Supplementary Material

**The global biogeography of avian haemosporidian parasites is characterized by local diversification and intercontinental dispersal**

Vincenzo A. Ellis, Eloisa H. R. Sari, Dustin R. Rubenstein, Rebecca C. Dickerson, Staffan Bensch, and Robert E. Ricklefs

Table S1—We captured individuals of the sympatric starling species *Lamprotornis hildebrandti* (n = 24) and *L. superbus* (n = 10) using baited traps and mist-nets at the Mpala Research Centre, Laikipia, Kenya (08.17°N, 378.52°E). Blood samples were collected from the brachial or jugular veins and stored in 2% SDS Queens Lysis Buffer. We extracted DNA from each blood sample using Qiagen DNeasy Blood & Tissue Kits and screened them for avian haemosporidians and sequenced the cytochrome *b* genes of parasites in infected birds using established protocols (Waldenström *et al.*, 2004; Fecchio *et al.*, 2013; Svensson-Coelho *et al.*, 2013).

|  |  |  |
| --- | --- | --- |
| **Host species** | **Infected/Sampled** | **Lineages found** |
| *Lamprotornis hildebrandti* | 6/24 | SGS1, WW4, SYAT05, AFS3 |
| *Lamprotornis superbus* | 3/10 | SGS1, WW4, SYAT05 |

Table S2—Lineages that are identical between MalAvi and the Ricklefs lab database.

|  |  |  |
| --- | --- | --- |
| **MalAvi Name** | **Ricklefs lab Name** | **Reference** |
| SGS1 | AFS1 | Rubenstein Ellis and Ricklefs unpublished data |
| WW4 | AFS2 | Rubenstein Ellis and Ricklefs unpublished data |
| SYAT05 | AFS4 | Rubenstein Ellis and Ricklefs unpublished data |
| CYPHIR03 | CEhapB | Ricklefs *et al.*, 2014 |
| NEOFAS01 | CEhapP | Ricklefs *et al.*, 2014 |
| VIOLI03 | OZ36 | Ricklefs *et al.*, 2014 |
| LAIRI01 | CHI17PL | Ricklefs *et al.*, 2014 |
| LOXLEU01 | CHI08PA | Ricklefs *et al.*, 2014 |
| COLL2 | CHI19PA | Ricklefs *et al.*, 2014 |
| GYMSAL01 | CHI20PA | Ricklefs *et al.*, 2014 |
| VIOLI06 | CHI29PA | Ellis and Ricklefs unpublished data |
| CATUST22 | CHI32PA | Ricklefs *et al.*, 2014 |
| PHAPAL01 | DR01 | Ricklefs *et al.*, 2014 |
| SPIDOM01 | DR05 | Ricklefs *et al.*, 2014 |
| ZEAUR05 | DR09 | Ricklefs *et al.*, 2014 |
| COLPAS03 | GA01 | Ricklefs *et al.*, 2014 |
| COLPAS04 | GA02 | Ricklefs *et al.*, 2014 |
| VIGIL07 | GD03 | Ricklefs *et al.*, 2014 |
| ICTLEU01 | JA01 | Ricklefs *et al.*, 2014 |
| RAMCAR01 | JA09 | Ricklefs *et al.*, 2014 |
| BT7 | KZ02 | Ricklefs *et al.*, 2014 |
| DENMAG01 | KZ04 | Ricklefs *et al.*, 2014 |
| MAFUS02 | LA01 | Ricklefs *et al.*, 2014 |
| COFLA06 | LA07 | Ricklefs *et al.*, 2014 |
| MAFUS04 | LA19 | Ricklefs *et al.*, 2014 |
| MOLBON01 | LA20 | Ricklefs *et al.*, 2014 |
| PHEMEL02 | LA22 | Ricklefs *et al.*, 2014 |
| AGICT01 | LA24 | Ricklefs *et al.*, 2014 |
| TIABIC01 | LA27 | Ricklefs *et al.*, 2014 |
| TABI02 | MI04 | Ricklefs *et al.*, 2014 |
| RWB01 | NA01 | Ricklefs *et al.*, 2014 |
| TUMIG03 | NA03 | Ricklefs *et al.*, 2014 |
| TOXRUF01 | NA05 | Ricklefs *et al.*, 2014 |
| TATHA01 | NA07 | Ricklefs *et al.*, 2014 |
| ZOLEU01 | NA11 | Ricklefs *et al.*, 2014 |
| TUMIG06 | NA15 | Ricklefs *et al.*, 2014 |
| PADOM11 | OZ01 | Ricklefs *et al.*, 2014 |
| COFLA04 | OZ02 | Ricklefs *et al.*, 2014 |
| TABI02 | OZ03 | Ricklefs *et al.*, 2014 |
| ICTCAY01 | OZ04 | Ricklefs *et al.*, 2014 |
| VIGIL07 | OZ05 | Ricklefs *et al.*, 2014 |
| GEOTRI01 | OZ06 | Ricklefs *et al.*, 2014 |
| SPIARB01 | OZ07 | Ricklefs *et al.*, 2014 |
| ICTVIR01 | OZ08 | Ricklefs *et al.*, 2014 |
| COFLA10 | OZ19 | Ricklefs *et al.*, 2014 |
| LOXPOR01 | OZ21 | Ricklefs *et al.*, 2014 |
| BAEBIC03 | OZ25 | Ricklefs *et al.*, 2014 |
| VIGRI02 | OZ26 | Ricklefs *et al.*, 2014 |
| DENDIS01 | OZ34 | Ricklefs *et al.*, 2014 |
| WW3 | OZ45 | Ricklefs *et al.*, 2014 |
| BNOW03 | RP02 | Ricklefs *et al.*, 2014 |
| HYLNAE02 | TI-P14 | Ricklefs *et al.*, 2014 |
| MYRMYO02 | TI-P15 | Ricklefs *et al.*, 2014 |
| CYCYA01 | TI-P24L | Ricklefs *et al.*, 2014 |
| MYRFOR03 | TI-P27 | Ricklefs *et al.*, 2014 |
| LEPCOR02 | TI-P30 | Ricklefs *et al.*, 2014 |
| MYRMAX01 | TI-P32L | Ricklefs *et al.*, 2014 |
| THAMB01 | TI-P33L | Ricklefs *et al.*, 2014 |
| AUTINF03 | TI-P36 | Ricklefs *et al.*, 2014 |
| XIPPAR01 | TI-P41L | Ricklefs *et al.*, 2014 |
| MIMGIL01 | YU02 | Ricklefs *et al.*, 2014 |
| COFLA11 | YU04 | Ricklefs *et al.*, 2014 |

Table S3—Lineages from the Ricklefs lab database that were not found in MalAvi.

|  |  |  |
| --- | --- | --- |
| **Lineage Name** | **Genus** | **Reference** |
| AFS3 | *Plasmodium* | Rubenstein Ellis and Ricklefs unpublished data |
| CHI26PA | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| CHI28PA | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| CHI34PA | *Haemoproteus* | Ellis and Ricklefs unpublished data |
| CI02 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| DR02 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| DR03 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| DR07 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| EL02 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| EM00 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| JA02 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| JA03 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| JA04 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| JA06 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| JA08 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| LA02 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| LA16 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| LA26 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| MI01 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| MI03 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| MI02 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| NA04 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| NA14 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| NA16 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| OZ09 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| OZ10 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| OZ12 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| OZ13 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| OZ14 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| OZ17 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| OZ27 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| OZ28 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| OZ29 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| OZ35 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| OZ49 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| PR03 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| RP01 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| TI-H13 | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| TI-H17L | *Haemoproteus* | Ricklefs *et al.*, 2014 |
| TI-P02 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| TI-P04L | *Plasmodium* | Ricklefs *et al.*, 2014 |
| TI-P05L | *Plasmodium* | Ricklefs *et al.*, 2014 |
| TI-P07 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| TI-P09 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| TI-P29 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| YU01 | *Plasmodium* | Ricklefs *et al.*, 2014 |
| YU03 | *Haemoproteus* | Ricklefs *et al.*, 2014 |

Table S4—Updated biogeographic regions for lineages in MalAvi that previously had no location information or incomplete location information; found by looking through original publications and GenBank entries.

|  |  |
| --- | --- |
| **Lineage Name** | **Updated Biogeographic Region** |
| AFR084 | South Sahara |
| ASOT07 | North Africa and the Middle East |
| BUBO3 | North Africa and the Middle East |
| CARCAR01 | North America |
| CARMEX01 | North America |
| CXRES04 | North America |
| GEOTRI06 | North America |
| GYPBEN01 | Asia |
| MEAPI01 | Europe |
| MEAPI02 | Europe |
| OTSCO04 | North Africa and the Middle East |
| PROCAF01 | South Sahara |
| SFC10 | Europe; North Africa and the Middle East |
| TUMIG1 | North America |
| TYTAL1 | North Africa and the Middle East |
| TYTAL2 | North Africa and the Middle East |
| AFR227 | South Sahara |
| AIXGAL01 | Asia |
| ASIFLA01 | Asia |
| ATPAL01 | South America |
| ATSCHI01 | South America |
| BAEBIC01 | North America |
| BUBO4 | North Africa and the Middle East |
| BUL4 | North Africa and the Middle East |
| BUTMO01 | South America |
| BUTRUF01 | North Africa and the Middle East |
| CATUST02 | North America |
| COCOR02 | Europe |
| COCOR14 | Asia |
| COCOR15 | Asia |
| COCOR16 | Asia |
| CORMAC04 | Asia |
| CORMAC05 | Asia |
| CORMAC06 | Asia |
| DENJAV01 | Asia |
| DICYA01 | South America |
| DUTAE01 | South America |
| FICNAR01 | Asia |
| FICNAR02 | Asia |
| FULATR01 | Asia |
| GAVIM01 | North America |
| GORGOI03 | Asia |
| GYPTEN01 | Asia |
| HEATR01 | South America |
| HESUP01 | South America |
| HESUP02 | South America |
| HIRUS16 | Asia |
| HYPAM03 | Asia |
| LANMER01 | Europe |
| LANMER02 | Europe |
| LANMER03 | Europe |
| LANMER04 | Europe |
| LANMER05 | Europe |
| LARCRA02 | Asia |
| NINOX06 | Asia |
| NINOX07 | Asia |
| NINOX08 | Asia |
| NUMPHA01 | Asia |
| NYCNYC02 | Asia |
| OTULEM01 | Asia |
| OTULEM02 | Asia |
| OTULEM03 | Asia |
| OTULEM04 | Asia |
| OTULEM05 | Asia |
| PARMIN01 | Asia |
| PARUS23 | Europe |
| PARUS27 | Europe |
| PARUS39 | Europe |
| PARUS40 | Europe |
| PARUS41 | Europe |
| PARUS42 | Europe |
| PARUS43 | Europe |
| PARUS44 | Europe |
| PARUS45 | Europe |
| PARUS46 | Europe |
| PARUS47 | Europe |
| PARUS48 | Europe |
| PARUS49 | Europe |
| PARUS50 | Europe |
| PARUS51 | Europe |
| PARUS52 | Europe |
| PARUS53 | Europe |
| PARUS54 | Europe |
| PARUS55 | Europe |
| PARUS56 | Europe |
| PARUS57 | Europe |
| PARUS58 | Europe |
| PARUS59 | Europe |
| PLAMIN01 | Asia |
| SCORUS01 | Asia |
| SPOCIN01 | Asia |
| STAL3 | North Africa and the Middle East |
| STRORI04 | Asia |
| STRORI05 | Asia |
| STRURA01 | Asia |
| STRURA02 | Asia |
| TFUS08 | South America |
| TFUS09 | South America |
| TFUS10 | South America |
| TUCAR02 | Asia |
| TURNAU01 | Asia |
| ZOCAP07 | South America |

Table S5—Geographic information for all lineages in the study. See excel file.

Table S6—Information for all nodes in the three phylogenies with bootstrap support values greater than 80. Under each biogeographic region, a node is given a score of 0 (no sister lineages distributed in that region), 1 (sister lineages occur in that region on one side of the node only), or 2 (sister lineages occur in that region on both sides of the node). See excel file.

Table S7—Lineages associated with nodes from the three phylogenies with bootstrap values greater than 80. See excel file.

Table S8—Lineages found infecting hosts in more than one biogeographic region. See excel file.

Table S9—Biogeographic regions of allopatrically distributed sister lineages grouped by node from the phylogenetic analysis. For each node, the biogeographic regions are listed for parasites in each of the two descendant lineages (arbitrarily called Sister Lineages A and B); the specific parasite lineages found in those regions follow in parentheses. Node numbers and the associated parasite genus (*P* = *Plasmodium*, *H* = *Haemoproteus*, *L* = *Leucocytozoon*) appear with further information in Tables S6 and S7.

|  |  |  |  |
| --- | --- | --- | --- |
| **Genus** | **Node** | **Locations Sister Lineages A** | **Locations Sister Lineages B** |
| *P* | 1024 | Europe (FIPAR01) | S. Sahara (CYAOLI02) |
| *P* | 1104 | Europe (SW2, PARUS66, CRECRE01), S. Sahara (SW2), N. Africa & M. East (SW2), Asia (SW2, FULATR01, EMSPO06) | N. America (RWB01) |
| *P* | 1166 | Europe (PADOM04, CIAE01) | S. Sahara (CXPOI01), Asia (GYPTEN01, GYPBEN01) |
| *P* | 1267 | Australia & N. Zealand (PACPEC01) | Europe (ARAMAG01, CXPIP11), Asia (ARAMAG01, GW6, GW4, CXPIP11, CXPIP12, CXPIP13) |
| *P* | 1283 | N. America (CATUST06), C. America (CATUST06) | S. America (CATUST21) |
| *P* | 1288 | S. Sahara (AFTRU4) | N. America (COREG01) |
| *P* | 1388 | Europe (DONANA04) | S. America (SPMAG11), Asia (NYCNYC02, CXBIT01) |
| *P* | 1468 | N. America (BWTE16) | S. America (CERNOV01) |
| *P* | 1596 | Europe (LUME2) | S. Sahara (TURPEL03) |
| *P* | 1680 | Europe (TERUF02, COLL4), S. Sahara (TERUF02), N. America (COLL4), S. America (COLL4, GLYSPI07) | Asia (RHIAUR01), Australia & N. Zealand (LICVER08) |
| *P* | 1681 | Australia & N. Zealand (LICVER08) | Asia (RHIAUR01) |
| *H* | 1047 | Australia & N. Zealand (CLIPIC02) | S. Sahara (HIP4) |
| *H* | 1103 | N. Africa & M. East (SYHOR01) | Europe (LWT2) |
| *H* | 1133 | N. America (CATUST07) | S. America (MYMAC01) |
| *H* | 1136 | S. America (PHAMAL01) | N. America (SETGRA01) |
| *H* | 1171 | Asia (PACHOM02, ALBRE01) | S. Sahara (PRIMOL01) |
| *H* | 1257 | S. Sahara (ILCLE01) | Europe (SFC3), N. Africa & M. East (SFC3) |
| *H* | 1288 | Asia (APPAT01) | Europe (CIRCUM05) |
| *H* | 1301 | S. Sahara (AFR053) | Europe (ORORI03) |
| *H* | 1396 | S. Sahara (AFR150) | Europe (SFC1), N. Africa & M. East (SFC1) |
| *H* | 1529 | C. America (MELFUS01) | N. America (CATUST10) |
| *H* | 1660 | S. Sahara (MEBRE01) | Europe (MEAPI02) |
| *H* | 1661 | Asia (CYAPIC01) | Europe (MEAPI01) |
| *H* | 1690 | Europe (CIRCUM02) | N. Africa & M. East (PICVAI01) |
| *H* | 1692 | S. America (TROAED18) | C. America (DR07) |
| *H* | 1715 | S. America (DENAUT01) | Asia (DENJAV01) |
| *H* | 1741 | Asia (OTUSUN01) | Europe (OTSCO05) |
| *H* | 1789 | Asia (STRURA01) | Europe (CULKIB01) |
| *H* | 1794 | Europe (MILANS03, MILANS02, MILANS01) | S. Sahara (AFR048) |
| *H* | 1819 | S. America (ZEGAL05) | C. America (COLTAL01) |
| *H* | 1830 | C. America (JA08) | S. America (LEPRUF02) |
| *H* | 1854 | Europe (HIRUS05, DELURB1, DELURB7, HIRUS14, HIRUS01, HIRUS03, HIRUS02, HIRUS04, DELURB2, DELURB3), N. Africa & M. East (DELURB1, DELURB2) | N. America (EM00, TATHA01) |
| *H* | 1891 | Europe (SERSER03) | N. Africa & M. East (IDUOPA01) |
| *H* | 1898 | Europe (ACSTE1), Asia (ACSTE1) | S. Sahara (LSW2) |
| *L* | 676 | Europe (ACCGEN03, ACCGEN01), N. America (ACCOP01) | Asia (ACNI04) |
| *L* | 677 | Europe (ACCGEN03, ACCGEN01) | N. America (ACCOP01) |
| *L* | 683 | N. Africa & M. East (BUTRUF01) | Europe (ACCGEN02) |
| *L* | 695 | Asia (CRIPIS01) | Europe (MILVUS02) |
| *L* | 733 | N. Africa & M. East (HAWF7) | Europe (HAWF3) |
| *L* | 866 | Asia (COLIV04) | S. Sahara (STPIC01) |
| *L* | 907 | S. Sahara (TURPEL01) | Europe (TUMER02, TUPHI04, TUPHI02), N. Africa & M. East (TUMER02), N. America (COLBF10), S. America (TFUS07, TFUS10), Asia (TURNAU01) |
| *L* | 950 | Europe (TUMER03) | N. America (COLBF08) |
| *L* | 1082 | N. Africa & M. East (CCF15, CCF13) | Europe (CCF22) |
| *L* | 1122 | Europe (ASOT06, ASOT2), N. Africa & M. East (SITTAKRU3) | N. America (BUVIR03) |
| *L* | 1137 | Europe (ASOT1) | N. America (STOCC13, STOCC12, STOCC11) |
| *L* | 1169 | N. America (TUMIG09) | Europe (TUOBS01), S. Sahara (AFTRU1) |
| *L* | 1247 | N. Africa & M. East (SYAT39) | S. Sahara (AFR235) |
| *L* | 1335 | N. America (BUTJAM11) | Europe (BUBT2) |

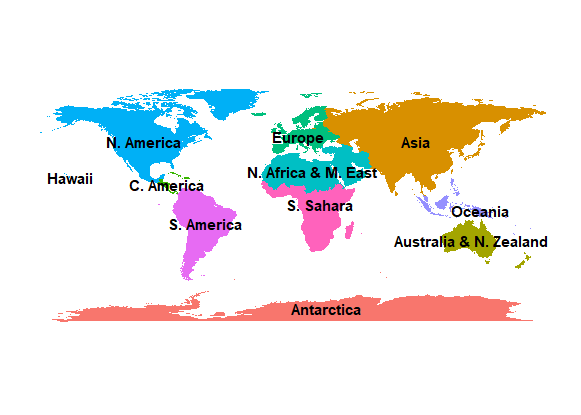


Fig S1—Map depicting the biogeographic regions used in this analysis.

Fig S2—Maximum likelihood phylogeny of the *Plasmodium* lineages used in this analysis. Lineages colored in red were found in more than one biogeographic region. See attached PDF.

Fig S3—Maximum likelihood phylogeny of the *Haemoproteus* lineages used in this analysis. Lineages colored in red were found in more than one biogeographic region. See attached PDF.

Fig S4—Maximum likelihood phylogeny of the *Leucocytozoon* lineages used in this analysis. Lineages colored in red were found in more than one biogeographic region. See attached PDF.

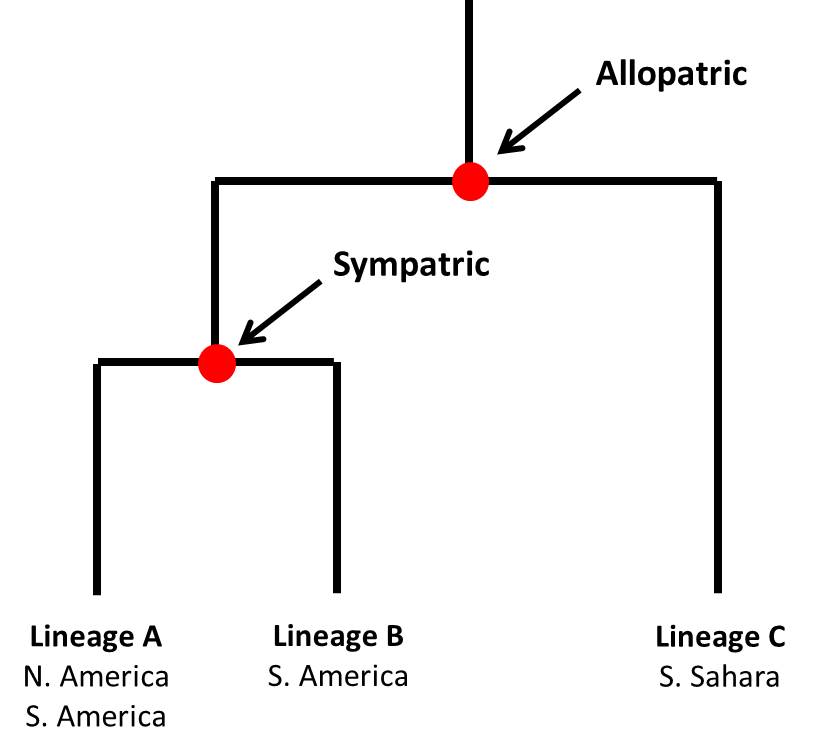


Fig S5—Schematic showing how nodes were assigned as either allopatric or sympatric. Nodes were assigned as sympatric when at least two lineages, one on each side of the node, were found in the same region. Nodes were assigned as allopatric when there was no overlap in geographic location among the two sides of the node. In the example here the more basal node is allopatric because Lineage C was found in South Sahara while its sister lineages, A and B, were found in North and South America. The other node is sympatric because Lineages A and B are both found in South America (even though Lineage A is also found in North America, the node is still classified as sympatric because there is overlap in distributions).

**References**

**Fecchio, A., Lima, M. R., Svensson-Coelho, M., Marini, M. Â. and Ricklefs, R. E.** (2013). Structure and organization of an avian haemosporidian assemblage in a Neotropical savanna in Brazil. *Parasitology* **140**, 181–192. doi: 10.1017/S0031182012001412.

**Ricklefs, R. E., Outlaw, D. C., Svensson-Coelho, M., Medeiros, M. C. I., Ellis, V. A. and Latta, S.** (2014). Species formation by host shifting in avian malaria parasites. *Proceedings of the National Academy of Sciences* **111**, 14816–14821. doi: 10.1073/pnas.1416356111.

**Svensson-Coelho, M., Blake, J. G., Loiselle, B. A., Penrose, A. S., Parker, P. G. and Ricklefs, R. E.** (2013). Diversity, prevalence, and host specificity of avian *Plasmodium* and *Haemoproteus* in a western Amazon assemblage. *Ornithological Monographs* **76**, 1–47. doi: 10.1525/om.2013.76.1.1.

**Waldenström, J., Bensch, S., Hasselquist, D. and Östman, Ö.** (2004). A new nested polymerase chain reaction method very efficient in detecting *Plasmodium* and *Haemoproteus* infections from avian blood. *The Journal of Parasitology* **90**, 191–194.