STATUS OF MOTH DIVERSITY AND TAXONOMY: A COMPARISON BETWEEN AFRICA AND NORTH AMERICA NORTH OF MEXICO

BY

JOHN PICKERING, DOROTHY MADAMBA, TORI STAPLES AND REBECCA WALCOTT

Abstract -- We analyzed 21,375 African and 11,799 North American moth species from AfroMoths and Discover Life. For North, West, Central, East and Southern African regions and North America north of Mexico, we compared species totals for selected higher taxa and for when taxonomists published species descriptions. Currently Africa has 1.8 times as many described moths as North America north of Mexico, but this number underestimates the relative richness of African moth diversity. Trends in the annual rate of species descriptions suggest that there are many yet undescribed African moths relative to the United States and Canada. For the "*macro moths*" (Geometroidea, Drepanoidea, Noctuoidea, Bombycoidea, Lasiocampidae) there are 2.3 times as many described African species. For "*other moths*", there are only 1.4 times as many, suggesting that for much of Africa, the relative exception being South Africa, a higher proportion of small species may remain yet undescribed. Notably, there are currently more described species in Tortricidae, Gelechioidea, Yponomeutoidea and Gracillarioidea for North America than Africa. Taxonomists are still describing many new species within charismatic groups of large moths, namely the Arctiinae, Saturniidae and Sphingidae, in East and Central Africa. We frame this article in the context of the *African Moth Inventory*, a new initiative of Discover Life, which we invite Southern Lepidopterists' Society members to join.

Introduction -- With the SLS and other partners, Discover Life's *Mothing* project (discoverlife.org/moth) is building a network of study sites to compare how moth communities differ geographically and respond to environmental factors. This article is the fourth SLN article on *Mothing*. Previously Pickering (2015) gave a project overview and invited SLS members to participate. Pickering (2016) considered how '*pupa banks*' and moth coloration might help explain observed seasonal flight patterns. Also Pickering & Staples (2016) analyzed 1,825 nightly samples from a site in Georgia to determine how to sample moth diversity efficiently. They found that 13 samples/year (3.6% of all nights) taken on each new moon, the most productive night of the lunar cycle, yielded 48% of the 1,256 species recorded by sampling every night.

Mothing has now collected 610,000 photographs on over 3,000 moth species at study sites in eastern North America and Costa Rica. With the help of Moth Photographers' Group and others, it has assembled photographs and provides online identification guides to many North and Central American species. Discover Life is expanding *Mothing* to other places. With the Natural History Museum of Zimbabwe, Bulawayo, and the Sam Houston State Natural History Collections, Huntsville, Texas, we here propose the *African Moth Inventory*.

African Moth Inventory

Our first goal for this initiative is to enhance online tools so that one can rapidly database and identify African moths using photography. We envision developing capabilities for Africa similar to those available for the United States and Canada from Discover Life, Moth Photographers' Group, and related websites. Notably, we plan to build country- and local- level identification guides to African moths that use diagnostic images. Using these tools with sampling protocols, we plan to train participants to inventory parks and other areas. Our ultimate goal is to provide high-quality inventories to policy makers and land managers to help improve nature conservation in Africa.

Our inventory will require authority files of valid taxa, diagnostic photographs, local checklists based on occurrence records, identification guides, and sampling sites. Below we address the first of these requirements, using www.AfroMoths.net, an extensive database of moths in the Afrotropical biogeographic region (De Prins & De Prins 2016). We show the status of African versus North American moth taxonomy with respect to a) 5 regions and 18 selected countries within mainland Africa, b) a phylogeny showing 38 higher taxa, and c) the accumulative number of valid species by year since Linnaeus described the first ones in 1758. This taxonomy is the foundation upon which we will work to address the other requirements.

Methods & Results

Databases

We extracted moth species data from AfroMoths and Discover Life. For Africa we captured all taxon pages served by AfroMoths using a web robot and parsed the data, filtering them for valid species binomials, years of publication, higher taxa, and geographic ranges by country. Of the 27,635 valid moth species served by AfroMoths, we excluded species from Arabia,

Madagascar, and elsewhere that are not explicitly listed with a range on the African mainland. This resulted in a total of 21,375 continental species in 46 countries.

For North America we processed the 12,036 moth species in Discover Life's identification guide and checklist of North America north of Mexico (Pickering 2010), excluding the names of unpublished morphospecies and for which Discover Life's database did not include an occurrence record on the continent north of Mexico. This resulted in 11,799 species.

Discover Life currently has 1.3 million species names in its taxonomic authority files. It attempts to keep these current, but its lists are incomplete and contain errors. Its checklist for North American moths was initially obtained from Nearctica.com (Poole & Gentili 1996-1997) and has been updated with information from Moth Photographers' Group and other sources. As a test of its completeness, we compared its Pyraloidea with Scholtens & Solis's (2015) recent checklist of this superfamily which Discover Life has not yet used to update its names. Scholtens & Solis list 1,542 species (861 Crambidae and 681 Pyralidae). Discover Life has 1,538.

African regions

There is considerable work on the biogeography of Afrotropical butterflies that covers over 4,000 species in sub-Saharan Africa, Arabia, and Madagascar (Ackery et al. 1995; Larsen 2005; Pringle et al. 1994, Williams 2007). This work guided us in clustering moth species into five continental regions to present trends across Africa. Our regions are North, West, Central, East and Southern Africa. As the initial foundation for each, we used the species lists of Egypt, Nigeria, Democratic Republic of Congo, Kenya, and South Africa, respectively. These countries have the longest species lists in their regions. We then iteratively clustered the remaining 41 countries' lists into regions based on the number of species within each country overlapping with those in the growing regions. To reduce statistical issues associated with differences between regional sample sizes, we attempted to add country lists such that the number of species in each region remained similar. This was largely possible for Central, East and Southern Africa which finally totaled 7,903, 8,847, and 8,563 species, respectively, but not for North and West Africa which finally totaled 1,223 and 4,346, respectively.

Table 1 presents the overlap in species across the five regions and 18 selected countries (Egypt, Sudan, and the 16 countries with lists exceeding 1,000 species). Details on each region are given below and shown on the map, with the circles increasing in size with the number of species in each country list.

North Africa (cyan) includes Algeria, Egypt, Western Sahara, Chad, Mali, Mauritania, Niger, Sudan (Morocco, Tunisia and Libya). In considering butterflies, Larsen (2005) includes Mali, Mauritania and Niger in West Africa. As these three countries are largely desert, we lumped them in with North Africa based on relatively few species: 59, 217, and 213 species, respectively. AfroMoths had no records for Morocco, Tunisia and Libya.

		North	EG	SU	West	GH	NI	SL	Cent.	AO	CM	CG	GB	East	ET	KE	MI	TZ	UG	ZA	South.	MZ	SF	ZI
North		**1,223**																						
Egypt	EG	423	**423**																					
Sudan	SU	648	162	**648**																				
West		456	102	275	**4,346**																			
Ghana	GH	188	37	110	1,442	**1,442**																		
Nigeria	NI	297	54	182	2,109	677	**2,109**																	
Sierra Leone	SL	151	28	89	1,258	491	546	**1,258**																
Central		398	78	248	2,224	930	1,193	808	**7,903**															
Angola	AO	131	24	90	467	266	309	208	1,095	**1,095**														
Cameroon	CM	172	29	102	1,225	578	720	511	2,559	357	**2,559**													
D.R. Congo	CG	320	68	203	1,604	733	891	630	5,100	615	1,200	**5,100**												
Gabon	GB	59	11	33	621	314	367	260	1,245	191	648	645	**1,245**											
East		556	143	378	1,686	732	915	628	3,095	674	1,025	2,502	423	**8,847**										
Ethiopia	ET	265	75	201	431	181	263	164	593	188	237	482	79	1,545	**1,545**									
Kenya	KE	374	95	258	921	421	507	361	1,586	409	565	1,287	200	3,685	698	**3,685**								
Malawi	MI	191	39	133	574	271	344	240	962	332	324	825	117	1,839	298	783	**1,839**							
Tanzania	TZ	280	64	200	763	340	433	310	1,371	408	498	1,150	194	3,066	533	1,314	824	**3,066**						
Uganda	UG	241	44	175	901	462	554	392	1,572	359	701	1,301	296	2,508	401	1,132	527	805	**2,508**					
Zambia	ZA	170	31	123	490	212	271	224	928	333	274	811	123	1,452	248	623	651	661	412	**1,452**				
Southern		400	113	266	1,063	411	556	407	1,772	490	469	1,455	170	2,657	575	1,497	1,118	1,263	805	996	**8,563**			
Mozambique	MZ	154	39	102	411	193	228	185	672	245	222	583	83	960	235	600	602	581	348	558	1,364	**1,364**		
South Africa	SF	353	104	230	890	350	475	348	1,414	398	376	1,162	135	2,103	513	1,265	877	1,017	657	771	6,810	914	**6,810**	
Zimbabwe	ZI	243	58	166	632	263	346	267	1,118	368	325	943	117	1,632	390	952	866	877	539	849	2,563	842	1,717	**2,563**

Table 1 -- Overlap in moth species across Africa.
Values are for 5 regions (pink cells) and 18 countries. The bold values along the diagonal give total species. The remaining values give the number overlapping. The green cell value of 1,287, for example, is the number of Kenya's 3,685 species that overlap with the Democratic Republic of the Congo's (column CG) 5,100.

Map - Five African moth regions as of 2016.

West Africa (orange) includes Benin, Burkina Faso, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Nigeria, Senegal, Sierra Leone and Togo. Based on butterflies, Larsen (2005) includes parts of Cameroon as West Africa. The values in Table 1 tend to confirm Cameroon as the transitional country between our East and Central regions. Of the 2,559 moth species in Cameroon, 1,225 occur in West Africa and 1,200 in the Democratic Republic of Congo.

Central Africa (blue) includes Angola, Burundi, Cameroon, Central African Republic, Congo, Democratic Republic of Congo, Equatorial Guinea, Gabon and Rwanda.

East Africa (red) includes Djibouti, Eritrea, Ethiopia, Kenya, Malawi, Somalia, South Sudan, Tanzania, Uganda and Zambia.

Southern Africa (green) includes Botswana, Lesotho, Mozambique, Namibia, South Africa, Swaziland and Zimbabwe. Based on butterflies, Ackery et al. (1995) consider Southern Africa to extend from the Cape to Cunene River (on the southern border of Angola) in the west and to the Zambezi River (splitting Mozambique) in the east. Based on the overlap of moth species, we clustered Mozambique in Southern Africa.

Phylogeny

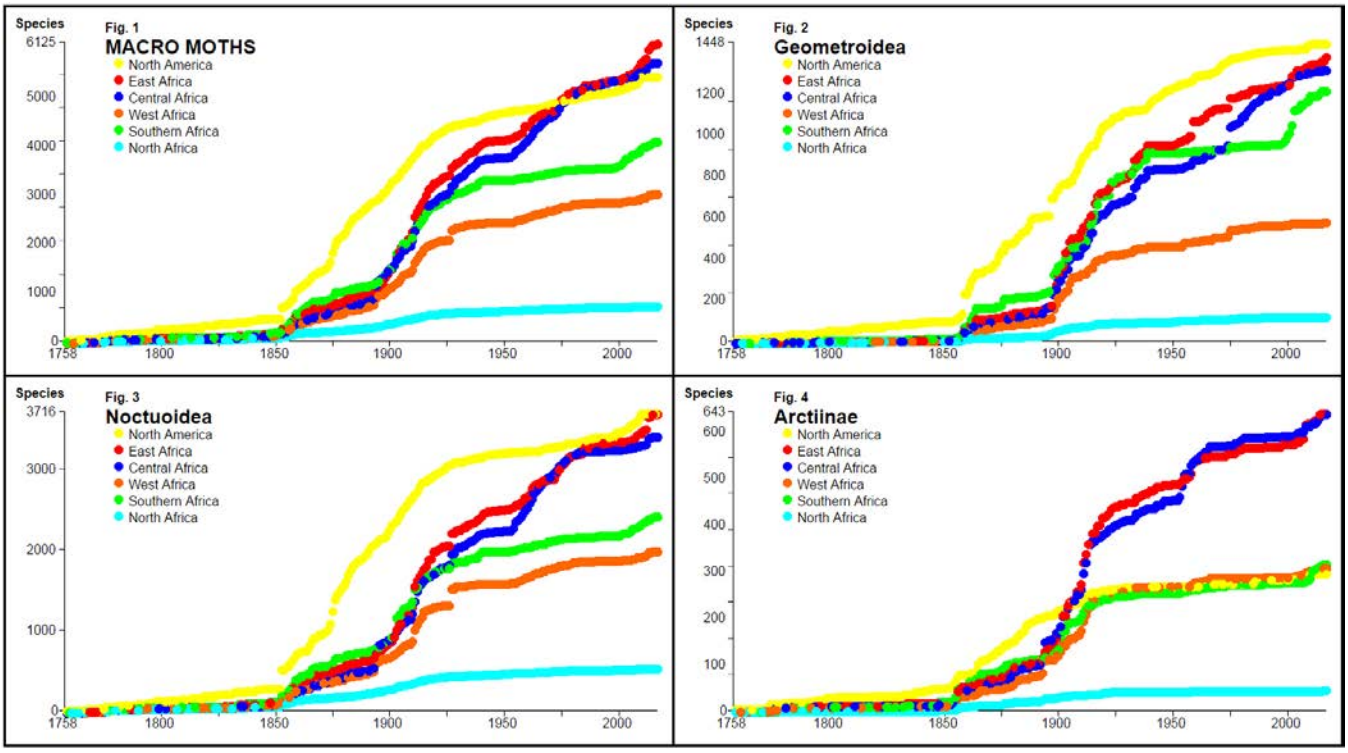
We tabulated all species into higher taxa based on the list at discoverlife.org/moth/highertaxa.txt These higher taxa follow the phylogeny for Lepidoptera of the Tree of Life web project (tolweb.org). Notably we divide moth species into *macro moths* (Geometroidea, Drepanoidea, Noctuoidea, Bombycoidea, Lasiocampidae) and *other moths*, the micros and primitive groups. Table 2 presents the number of *macro moths* and *other moths* for Africa, North America north of Mexico, and the five African regions. It also gives the number of described species in 36 selected superfamilies, families, and subfamilies. We tallied values for all species within their appropriate higher groups but only show selected higher taxa. Thus, for example, we added the Arctiinae values to Erebidae (not shown), Noctuoidea, and *macro moths*. The *ratio* column is the multiplier of Africa (pink) and North America (green) values. Its cells are pink when there are more African species and green with more North American. For example, there are 29.3 times as many African than North American species in Lymantriinae (Noctuoidea: Erebidae).

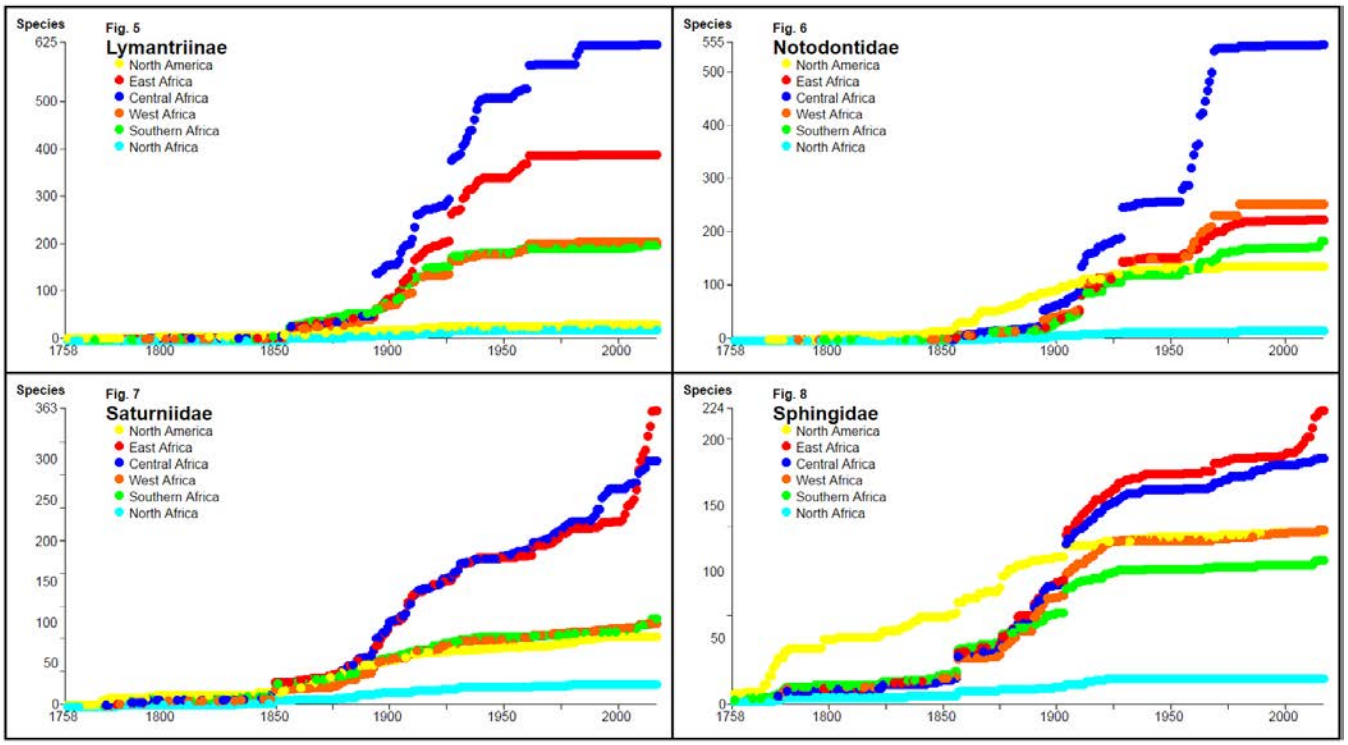
Table 2	Africa	North America	ratio	North Africa	West Africa	Cent. Africa	East Africa	South. Africa
Total	**21,375**	**11,799**	**1.8**	**1,223**	**4,346**	**7,903**	**8,847**	**8,563**
MACRO MOTHS Fig.1	12,788	5,444	2.3	756	3,042	5,736	6,125	4,123
Geometroidea Fig.2	3,092	1,448	2.1	126	583	1,319	1,384	1,220
Noctuoidea Fig.3	7,863	3,716	2.1	552	1,998	3,431	3,709	2,436
Arctiinae Fig.4	1,201	298	4.0	48	310	642	643	320
Lymantriinae Fig.5	997	34	29.3	23	209	625	392	201
Nolidae	605	28	21.6	26	189	202	300	150
Notodontidae Fig.6	824	138	6.0	19	256	555	227	187
Bombycoidea	1,135	223	5.1	49	284	627	698	295
Eupterotidae	218	0	-	1	39	111	78	65
Saturniidae Fig.7	565	86	6.6	27	102	302	363	108
Sphingidae Fig.8	300	132	2.3	21	134	188	224	111
Lasiocampidae	645	36	17.9	29	151	319	314	166
OTHER MOTHS Fig.9	8,587	6,355	1.4	467	1,304	2,167	2,722	4,440
Thyrididae	188	12	15.7	9	74	120	112	67
Pyraloidea Fig.10	2,404	1,538	1.6	248	507	729	759	1,084
Crambidae	1,283	859	1.5	104	312	533	543	500
Pyralidae	1,120	679	1.6	144	195	196	215	583
Tortricidae Fig.11	841	1,317	1.6	17	180	209	341	303
Zygaenoidea	637	101	6.3	13	129	294	247	195
Limacodidae Fig.12	423	52	8.1	10	105	183	171	126
Pterophoridae	315	161	2.0	14	36	95	194	170
Sesioidea	256	130	2.0	1	41	61	98	98
Cossoidea Fig.13	400	48	8.3	33	79	102	167	135
Gelechioidea Fig.14	1,717	1,808	1.1	61	89	229	311	1,253
Coleophoridae	97	284	2.9	3	2	16	24	65
Cosmopterigidae	125	171	1.4	11	10	27	20	82
Gelechiidae	725	881	1.2	16	33	79	83	611
Lecithoceridae	120	0	-	3	16	35	35	54
Oecophoridae	116	187	1.6	1	2	11	6	99
Scythrididae	274	43	6.4	14	9	12	93	175
Yponomeutoidea	132	240	1.8	3	8	31	35	85
Gracillarioidea Fig.15	280	413	1.5	5	30	26	62	198
Gracillariidae	251	302	1.2	4	29	25	60	174
Tineoidea Fig.16	895	218	4.1	59	111	218	310	448
Acrolophidae	0	69	-	0	0	0	0	0
Psychidae	278	25	11.1	19	31	70	94	126
Tineidae	550	124	4.4	40	78	143	205	263
Nepticulidae	136	96	1.4	1	9	0	2	124

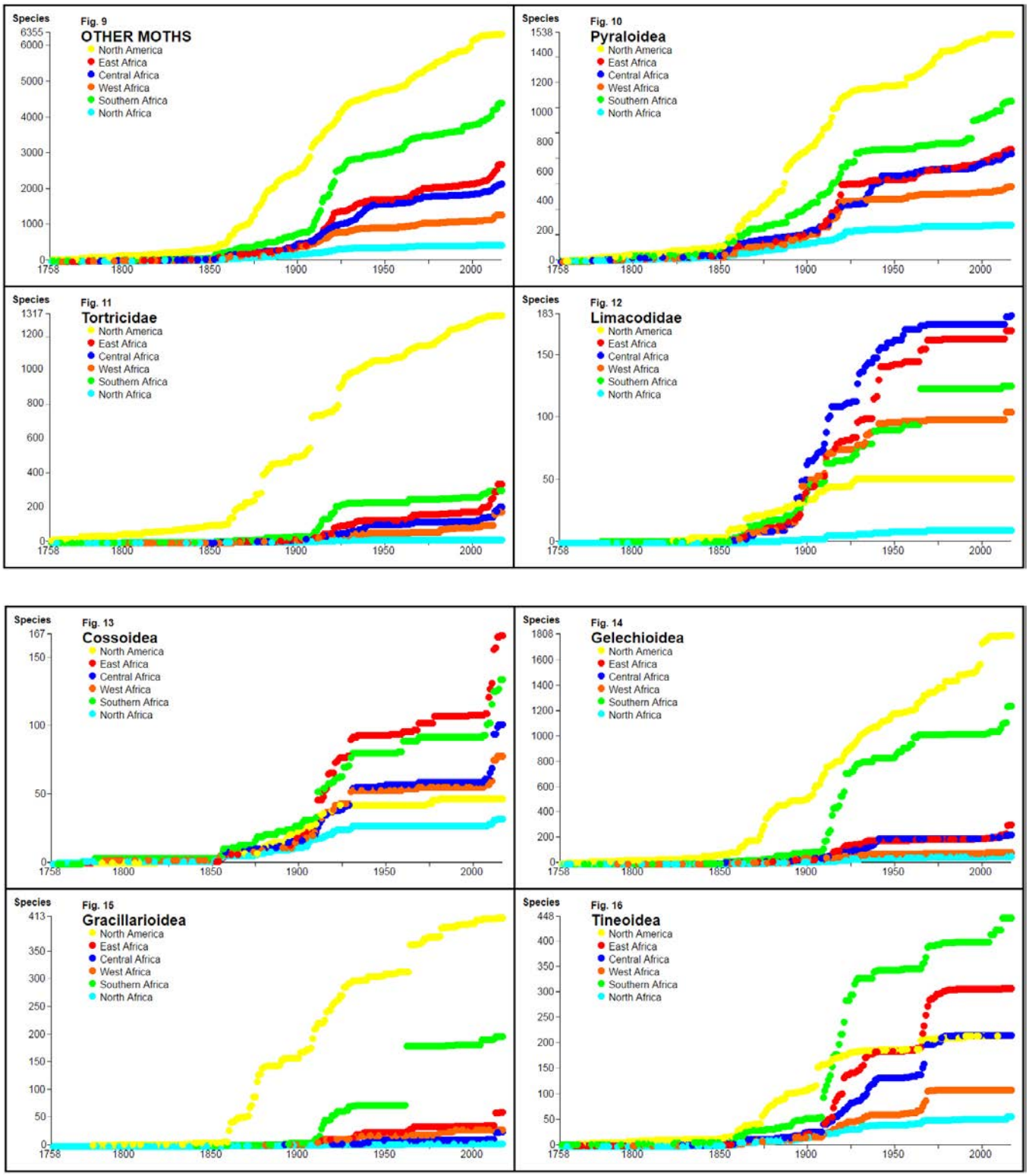
African and North American moth species tabulated by higher taxa.

Accumulated species published by year

For the North American species and five African regions Figures 1 - 16 present the annual accumulation of valid species names published by taxonomists, starting with Linnaeus in 1758. They are listed in Table 2 and cover *macro moths* (in total, plus Geometroidea, Noctuoidea, Arctiinae, Lymantriinae, Notodontidae, Saturniidae, Sphingidae treated individually) and *other moths* (in total, plus Pyraloidea, Tortricidae, Limacodidae, Cossoidea, Gelechioidea, Gracillarioidea, Tineoidea treated individually).







Discussion

Four factors greatly influence our knowledge of species richness and distribution across geographic scales: 1) the underlying biological and environmental processes over millions of years that drive species diversity and distributions, 2) taxonomic naming, the completion of which differs across regions and higher taxa for numerous economic, political, and social reasons, 3) inventory effort to record what's where and when, once species have names, and 4) informatics and dissemination, which have a time-lag in gathering, integrating, and presenting data from the multitude of available sources. So, that said, *caveat emptor*. Our results show moth biogeography across continents through the fog of incomplete taxonomy and informatics!

We begin with a cautionary note of the importance of changes in human effort. Our results reflect in part how the Second World War impacted the taxonomy of African moths more than for the United States and Canada. Taxonomists published 1,545 new African species between 1929-1939, which dropped to 365 between 1939-1949, and recovered to 829 between 1949-1959. For the United States and Canada, the comparable numbers for these respective decades are 271, 300, and 199.

Table 1 is a first approximation in the overlap of species between African regions and countries. It is based only on the countries listed for each species in AfroMoths. Our next step is to refine this table by including existing occurrence records from the Global Biodiversity Information Facility (GBIF), digitizing museum collections, partnering with relevant websites, and eventually, inventorying moths at parks and other sites.

Table 2 shows that continental Africa has a larger moth fauna than North America north of Mexico, with totals in the source databases when accessed being 21,375 and 11,799, respectively, or 1.8 times as many moths in Africa than North America. This comparison is beset with two major problems. First, it lacks Mexican data and the associated tropical species richness of North America. Secondly, as shown by Figures 1 - 16, the completion of taxonomic naming differs considerably across higher taxa and regions.

In general our results show that there are large differences between the African and North American rates of species publications across taxa. While *macro moths* are still being described in the United States (Fig. 1), particularly for the Geometroidea (Fig. 2) and Noctuoidea (Fig. 3), the naming of large, charismatic species is largely complete, as is shown for the Arctiinae (Fig. 4), Lymantriinae (Fig. 5), Notodontidae (Fig. 6), Saturniidae (Fig. 7) and Sphingidae (Fig. 8). This is not true for Africa where large numbers of these higher taxa, except for the Lymantriinae and Notodontidae, are being described, particularly for East and Central Africa (red and blue points).

Fig. 9 compares the overall trends for *other moths*. For the most part, new species descriptions have slowed in the last decade for the United States and Canada, a trend that may be because alpha taxonomy is less fashionable than it once was, rather than nearing completion in describing all species. The Pyraloidea (Fig. 10) show strong recent taxonomy in Africa, especially for the Southern region. The Tortricidae (Fig. 11) may reflect minimal work in Africa until recently, as shown by the recent increase for East Africa. The Limacodidae (Fig. 12) show no increase in species for decades in North America but recently have some new descriptions published for Africa. Cossoidea (Fig. 13) are flat for North America but are still being described in numbers within Africa. The small micros in the superfamilies Gelechioidea (Fig. 14), Gracillarioidea (Fig. 15) and Tineoidea (Fig. 16) show growth in numbers, particularly for Southern Africa. Their values caution that all the growth curves depend on the productivity of individual taxonomists. For example, Fig. 15 has a large step for Southern Africa (green) when Vári (1961) published 106 new species in Gracillarioidea.

In terms of family level biogeographical absences and large differences shown in Table 2, there are no Eupterotidae and Lecithoceridae in North America north of Mexico and no Acrolophidae in Africa. There are over 6 times as many Lymantriinae, Nolidae, Saturniidae, Thyrididae, Zygaenoidea, Lasiocampidae, Cossoidea, Scythrididae and Psychidae in Africa than in North America north of Mexico. Some of these differences may reflect underlying temperate versus tropical factors rather than biogeographical differences between the continents per se.

Conclusions

We posit that inventories of diverse lepidopteran communities can serve as both bioindicators of environmental changes over time and proxies of differences across geographic scales of the broader flora and fauna. Lepidopteran species are restricted by their larval host specificity, typically, to a limited number of plant, lichen, or fungal taxa. As such, we expect that a site's resident lepidopteran species will reflect its flora and differ with other sites in response to changes across their host communities. Because moths are attracted to lights, they are easy to inventory rapidly and safely (Pickering & Staples 2016). They do not require the considerable effort needed in bashing around the bush, finding primates, plants, birds, butterflies and other groups typically used to classify and compare biota. Because of the paucity of information about the composition of the biota of many African parks and conservation areas, we call for the *African Moth Inventory* as a first approximation to fill in gaps in our knowledge.

In 2017 Discover Life plans to study moths across more sites in the Americas and refine our standardized sampling methods to document and compare communities. We are recruiting museums, websites, other organizations, and individual participants to provide expertise and data for the *African Moth Inventory*, help inventory sites, and determine specimens. We plan to start photographing synoptic specimens of moths in the Natural History Museum of Zimbabwe and building identification guides for Africa. We will make all images, guides and associated data freely available online to everyone.

We encourage SLS members to help. We will host two organizational and training meetings in 2016: 30 October in Gainesville, Florida, at the end of the SLS meeting; and 9-11 December in Athens, Georgia, when Discover Life will celebrate 4 billion hits and plan for the future. For details go to Discover Life's *Events* page. Please, join us!

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John Pickering, Odum School of Ecology, University of Georgia, Athens, GA 30602
pick@discoverlife.org and (706) 254-7446 (cell)

Dorothy Madamba, Natural History Museum of Zimbabwe &
Natural History Collections, Sam Houston State University, Huntsville, TX 77341
madambadc@shsu.edu

Tori Staples, Discover Life, Stanford, CA
tori@discoverlife.org

Rebecca Walcott, Discover Life, Athens, GA
dl@discoverlife.org

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