oxidase (COI), including the barcode region, as well as the nuclear gene regions carbamoylphosphate synthase domain protein (CAD), glyceraldehyde-3-phosphate dehydrogenase (GAPDH), isocitrate dehydrogenase (IDH), cytosolic malate dehydrogenase (MDH), elongation factor 1-a protein (Ef1a), ribosomal protein subunit S5 (RpS5) and wingless (WGS).

DNA extraction was conducted using the DNeasy Blood+Tissue extraction kit (Qiagen, Hilden, Germany) both in Turku and Jyväskylä according to the manufacturer’s protocols, but assisted by a robot (Kingfisher, Waltham, MA, U.S.A.) in Jyväskylä. Washing and eluting DNA in Jyväskylä was thus done using MagAttract tubes and the KingFisher robot with the programme Qiagen Blood. For polymerase chain reaction (PCR) and primer pairs we followed the laboratory protocols of Wahlberg & Wheat (2008). However, for some older samples processed in Jyväskylä, in cases where we did not obtain enough product to be visualized and purified from agarose gel during the first PCR, we did a second PCR using the first PCR product as a template with the same primers. PCR products were sent to Macrogen Europe in the Netherlands for sequencing, except for part of the barcode region (the 5′ half of COI) samples, which were sequenced in Jyväskylä with Big-Dye terminator v3.1, Cycle Sequencing kit (Applied Biosystems, Carlsbad, CA, U.S.A.) and run on an ABI 3130x1 Genetic Analyzer (Applied Biosystems). Finally, we aligned DNA sequences manually using MEGA version 5.2.2 (Tamura...
Phylogenetic analysis and checking for errors

To check for erroneous sequences, we performed neighbour-joining and Bayesian analyses on single-gene alignments. These analyses were compared with the combined analysis of all genes, and if the species were placed in a radically different relationship between these two, the original sequence data for the differing gene were examined, and, in cases of possible contamination or low-quality sequence, omitted from further analysis.

We performed both maximum likelihood (ML) and Bayesian inference (BI) analyses on the combined dataset of a minimum of two successfully sequenced gene regions (min. of approximately 1000 bp). The Bayesian information criterion using PARTITION FINDER v. 1.1.1 (Lanfear et al., 2012) was used to determine the best-fit partitioning scheme and evolutionary model for the dataset, which was partitioned into each codon position for each gene region. For ML analysis we used raxml-HPC2 (Stamatakis, 2014) on XSEDE (Towns et al., 2010). The BI analyses were carried out using MRBAYES v3.2.3 (Ronquist et al., 2012) on the Cipres science gateway (Miller et al., 2010). The BI analyses were performed 10 million generations, with sampling every 1000 generations and four chains, one cold and three heated, in two independent runs. The parameters and models of evolution were unlinked across character partitions and the mixed evolutionary model was used. The convergence of the two runs was ascertained by visual inspection of the log-likelihoods stationary distribution, discarding the first 25% of sampled trees, as well as by checking that the final average standard deviation of split frequencies was below 0.05 and that the potential scale reduction factor for each parameter was close to 1. Resulting trees for both ML (Fig. 2) and BI analyses (Appendix S2) were visualized using FIGTREE v.1.4.2. (Rambaut, 2014).

Results

The most optimal partitioning scheme found by PARTITION FINDER had 16 partitions (out of a total of 24). Most codon positions of each gene were kept in their own partition, except for the following, which were combined: position 3 of CAD and position 3 of MDH; position 2 of CAD and position 2 of IDH; position 3 of GAPDH, position 3 of IDH and position 3 of WGS; position 2 of GAPDH, position 2 of MDH; and position 1 of MDH, position 1 of RpsS and position 1 and 2 of WGS.

Both ML and BI analyses resulted in well-resolved topologies with nearly identical branching patterns (Fig. 2, Appendix S2). The topologies are rooted with Lithosiini (Setina sp.) and the sample representing Syntomini (Amata sp.) is positioned as sister to all other clades [bootstrap (BS) = 100, Bayesian posterior probability (BP) = 1.0]. Our 11 species formally placed in Callimorphina are divided into two strongly supported clades, eight species forming Callimorphina (BS = 99, BP = 1.0) and three species of Nyctemera + Secusio forming another clade (BS = 100, BP = 1.0). The latter is sister to Arctiina with strong support. Within Arctiina s.l., we find strong support for the monophyletic group of spilosomine genera (BS = 100, BP = 1.0) separate from Arctiina s.s. (BS = 49, BP = 0.94).

Within Arctiina s.s., several clades are formed, but the relationships between and within some of these groups are not clear. The first clade comprises Diacrisia, Rhymparia and Rhyparioides (the Diacrisia-clade), which form a strongly supported monophyletic group (BS = 100, BP = 1.0). Hyperborea, Sibirarctica, Chelis and Neoarctica + Holoarctica + Palearctica + Tancrea + Centrarctica also form a clade with strong support (the Chelis clade; BS = 99, BP = 1.0) as do Holarctica, Grammia, Apantesis and Notarctica (the Apantesis clade; BS = 99, BP = 1.0).

Micractia trigona (Leech) is placed alone as a sister to the monophyletic grouping of ‘Arctica’ species (the Arctica clade; BS = 86, BP = 0.99), which is divided in two subclades, which we term the ‘Northern Arctica’ (BS = 98, BP = 1.0) and the ‘Mediterranean Arctica’ (BS = 100, BP = 1.0). Six species of Arctica form a monophyletic ‘Arctica caja’ group’, of which A. intercalaris (Eversmann) + A. thibetica Felder are placed as sister to A. caja + A. martinibonii Dubatolov & Gurko + A. brachyptera Troubridge & Lafontaine + A. opulenta (H. Edwards), which show very little difference in the molecular data. We consider the ‘Arctica caja group’ as part of the sister ‘Northern Arctica’ subclade, where Platyprepia and Oroncus form the most basally arising branches, with some support for a monophyletic grouping of Preparctica [including Sinoarctica sieversi (Grum-Grshimailo)] + Gondera + Platarctica souliei (Oberthür) placed as sister to Orontobia secreta (Draudt) + Acerbia seitzi (Bang-Haas) + Arctia raeckbeili Püngeler and a grouping of Pararctica + Acerbia alpina (Quensel), Platarctica parthenos (Harris), Pericallia matronula (Linnaeus), Borearctica menetriesii (Eversmann) and Arctica flavia (Fuessly) with a non-resolved branching structure. The other subclade of the monophyletic group of ‘Arctica’ is the ‘Mediterranean Arctica’, which comprises our focal study species P. plan tasiginis placed as sister to Eucharia (=Ammobiota/Arctica) festiva (Hufnagel) (BS = 94, BP = 1.0), next to all three Hyphoracia species, which in turn form the sister clade of Atlantarctica ungemachi (Le Cerf), Atlantarctica (=Arctica) tigrina (Villas) and Epicallia (=Arctica) villica (Linnaeus).

Discussion

A molecular hypothesis of Arctiina phylogenetic relationships

We were able to sample a wide range of Arctiina species throughout their distribution ranges in the Holarctic, while aiming to find all the potential relatives of Parasemia. Our sampling is the most comprehensive to date of the subtribe Arctiina and brings many species that have been difficult to place in a phylogenetic context for the first time. The resolution of our hypothesis could well be further improved by adding samples...
Fig. 2. Phylogram of the potentially closest relatives of Arctia plantaginis. Bootstrap/Bayesian posterior probability support values are given next to the nodes. Lines on the right delimit the revised genera and other monophyletic groupings formed. Tiger moths illustrated in the pictures from top down are Callimorpha dominula, Nyctemera adversata, Spilossoma lubricipedium, Diacrisia sannio, Chelis dahurica, Apanesis vittata, Micractia trigona, Arctia caja, Arctia lapponica comb.n. and Arctia planagin ssp. caucasica comb.n.
Table 1. Formal generic revision of Arctiina s.s.

| Valid genera          | Synonymized genera                                                                 |
|-----------------------|-------------------------------------------------------------------------------------|
| **Apantesis** Walker, 1855 | Granumia Rambur, 1866 syn.n.                                                      |
|                       | Orodemnia Wallengren, 1885 syn.n.                                                |
|                       | Mimarctia Neunoegen & Dyar, 1894 syn.n.                                           |
|                       | Notarctia Smith, 1938 syn.n.                                                      |
|                       | Holarctia Smith, 1938 syn.n.                                                      |
| **Chelis** Rambur, 1866 | Neocarctia Neunoegen & Dyar, 1893 syn.n.                                          |
|                       | Tancrea Püngeler, 1898 syn.n.                                                     |
|                       | Hyperborea Grun-Grshimalo, 1900 syn.n.                                            |
|                       | Palearctia Ferguson, 1984 syn.n.                                                 |
|                       | Holarctia Ferguson, 1984 syn.n.                                                  |
|                       | Sibarctia Dubatolov, 1987 syn.n.                                                 |
|                       | Centrarctia Dubatolov, 1992 syn.n.                                               |
| **Diacrisia** Hübner, [1819] 1816 | Rhyaria Hübner [1820] 1816 syn.n.                                                |
|                       | Rhyparoides Butler, 1877 syn.n.                                                  |
| **Micrarctia** Seitz, 1910 | Eyprepia Ochsenheimer, 1810 junior objective synonym of Arctia Schranck, 1802.  |
|                       | Epicallia Hübner, [1820] 1816 syn.n.                                              |
|                       | Eucharia Hübner, [1820] 1816 syn.n.                                               |
|                       | Hyphoraia Hübner, [1820] 1816 syn.n.                                              |
|                       | Parasemia Hübner, [1820] 1816 syn.n.                                              |
|                       | Zoöe Hübner, [1820] 1816 junior objective synonym of Arctia Schranck, 1802.      |
|                       | Pericallia Hübner [1820] 1816 syn.n.                                              |
|                       | Nemeophila Stephens, 1828 syn.n.                                                  |
|                       | Ammobiota Wallengren, 1855 syn.n.                                                 |
|                       | Callarctia Packard, 1864 junior objective synonym of Arctia Schranck, 1802.     |
|                       | Platarticia Packard, 1864 syn.n.                                                  |
|                       | Chionophila Guénéé 1865 syn.n.                                                     |
|                       | Eupsychoma Grote, 1865 syn.n.                                                     |
|                       | Gonerda Moore, 1879 syn.n.                                                        |
|                       | Platyprepia Dyar, 1897 syn.n.                                                     |
|                       | Preparea Hampson, 1901 syn.n.                                                     |
|                       | Acerbia Sotavaltia, 1963 syn.n.                                                   |
|                       | Pararctia Sotavaltia, 1965 syn.n.                                                 |
|                       | Borearctia Dubatolov, 1984 syn.n.                                                 |
|                       | Sinoarctia Dubatolov, 1987 syn.n.                                                 |
|                       | Atlantarctia Dubatolov, 1990 syn.n.                                               |

of the rarer species, e.g. from the small genera Atlantarctia Dubatolov, Divarctia Dubatolov, Ebertarctia Dubatolov, Leparticia Stretch, Ocynoga Lederer, Oroncus Seitz, Orontobia de Freina, Palerontobia Dubatolov, Sonorarctia Ferguson, Allanwatsonia Ferguson and Pseudalus Schaus. However, many of the missing species are described from only a few specimens, or from the type series only, and fresh samples are thus extremely difficult to obtain.

Both ML and BI analyses resulted in nearly identical topologies. Within Arctini, the selected 11 species of Callimorphina are segregated into the Callimorphina clade and Nyctemera + Secusto, forming a clade sister to Arctiina. Whether reinstating Nycetermina as a separate subtribe would be necessary, as discussed in Zaspel et al. (2014), is beyond the scope of this study. We find strong support for a large monophyletic grouping of the spilosome genera as separate from Arctiina s.s. Within Arctiina s.s., four well-supported clades are recovered. We find it most informative, and probably also most stable, to consider these clades to represent the generic level within the subtribe. Each clade and the implications of our results on the taxonomy of Arctiina are discussed further in the following. Formal taxonomic revision of the genera is given in Table 1.

In the broad sense, our molecular hypothesis of the evolutionary history of P. plantaginis and relatives is in concordance with earlier phylogenies by Ferguson (1985), Schmidt (2007) and Dubatolov (2008, 2009), which were based on morphological characters, as well as the COI barcode region in Schmidt (2007). Dubatolov (2008, 2009) divided the Arctiina s.s. into ‘Micrarctiini’ and ‘Arctiini’. Dubatolov’s (2009) ‘Micrarctiini’ comprises mostly same genera as in our Diacrisia, Chelis and Apantesis clades, but with different hypothesized phylogenetic relationships. All of Dubatolov’s (2008) ‘Arctiini’ are placed in Arctia as delimited below. Dubatolov (2008) divided ‘Arctiini’ into two clades, one associated with ‘northern and mountainous areas of Asia and North America’ and the other with ‘plains of moderate altitudes’, which correspond largely to our subclades.
‘Northern Arctia’ and ‘Mediterranean Arctia’, but again his tree derived from morphology has a different branching order. Interestingly, Micrarctia is placed as sister to our Arctia.

**Spilosomine genera**

The Spilosoma group has been considered part of Arctiina s.l. (e.g., Ferguson, 1985) or as a separate tribe or subtribe called Spilosomina (e.g., Schmidt, 2007; Vincent & Laguerre, 2014). Zaspel et al. (2014) did not find Spilosomina separate from Arctiina and discussed whether the division has been made in an attempt to categorize moths by similar appearance. In our tree with a larger sampling of Arctiina, the spilosomine genera come out as a well-supported monophyletic group corroborating the preliminary results of Schmidt (2007) – a hypothesis that is also supported by the light wing coloration shared by many species within the group. However, as the spilosomine genera are highly diverse and globally distributed, with hotspots of diversity in the tropical Asia and Africa (Ferguson, 1985), our sampling does not allow substantive interpretation of the interrelationships within the clade. We agree with Fibiger et al. (2011) that this species group needs more work and a thorough phylogenetic revision. We thus prefer to retain the spilosomine genera in the subtribe Arctiina s.l. for the time being.

**Arctina s.s.: Diacrisia, Chelis and Apantesis clades**

Diacrisia, Rhyparia and Rhyparioides have been suggested to be closely related in several studies (Ferguson, 1985; Koda, 1987; Dubatolov, 2009). Our analyses corroborate these studies as we also find them to form a monophyletic entity. Species in this clade differ in their adult forewing coloration and pattern from other Arctiina by their bright yellow and red hues. This group has the highest species diversity in Asia. As Diacrisia is the oldest available genus name for these, we synonymize Rhyparia syn.n. and Rhyparioides syn.n. with Diacrisia.

The second clade combines the rather large genera Chelis and Palaecaria together with many smaller genera. Ferguson (1985) noted the close relationship of Neoarctia, Holarctia, Palaecaria and Hyperborea. The internal relationships of this clade are not well resolved and would benefit from adding more samples of species and genera than are included in our analysis. Due to the well-supported monophyly of this clade, all genera in the Chelis clade are here combined into Chelis.

The third clade comprises almost solely species assigned to Grammia, but also Notarctia proxima (Guérin-Méneville), Apantesis nais (Drury) and A. vittata (Fabricius). The close relationship of Grammia, Notarctia and Apantesis has previously been suggested based on morphological characters (Ferguson, 1985). Arctia [later in Grammia] obliterata Stretch was placed in its own genus Holarctia by Smith, based on its more variable morphology and wider distribution than other Grammia species. Schmidt (2009) considered the species obliterata to be related and probably basal to Grammia, a view corroborated by our analysis. Contrary to Schmidt (2009), however, we find the clade consisting of Grammia syn.n., Holarctia syn.n., Notarctia syn.n. and Apantesis monophyletic with high support, and therefore place all these genera under Apantesis (see Table 1). Synonymy of Holarctia with Apantesis and Holarctia syn.n. with Chelis will also clarify the confusion caused by the similar orthography of these two genus names (Ferguson, 1985).

**Micrarctia**

*Micrarctia trigona* is an especially interesting case of Arctiina tiger moths. The tribe Micrarctini (originally established by Seitz as Micrarctinae) was used by Dubatolov (1990, 2009) to host many superficially similar arctine genera that could not be placed elsewhere. Later, most of these genera were moved to other (sub)tribes, leaving *M. trigona* the only genus and species of Micrarctini. Recently, a second species was described in *Micrarctia* that is sympatric with *M. trigona* (Saldaútas & Pekarsky, 2015). This species, *M. kautti*, is nocturnal, unlike its sister species, and perhaps this is why it had remained unnoticed for so long. It would be intriguing to include *M. kautti* in an analysis to further elucidate the position of *Micrarctia* and thus potentially help to resolve the branching order of all four clades within Arctiina s.s. As the position of *Micrarctia* is not as strongly supported (BS = 86, BP = 0.99) as the other clades (BS = 99–100, BP = 1.0), we prefer to retain it as a valid genus until further work can ascertain its phylogenetic position.

**The Arctia clade**

The unusually short branching within the *Arctia* clade and low support values for internal nodes suggest rapid radiation. This type of quick speciation leaves little phylogenetic evidence in the nuclear genes to study the species-level branching. ‘Arctia’ species (excluding *Micrarctia* at the base of the clade) form a well-supported clade. The superfluous number of monotypic genera that also causes polyphyly of *Arctia* is obviously unwarranted. To render the classification more natural, and also simplify it, we combine all these species under *Arctia* (see Table 1). However, two well-supported subclades can be distinguished – our ‘Northern Arctia’ and ‘Mediterranean Arctia’.

**Northern Arctia and A. caja group**

Many Arctiina species, especially in the ‘Northern Arctia’ clade, are better adapted to cooler environments than most other noctuid moths (Ferguson, 1985). Adapting to cold environments could be one mechanism behind the apparently rapid diversification that has occurred in this clade. The subclade has been divided into many monotypic genera containing some of the most rarely encountered species with almost mysterious life histories. For example, there was a gap lasting for decades between the observations of the Menetries’s Tiger Moth *Borearctia menetriesii* in Finland and the next discovered sites are not only separated by hundreds of kilometres but are also in different habitats (Bolotov et al., 2013).
The species in this subclade are very distinctive, with their conspicuous wing patterns, bright colours and large size. The Garden Tiger Moth *Arctia caja* is no exception, but is in addition very variable in its patterning. Many species, such as *A. intercalaris*, *A. martinhoneyi*, *A. thibetica*, *A. brachyperta* and *A. opulenta*, have been split from *A. caja* based on appearance, but in our molecular hypothesis all these species group together with high support and very little genetic difference. However, as the molecular markers we used in this study are too conservative for inferring interrelationships between very closely related species, other markers should be used to study patterns and levels of differentiation at the species level. We consider the *A. caja* group to be part of the ‘Northern Arctia’ clade.

Dubatolov (2008) arranged his ‘Northern mountainous clade’ to (*Gonerta + Preparctica*) + *Sinoarctia* (*Borearctia + (Pararctica + Platarctica)) + *(Oromotobia + (Oroncus + (Acerbia + Platyprepia))). These genera form our ‘Northern Arctia’ subclade, supplemented with *A. caja* group, *A. flavia*, *A. rueckebeli* and *Pericalia matronula*. There is also some evidence in our dataset (Appendix S1) indicating that *Ebertarctia nordstroemi* (Brandt) could belong to the ‘Northern Arctica’. According to our hypothesis the Nearctic genus, *Platyprepia* is closer to the base and not at the tip of the subclade and *Sinoarctica sieversi* is nested within *Preparctica*. Based on the short branching, we combine all these genera under *Arctia* (see Table 1). By so doing, we again move away from the uninformative monotypic genera.

Some other monotypic genera, such as *Leptarctia* and *Paleronotobia*, that we were not able to sample or to obtain good-quality sequences of, are likely to belong to this subclade, and including them could help to resolve the internal relationships within the subclade. However, we consider it more likely that the low resolution within this subclade results from rapid diversification rather than sparse sampling, as both morphological and molecular data have repeatedly proved indecisive within this subclade (Ferguson, 1985; Dubatolov, 2008, 2009; Weller et al., 2009).

**Mediterranean Arctia**

This is another subclade consisting of the equally showy and colourful *Atlantarctia ungemachi*, *Arctia (=Epicallia) villica*, *Arctia (=Atlantarctia) tigrina*, *Eucharis (=Ammobiota/Arctia) festiva*, *Hyphoraia* spp. and *Parasemia*. As their distribution ranges meet at the Mediterranean, we call this group ‘Mediterranean Arctia’. This monophyletic group includes only a few species, and several of them are already ascribed to *Arctia*. We combine both this subclade and the ‘Northern Arctia’ subclade under *Arctia* (see Table 1). The species in the two subclades are also morphologically quite similar to each other, and these clades lack reliable synapomorphies.

**Concluding remarks and future applications of the phylogeny of Arctiina**

This study stemmed from the need to find the closest relatives of *Arctia plantaginis* to be able to further understand the evolutionary origins of its peculiar polymorphic warning coloration and also tiger moths in general. *Arctia plantaginis* has been suggested to originate in the Caucasus or south-eastern Europe based on COI, ten microsatellite loci haplotypes and species distribution modelling (Hegna et al., 2015). Hegna et al. (2015) hypothesized that, as sexually monomorphic hindwing coloration seems to be ancestral in arctiines, the Caucasian form, *A. plantaginis caucasica*, of which hindwing coloration varies continuously from yellow to red in both sexes, would be ancestral to all other *A. plantaginis*. In other populations, female hindwing coloration still varies continuously from yellow to red, but male hindwing coloration is polymorphic and the ground colour can be white, yellow or black (Fig. 1A–D). Based on our results, the closest relatives of *A. plantaginis*, like *Arctia festiva* (Fig. 1E), are indeed sexually monomorphic in their hindwing coloration, although many species continuously vary in forewing pattern. This comparison implies that the polymorphism in *A. plantaginis* male hindwing coloration is a more recent development.

Another obvious application of our phylogenetic hypothesis is in the study of diversification patterns of Arctiina species. Most Arctiina species are diurnal with polyphagous larvae, feeding on, amongst others, dandelion (*Taraxacum* spp.) and plantain (*Plantago* spp.), including in the Nearctic, where these plants are naturalized European species (Conner, 2009). Dubatolov (2008, 2009) suggests that Arctiina most probably originated in Asia, from where they have spread in multiple occasions to the Western Palearctic and Nearctic. It is also possible, however, that there were some refugia during glaciation periods in the Mediterranean region, which enhanced diversification.

In conclusion, we would like to encourage researchers to study below the surface of these popular, colourful and dazzling species, so as to gain information that escapes our eyes. Our work offers long-awaited clarification of the phylogenetic relationships of Arctiina, especially within Arctiina s.s. – a group of spectacular and popular moths that have been much studied, yet proven difficult to classify with traditional methods. It was beyond our scope to provide a complete systematic revision of *Arctiina* s.l., with a vast majority of the 4000 species occurring in the tropics, and more work needs to be done to solve the evolutionary relationships between and within clades in this highly diverse and specialized group of moths. We hope that our molecular hypothesis for *Arctiina* will work as a backbone, where many more tiger moth species can find their relatives. With rigorous phylogenetic hypotheses, it will be possible to tackle many interesting evolutionary questions to come.

**Supporting Information**

Additional Supporting Information may be found in the online version of this article under the DOI reference: 10.1111/syen.12194

**Appendix S1. Taxon sampling table.** Letter A or B after the species name refers to the voucher positioned to the trees in Fig. 2 and Appendix S2. Samples with less than two
successfully sequenced gene region (min. of approximately 1000 bp) were not included in the final analysis. Samples marked with an asterisk (*) in collection country are from Zaspel et al. (2014).

Appendix S2. Bayesian topology for the same dataset as in the maximum likelihood phylogram in Fig. 2.

Acknowledgements

This work was supported by the Academy of Finland via the Finnish Centre of Excellence programme (Biological Interactions project no. 252411). NW also acknowledges funding from the Academy of Finland. We could not have succeeded without the following samples and valuable information provided to us by Marko Mutanen, Kari Nupponen, Chris Schmidt, Kari Kulmala, Kimmio Silvonen, Ossi Nokelainen, Juan Pino, Hannu Saarenmaa, Jaakko Kullberg, Toomas Tammaru, Peter Huemer, Janne Jokinen and Rogaiahe Ashrafi. We would also like to acknowledge Tōnis Tasane, Reza Zahiri, Jocelyn Gill, Carlos López-Vaamonde, Marko Tähtinen and Leif Aarvik for discussion and practical help with sampling. We are grateful to Sari Vinnikajou, Juho Niva, Sami Kyröläinen and Juan Galarza in Jyväskylä, and Jadranka Rota and Carlos Peña in Turku, for methodological guidance in the DNA laboratory, and Sari Vinnikajou, Juho Niva and Milla Ahola for laboratory assistance. We thank the Finnish Museum of Natural History (LUOMUS) and Kari Nupponen for allowing us to photograph moth samples for the tree in Fig. 2, as well as Bibiana Rojas and Zdenek Hanc for permission to use their photographs in Fig. 1. We would also like to thank three anonymous reviewers, participants of the University of Jyväskylä Ecology and Evolutionary Biology Division journal club, Juan Galarza and Emily Burdfield-Steel for their valuable comments on the manuscript.

Concept and study planning: KR, JM, NW. Laboratory work: KR. Data analysis: NW, KR. Contributing reagents/facilities: JM, NW. Writing of the paper: KR. Reading, commenting and approving the paper: NW, JM, LK. Formal taxonomical revision: LK.

References

Bendib, A. & Minet, J. (1998) Female pheromone glands in Arctiidae (Lepidoptera). Evolution and phylogenetic significance. Animal Biology and Physiology, 321, 1007–1014.

Bolotov, I.N., Gofarov, M.Y., Kolosova, Y.S. & Frolov, A.A. (2013) The maximum likelihood phylogram in Fig. 2. Appendix S2.

Dubatolov, V.V. (2009) Development of a phylogenetic model for the tribe Micractini (Lepidoptera, Arctiidae) with the SYNAP method. Entomological Review, 89, 306–313.

Dubatolov, V.V. & de Vos, R. (2010) Tiger-moths of Eurasia (Lepidoptera, Arctiidae). Neue Entomologische Nachrichten, 65, 1–106.

Ferguson, D.C. (1985) Contributions toward reclassification of the world genera of the tribe Arctini. Part I introduction and revision of the Neoarctia-gramma group (Lepidoptera: Arctiidae; Arctiinae). Entomography, 3, 181–275.

Fibiger, M., László, G., Ronkay, G. et al. (2011) Noctuidae Europeaeanae. Lymnaetinae and Arctiinae including Phylogeny and Check List of the Quadriñl Noctuoidea of Europe, Vol. 13. Entomological Press, Soro.

Galarza, J.A., Nokelainen, O., Ashrafi, R., Hegna, R.H. & Mappes, J. (2014) Temporal relationship between genetic and warning signal variation in the aposematic wood tiger moth (Parasemia plantaginis). Molecular Ecology, 23, 4939–4957. DOI: 10.1111/mec.12913.

Hall, T.A. (1999) BioEdit: a user-friendly biological sequence alignment editor and analysis program for Windows 95/98/NT. Nucleic Acids Symposium Series, 41, 95–98.

Hegna, R. & Mappes, J. (2014) Influences of geographic differentiation in the forewing warning signal of the wood tiger moth in Alaska. Evolutionary Ecology, 28, 1003–1017.

Honma, A., Mappes, J. & Valkonen, J. (2015) To quiver or to shiver: increased melanization benefits thermoregulation, but reduces warning signal efficacy in the wood tiger moth. Proceedings of the Royal Society of London Series B: Biological Sciences, 280, 20122812.

Hegna, R., Galarza, J. & Mappes, J. (2015) Global phylogeography and geographical variation in warning coloration of the wood tiger moth (Parasemia plantaginis). Journal of Biogeography, 42, 1469–1481.

Koda, N. (1987) A generic classification of the subfamily Arctiinae of the Palearctic and Oriental regions based on the male and female genitalia (Lepidoptera, Arctiidae) Part I. Transactions of the Lepidopterological Society of Japan, 38, 153–237.

Kozak, K.M., Wahlberg, N., Neild, A.F., Dasmahapatra, K.K., Mallet, J. & Jiggins, C.D. (2015) Multilocus species trees show the recent adaptive radiation of the mimetic Heliconius butterflies. Systematic Biology, 64, 505–524.

Lafontaine, D. & Schmidt, C. (2010) Annotated check list of the Noctuoidea (Insecta, Lepidoptera) of North America north of Mexico. Zokeys, 40, 1–239.

Lanfear, R., Calcott, B., Ho, S.Y.W. & Guindon, S. (2012) PartitionFinder: combined selection of partitioning schemes and substitution models for phylogenetic analyses. Molecular Biology and Evolution, 29, 1695–1701. DOI: 10.1093/molbev/msw020.

Lindstedt, C., Eager, H., Ihalainen, E., Kahlilainen, A., Stevens, M. & Mappes, J. (2011) Direction and strength of selection by predators for the color of the aposematic wood tiger moth. Behavioral Ecology, 22, 580–587.

Miller, M.A., Pfeiffer, W. & Schwartz, T. (2010) Creating the CIPRES Science Gateway for inference of large phylogenetic trees. Proceedings of the Gateway Computing Environments Workshop (GCE), New Orleans, Louisiana. 14 November 2010, pp. 1–8.

Nokelainen, O., Hegna, R.H., Reudler, J.H., Lindstedt, C. & Mappes, J. (2011) Trade-off between warning signal efficacy and mating
success in the wood tiger moth. Proceedings of the Royal Society of London Series B: Biological Sciences, 279, 257–265. DOI: 10.1098/rspb2010880.

Ojala, K., Julkunen-Tiitto, R., Lindström, L. & Mappes, J. (2005) Diet affects the immune defence and life-history traits of an Arctiid moth Parasemia plantaginis. Evolutionary Ecology Research, 7, 1153–1170.

Ojala, K., Lindström, L. & Mappes, J. (2007) Life-history constraints and warning signal expression in an arctic moth. Functional Ecology, 21, 1162–1167. DOI: 10.1111/j.1365-2435.2007.01322.x.

Peña, C. & Malm, T. (2012) VoSeq: a voucher and DNA sequence web application. PLoS ONE, 7, e39071. DOI: 10.1371/journal.pone.0039071.

Rambaut, A. (2014) FigTree: Molecular Evolution, Phylogenetics and Epidemiology. 2014 Sep 7–v1.4.2. Institute of Evolutionary Biology, University of Edinburgh, Ashworth Laboratories, Edinburgh [WWW document]. URL http://tree.bio.ed.ac.uk/software/figtree/ [accessed on 7 September 2014].

Ratnasingham, S. & Hebert, P.D.N. (2007) BOLD: the barcode of life data system (http://www.barcodinglife.org). Molecular Ecology Notes, 7, 355–364. DOI: 10.1111/j.1471-8286.2007.01678.x.

Ronquist, F., Teslenko, M., van der Mark, P. et al. (2012) MrBayes 3.2: efficient Bayesian phylogenetic inference and model choice across a large model space. Systematic Biology, 61, 539–542.

Saldaitis, A. & Pekarsky, O. (2015) A new species Micraria kauitti (Lepidoptera: Erebidae, Arctiinae) from West China. Zootaxa, 3955, 291–294.

Schmidt, B.C. (2007) Systematics of Grammia tiger moths (Lepidoptera: Noctuidae). PhD Thesis, University of Alberta, Canada.

Schmidt, B.C. (2009) Taxonomic revision of the genus Grammia Rambur (Lepidoptera: Noctuidae: Arctiinae). Zoological Journal of the Linnean Society, 156, 507–597.

Seitz, A. (1910) Familiie: Arctiidae, Bärenspinner. Die Gross-Schmetterlinge der Erde. I Abt.: Die Gross-Schmetterlinge des Palauarkischen Faunengebietes, Band 2: Die Palauarkischen Spinner & Schwarmer (ed. by A. Seitz), pp. 43–103, t. 10-18, 56. Alfred Kernen, Stuttgart.

Simmons, R. (2009) Adaptive coloration and mimicry. Tiger Moths and Woolly Bears: Behavior, Ecology, and Evolution of the Arctiidae (ed. by W.E. Conner), pp. 115–126. Oxford University Press, New York, New York.

Stamatakis, A. (2014) RAxML version 8: a tool for phylogenetic analysis and post-analysis of large phylogenies. Bioinformatics, 30, 1312–1313. DOI: 10.1093/bioinformatics/btu033.

Stevens, M. & Ruxton, G., D. (2012) Linking the evolution and form of warning coloration in nature. Proceedings of the Royal Society of London Series B, 279, 417–426.

Tamura, K., Peterson, D., Peterson, N., Stecher, G., Nei, M. & Kumar, S. (2011) MEGA5: molecular evolutionary genetics analysis using maximum likelihood, evolutionary distance, and maximum parsimony methods. Molecular Biology and Evolution, 28, 2731–2739, [WWW document]. URL http://www.megasoftware.net [accessed on 12 June 2013].

Towns, J., Cockerill, T., Dahan, M. et al. (2014) XSEDE: accelerating scientific discovery. Computing in Science & Engineering, 16, 62–74. DOI: 10.1109/MCSE.2014.80.

Vincent, B. & Laguerre, M. (2014) Catalogue of the Neotropical Arctiini Leach,[1815](except Ctenuchina Kirby, 1837 and Euchromiina Butler, 1876)(Insecta, Lepidoptera, Erebidae, Arctiinae). Zoosystema, 36, 137–533.

Wahlberg, N. & Wheat, C. (2008) Genomic outposts serve the phylogenomic pioneers: designing el nuclear markers for genomic DNA extractions of Lepidoptera. Systematic Biology, 57, 231–242.

Weller, S.J., Dacosta, M., Simmons, R., Dittmar, K. & Whiting, M. (2009) Evolution and taxonomic confusion in Arctiidae. Tiger Moths and Woolly Bears: Behavior, Ecology, and Evolution of the Arctiidae (ed. by W.E. Conner), pp. 11–30. Oxford University Press, New York, New York.

Zahiri, R., Kitching, I.J., Lafontaine, J.D., Mutanen, M., Kaila, L., Holloway, J.D. & Wahlberg, N. (2011) A new molecular phylogeny offers hope for a stable family level classification of the Noctuoidea (Lepidoptera). Zoologica Scripta, 40, 158–173.

Zahiri, R., Holloway, J.D., Kitching, I.J., Lafontaine, J.D., Mutanen, M. & Wahlberg, N. (2012) Molecular phylogenetics of Erebidae (Lepidoptera, Noctuoidea). Systematic Entomology, 37, 102–124.

Zaspel, J.M., Weller, S.J., Dacosta, M., Simmons, R., Dittmar, K. & Whiting, M. (2009) Evolution and taxonomic confusion in Arctiidae. Tiger Moths and Woolly Bears: Behavior, Ecology, and Evolution of the Arctiidae (ed. by W.E. Conner), pp. 11–30. Oxford University Press, New York, New York.

Zahiri, R., Kitching, I.J., Lafontaine, J.D., Mutanen, M., Kaila, L., Holloway, J.D. & Wahlberg, N. (2011) A new molecular phylogeny offers hope for a stable family level classification of the Noctuoidea (Lepidoptera). Zoologica Scripta, 40, 158–173.

Zahiri, R., Holloway, J.D., Kitching, I.J., Lafontaine, J.D., Mutanen, M. & Wahlberg, N. (2012) Molecular phylogenetics of Erebidae (Lepidoptera, Noctuoidea). Systematic Entomology, 37, 102–124.

Zaspel, J.M., Weller, S.J., Dacosta, M., Simmons, R., Dittmar, K. & Whiting, M. (2009) Evolution and taxonomic confusion in Arctiidae. Tiger Moths and Woolly Bears: Behavior, Ecology, and Evolution of the Arctiidae (ed. by W.E. Conner), pp. 11–30. Oxford University Press, New York, New York.

Zahiri, R., Kitching, I.J., Lafontaine, J.D., Mutanen, M., Kaila, L., Holloway, J.D. & Wahlberg, N. (2011) A new molecular phylogeny offers hope for a stable family level classification of the Noctuoidea (Lepidoptera). Zoologica Scripta, 40, 158–173.

Zahiri, R., Holloway, J.D., Kitching, I.J., Lafontaine, J.D., Mutanen, M. & Wahlberg, N. (2012) Molecular phylogenetics of Erebidae (Lepidoptera, Noctuoidea). Systematic Entomology, 37, 102–124.