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## Appendix 1

### Host and flea traits/properties: explanations and data sources

#### Hosts

##### *Body mass*

Body mass is the central characteristic of a species and is commonly employed in developing hypotheses related to physiological and behavioural responses. For example, Peters (1983) presented a large number of allometric relations between various animal characteristics and body mass. From a parasite perspective, host body mass may influence parasite's abundance (due to the obvious reasons) and host specificity. For example, a host body mass is associated with persistence of a host individual in time merely because a larger host species lives longer and, thus, represents a more predictable resource for a parasite (Peters 1983). As a result, parasite species with higher host specificity are expected to exploit large hosts, whereas small-bodied hosts are expected to be exploited mainly by generalist parasites. Indeed, our earlier findings indicated that the exploitation of large-bodied, and therefore long-lived, host species has likely promoted specialization in fleas (Krasnov et al. 2006a). Data on mean body mass of a host species were obtained from Silva and Downing (1995), Degen (1977) or PanTHERIA database (Jones et al. 2009).

##### *Basal metabolic rate*

Investment of host in a high basal metabolic rate (BMR) could be associated with parasitism as a compensation for a costly immune response when parasite challenges are either strong (e.g., in case of highly abundant parasite) or diverse (in case of attacks by multiple parasites) (Morand and Harvey 2000). Data on BMR were obtained from Kalabukhov (1969), McNab and Eisenberg (1989), Degen (1977), White and Seymour (2003) and PanTHERIA database (Jones et al. 2009). Metabolic rate in these sources was expressed either as O<sub>2</sub> consumption per unit time or in energetic

units. To ensure the consistency of the data, we recalculated all data in energetic units, assuming 20.08 J per ml O<sub>2</sub>. To control for interspecific differences in body mass, we used Kleiber's (1932) allometric relationship with a scaling exponent of 0.75.

#### *Hair density and skin thickness*

Skin and hair coat of a host is a habitat where a flea forages. Consequently, the morphology of a host's skin and hair is of utmost importance for a flea. Skin thickness determines whether and how easy a flea can obtain a bloodmeal. For example, mammals with relatively thick skin cannot serve as hosts for fleas with short mouthparts (Vashchenok 1988). Host hair density may determine how easily a flea can move among hairs and how heavily it should be armed to avoid the host's anti-flea grooming (Krasnov 2008). We took data on skin thickness and hair density of 50 host species from Sokolov (1973) and Feoktistova (2008). Both variables correlated positively (skin thickness;  $r^2 = 0.57$ ,  $F = 64.7$ ,  $p < 0.01$ ) or negatively (hair density;  $r^2 = 0.43$ ,  $F = 35.1$ ,  $p < 0.01$ ) with body mass. For the subsequent analyses, we substituted the original values of these variables with their residual deviations from the regression on body mass in log-log space.

#### *Population density and sociality*

The relationships between host population density or sociality and parasitism have been repeatedly discussed (Arneberg et al. 1998, Stanko et al. 2002, Altizer et al. 2003, Bordes et al. 2007). Higher density or living in groups may facilitate parasite transmission and thus lead to their increased abundance (Stanko et al. 2002), but may also decrease this abundance via a "dilution effect" (Mooring and Hart 1992) or sociality-related anti-parasite defenses (e.g. allogrooming; Moore 2002). Furthermore, host sociality may be associated with a characteristic strategy of a parasite for host search and location (Krasnov et al. 2002a). This suggests that the host population density and/or sociality could be an important factor affecting suitability of a given host for a given parasite. In this study, population density was a quantitative variable. Data on population density were taken from original sources, Stainer (1972), Damuth (1987) or PanTHERIA database (Jones et al. 2009). Sociality was represented by an ordinal variable with three levels (0 – solitary, 1 – simple family groups, 2 – complex groups or colonies). Data on sociality were obtained from personal field experience of authors (for gerbillines), Ognev (1928, 1940, 1947, 1948, 1950) for the majority of soricomorphs and rodents and Shenbrot et al. (1995) for jerboas and birch mice.

#### *Geographic range*

Hosts with larger geographic ranges would presumably encounter more parasite species. In addition, the size of the geographic range may be a proxy for habitat niche breadth of a host.

Consequently, broadly distributed hosts are exploited by more parasite species than hosts with a narrow distribution (Krasnov et al. 2004a). Data on geographic range were either taken from PanTHERIA database (Jones et al. 2009) or calculated as described elsewhere (Shenbrot and Krasnov 2005).

#### *Shelter depth and shelter complexity*

Host shelter is of utmost importance for fleas. In particular, it creates a favourable environment (e.g. temperature and relative humidity) for development of pre-imaginal fleas, provides flea larvae with food resources and flea pupae with material for camouflaging their cocoons (reviewed by Krasnov 2008). Different flea species (both adults and pre-imaginal) demonstrated different preferences to microclimate and substrate texture of a host burrow (Krasnov et al. 2001). Consequently, shelter depth and complexity (number of horizons, exits and nest chambers, ventilation etc.) could influence host selection by a flea species. We described shelter depth and complexity as ordinal variables with four and three levels, respectively (shelter depth: 0 – aboveground shelter or shelter in rock crevice, 1 – burrow with depth up to 25 cm, 2 – burrow with depth from 25 cm to 1 m, 3 – burrow with depth more than 1 m; shelter complexity: 0 – simple shelter or burrow with 1–2 exits, 1 – burrow with a single horizon and up to 10 exits, 3 – burrow with multiple horizons and more than 10 exits). Data on shelter depth and complexity were taken from the same sources as data on sociality.

#### *Hibernation*

Hibernation substantially changes many morphological and physiological characteristics of a mammalian host. These changes could strongly affect the ability of a haematophagous parasite to exploit a host during hibernation due to, for example, lower body temperature, periodical restriction of peripheral blood flow and thicker subcutaneous fat layer. As a result, some fleas exploiting hibernating hosts possess adaptations such as high tolerance to low temperature and larval haematophagy (reviewed by Suntsov and Suntsova 2006). In our study, hibernation was represented by an ordinal variable with three levels [0 – no hibernation, 2 – seasonal torpor (periods of somewhat reduced metabolic rate and body temperature lasting for days with frequent arousals; winter food storage), 3 – true hibernation (periods of substantially reduced metabolic rate and body temperature lasting for weeks or months; fat accumulation)]. Information on hibernation pattern was taken from the same sources as data on sociality.

## Fleas

### *Armament*

Fleas possess various morphological features that allow them to anchor themselves in the host's hairs and to resist the host's grooming (Traub 1980). These features are represented by sclerotized bristles such as helmets, ctenidia (combs), spines and setae. The most conspicuous structures of flea armament are ctenidia (=combs). Combs are rows of highly sclerotized spines below the head (genal comb) or at the back of the pronotum (pronotal comb). We used presence, absence and number of combs as an ordinal variable describing armament of a flea species (0 – no combs present, 1 – only pronotal comb present, 2 – both combs present). Information on combs in each flea species was taken from Hopkins and Rothschild (1953, 1956, 1962, 1966, 1971) and Traub et al. (1983).

### *Microhabitat preferences*

Flea species differ in the proportion of time they spend either on the body of their host or in its burrow or nest. Ioff (1941) proposed to distinguish “body” fleas (spending most of their lives on a host) and “nest” fleas (staying on a host only to acquire a blood meal). ‘Body fleas’ usually require prolonged contact with a host for their eggs to mature, while the reason for ‘nest’ fleas to spend much time in the nest seems to be due to the relative stability of the nest environment (Krasnov 2008). As a result of differential preferences, ‘body’ and ‘nest’ fleas may differ in their morphological and/or physiological traits. For example, surface of eggs of many ‘body’ fleas lacks sticky substrate, so they easily drop from a host's hair to ensure off-host pre-imaginal development (Ioff 1941). ‘Nest’ fleas are able to endure much longer periods without a bloodmeal than ‘body’ fleas (Ioff 1941). Some flea species cannot be unequivocally attributed to one or another category because they spend similar time on either the body or nest of a host. We assigned a flea species as a ‘body’ or a ‘nest’ or a ‘both body and nest’ species based on information and references from Ioff (1941), Vashchenok (1988), and Krasnov (2008).

### *Seasonality*

Survival and reproduction of fleas depends on a combination of factors including favourable climatic conditions for development of the immature stages and for adults to survive unpredictable and sometimes lengthy periods without a bloodmeal (reviewed by Krasnov 2008). This results in seasonal changes of life history parameters of fleas including reproduction rate and pattern of parasitism. Following Darskaya (1970), we characterized seasonal preferences of flea species according to seasonality of their main reproduction period, namely the warm season (that is, summer in temperate zone) or the cold season (winter in temperate zone) or year round. Information was taken from various literature sources (Darskaya 1970, Krasnov et al. 2002b and Krasnov 2008).

### *Abundance*

Abundances of a given flea species on a given host species, but in different localities, have been shown to (a) be more similar to each other than expected by chance and (b) vary significantly among flea species (Krasnov et al. 2006b). Consequently, abundance is a true flea species attribute that varies only within narrow species-specific boundaries. To estimate species-specific abundance of a flea species, we first identified the principal host species for this flea as the host species in which a flea attained the highest abundance (see details and explanations in Krasnov et al. 2006b). Then, we calculated abundances as the mean number of fleas per individual host per region and averaged these regional abundances across all regions (see also Krasnov et al. 2011, 2015).

### *Host specificity*

Host specificity is one of the most important attributes of a parasite species (Poulin et al. 2011). In this study, we used two different facets of host specificity, namely the size of the host and phylogenetic distinctness of host spectrum. The latter was estimated either as a mean of regional values or as a total across all studied regions. Size of host spectrum (the number of host species exploited) has been shown to be a true characteristic of a flea species (Krasnov et al. 2004b, Mouillot et al. 2006). We controlled the values of the number of hosts exploited in a region for unequal sampling effort as described in Krasnov et al. (2015) and then averaged these values across regions.

Another aspect of host specificity of a parasite, the phylogenetic host specificity, takes into account the phylogenetic affinities of the various host species and is independent of the number of host species (Poulin et al. 2011). As a measure of phylogenetic host specificity, Poulin and Mouillot (2003) proposed average phylogenetic distinctness between all pairs of host species used by a parasite and calculated as the  $\Delta+$  index of Clarke and Warwick (1999) and Warwick and Clarke (2001), thus placing the emphasis on the phylogenetic distance between hosts used by a parasite rather than on their number. To estimate phylogenetic host specificity of a flea within a region (PHS Regional) and across its entire geographic range (PHS Total), we modified the  $\Delta+$  index to take into account phylogenetic rather than taxonomic distances (based on patristic distances) and made calculations using the package “vegan” (Oksanen et al. 2013) implemented in R (<[www.r-project.org](http://www.r-project.org)>) (see main text and Supplementary material Appendix 2 for information on the construction of phylogenetic tree of hosts). The patristic distances between host species were calculated using the R package ‘adephylo’ (Jombart and Dray 2008). To calculate PHS Regional, we averaged values of PHS obtained for each region across all regions where a given flea was recorded.

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## Appendix 2

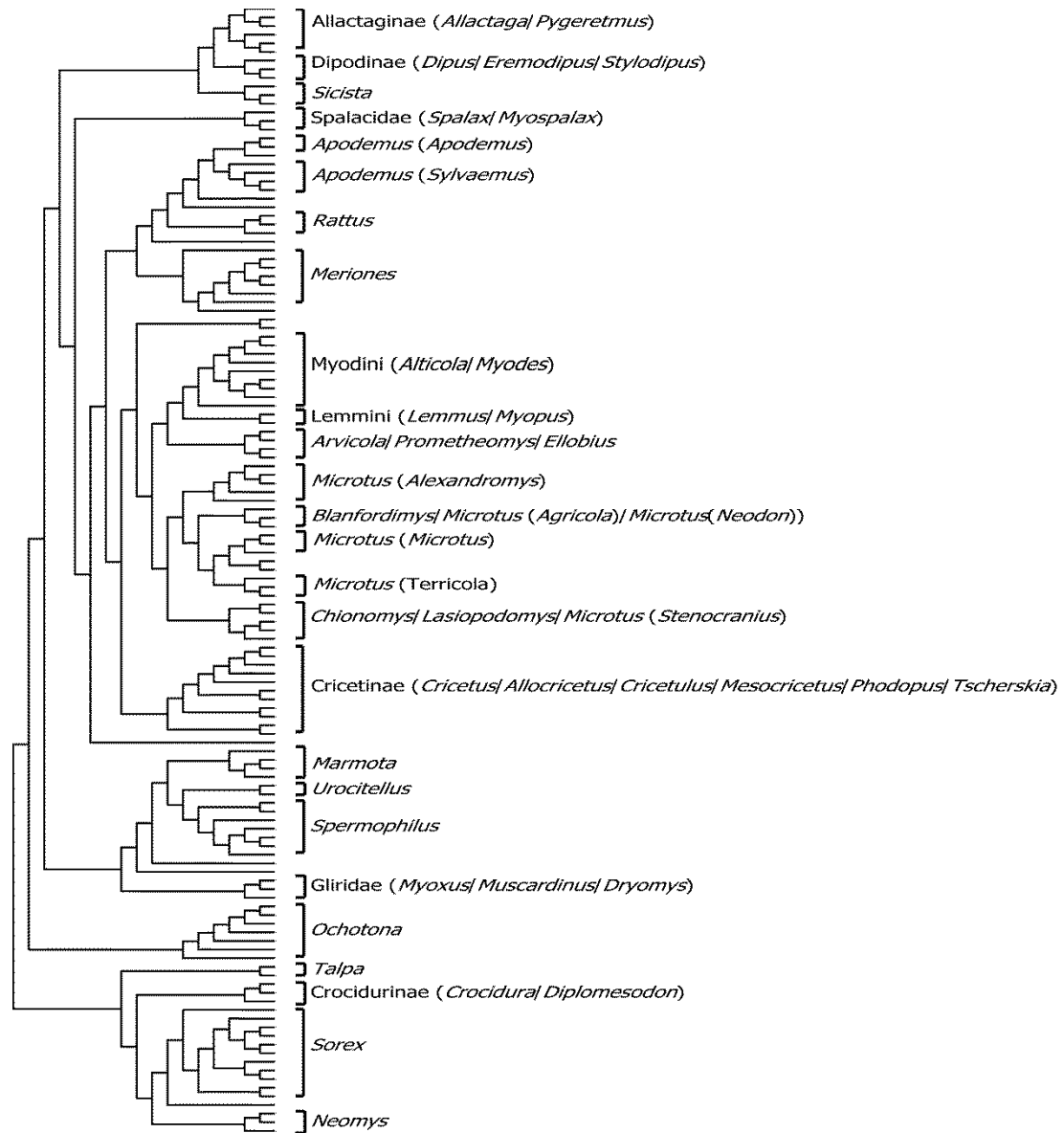


Figure A2a. A phylogenetic tree for hosts. Subgenera are in parentheses

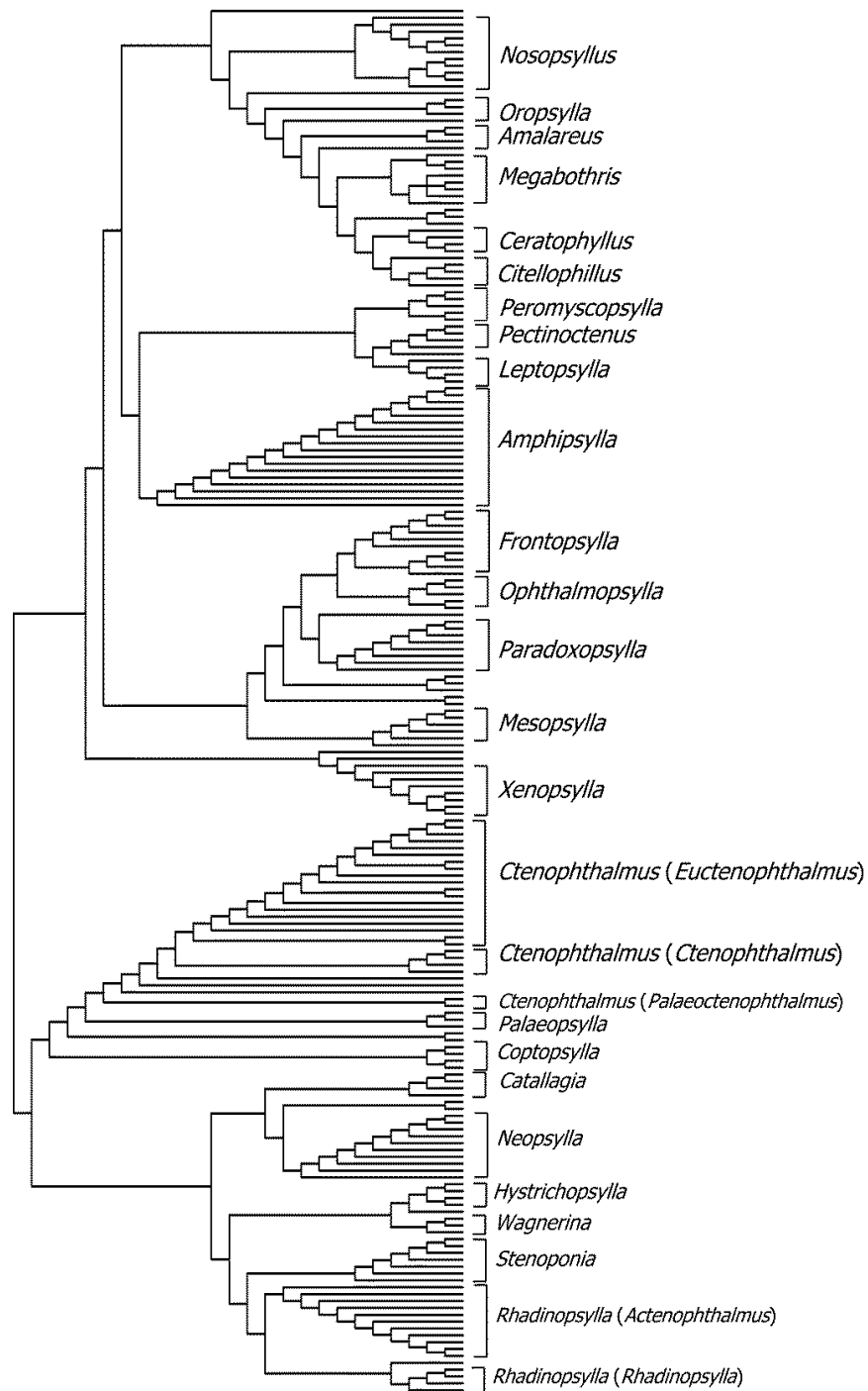


Figure A2b. A phylogenetic tree for fleas. Subgenera are in parentheses (redrawn from Krasnov et al. 2015). Assembly rules of ectoparasite communities across scales: combining patterns of abiotic factors, host composition, geographic space, phylogeny and traits. – Ecography, in press.

## Appendix 3

Taxonomic information and names of species of fleas and small mammals. Order of species names is respective to their positions on the phylogenetic tree.

### Fleas

#### Family Ceratophyllidae

*Myoxopsylla jordani*  
*Nosopsyllus mokrzeckyi*  
*Nosopsyllus fidus*  
*Nosopsyllus consimilis*  
*Nosopsyllus simla*  
*Nosopsyllus philippovi*  
*Nosopsyllus fasciatus*  
*Nosopsyllus aralis*  
*Nosopsyllus turkmenicus*  
*Nosopsyllus iranus*  
*Nosopsyllus laeviceps*  
*Nosopsyllus tersus*  
*Rostropsylla daca*  
*Oropsylla ilovaiskii*  
*Oropsylla silantiewi*  
*Oropsylla alaskensis*  
*Amphalius runatus*  
*Amalaraeus penicilliger*  
*Amalaraeus ioffi*  
*Amalaraeus dissimilis*  
*Paramonopsyllus scalonae*  
*Megabothris rectangulatus*  
*Megabothris turbidus*  
*Megabothris advenarius*  
*Megabothris beljaevi*  
*Megabothris calcarifer*  
*Megabothris walkeri*  
*Megabothris bispinosa*  
*Megabothris asio*  
*Callopsylla caspia*  
*Callopsylla lagomys*  
*Callopsylla saxatilis*  
*Ceratophyllus sinicus*  
*Ceratophyllus sciurorum*  
*Ceratophyllus indages*  
*Ceratophyllus anisus*  
*Citellophilus transcaucasicus*  
*Citellophilus lebedewi*  
*Citellophilus trispinus*

*Citellophilus tesquorum*  
*Citellophilus ullus*

Family Leptopsyllidae

*Peromyscopsylla bidentata*  
*Peromyscopsylla ostsibirica*  
*Peromyscopsylla tikhomirovae*  
*Peromyscopsylla fallax*  
*Peromyscopsylla silvatica*  
*Pectinoctenus nemorosa*  
*Pectinoctenus pamirensis*  
*Pectinoctenus lauta*  
*Pectinoctenus pectiniceps*  
*Pectinoctenus pavlovskii*  
*Leptopsylla taschenbergi*  
*Leptopsylla sicistae*  
*Leptopsylla segnis*  
*Leptopsylla nana*  
*Amphipsylla anceps*  
*Amphipsylla dumalis*  
*Amphipsylla georgica*  
*Amphipsylla argoi*  
*Amphipsylla schelkovnikovi*  
*Amphipsylla longispina*  
*Amphipsylla kuznetzovi*  
*Amphipsylla vinogradovi*  
*Amphipsylla primaris*  
*Amphipsylla kalabukhovi*  
*Amphipsylla parthiana*  
*Amphipsylla montana*  
*Amphipsylla phaiomydis*  
*Amphipsylla asiatica*  
*Amphipsylla marikovskii*  
*Amphipsylla rossica*  
*Amphipsylla prima*  
*Amphipsylla sibirica*  
*Frontopsylla elata*  
*Frontopsylla elatoides*  
*Frontopsylla luculenta*  
*Frontopsylla hetera*  
*Frontopsylla semura*  
*Frontopsylla wagneri*  
*Frontopsylla ornata*  
*Frontopsylla ambigua*  
*Frontopsylla protera*  
*Frontopsylla macrophthalma*  
*Ophthalmopsylla praefecta*  
*Ophthalmopsylla volgensis*  
*Ophthalmopsylla kukuschkini*  
*Ophthalmopsylla karakum*

*Ophthalmopsylla kiritschenkovi*  
*Paradoxopsyllus teretifrons*  
*Paradoxopsyllus integer*  
*Paradoxopsyllus repandus*  
*Paradoxopsyllus naryni*  
*Paradoxopsyllus dashidorzhii*  
*Paradoxopsyllus scorodumovi*  
*Paradoxopsyllus kalabukhovi*  
*Paradoxopsyllus microphthalmus*  
*Paradoxopsyllus hesperius*  
*Ctenophyllus armatus*  
*Ctenophyllus subarmatus*  
*Ctenophyllus hirticrus*  
*Phaenopsylla tiflovi*  
*Phaenopsylla kopetdag*  
*Mesopsylla hebes*  
*Mesopsylla tuschkan*  
*Mesopsylla apscheronica*  
*Mesopsylla eucta*  
*Mesopsylla lenis*  
*Desertopsylla rothschildi*

#### Family Pulicidae

*Echidnophaga oschanini*  
*Synosternus longispinus*  
*Xenopsylla cheopis*  
*Xenopsylla hirtipes*  
*Xenopsylla nuttalli*  
*Xenopsylla magdalinae*  
*Xenopsylla gerbilli*  
*Xenopsylla persica*  
*Xenopsylla conformis*  
*Xenopsylla skrjabini*

#### Family Hystrichopsyllidae I

*Ctenophthalmus (Euctenophthalmus) arvalis*  
*Ctenophthalmus (Euctenophthalmus) breviatus*  
*Ctenophthalmus (Euctenophthalmus) teres*  
*Ctenophthalmus (Euctenophthalmus) assimilis*  
*Ctenophthalmus (Metactenophthalmus) wagneri*  
*Ctenophthalmus (Euctenophthalmus) wladimiri*  
*Ctenophthalmus (Euctenophthalmus) uncinatus*  
*Ctenophthalmus (Euctenophthalmus) obtusus*  
*Ctenophthalmus (Metactenophthalmus) hypanis*  
*Ctenophthalmus (Euctenophthalmus) orientalis*  
*Ctenophthalmus (Euctenophthalmus) secundus*  
*Ctenophthalmus (Euctenophthalmus) congener*  
*Ctenophthalmus (Euctenophthalmus) congeneroides*  
*Ctenophthalmus (Euctenophthalmus) bogatschevi*

*Ctenophthalmus (Euctenophthalmus) euxinicus*  
*Ctenophthalmus (Euctenophthalmus) shovi*  
*Ctenophthalmus (Euctenophthalmus) pisticus*  
*Ctenophthalmus (Medioctenophthalmus) chionomydis*  
*Ctenophthalmus (Medioctenophthalmus) golovi*  
*Ctenophthalmus (Ctenophthalmus) agyrtes*  
*Ctenophthalmus (Ctenophthalmus) proximus*  
*Ctenophthalmus (Ctenophthalmus) solutus*  
*Ctenophthalmus (Ctenophthalmus) bisoctodentatus*  
*Ctenophthalmus (Ducictenophthalmus) dux*  
*Ctenophthalmus (Paractenophthalmus) dolichus*  
*Ctenophthalmus (Neoctenophthalmus) dilatatus*  
*Ctenophthalmus (Palaeoctenophthalmus) acuminatus*  
*Ctenophthalmus (Palaeoctenophthalmus) inornatus*  
*Palaeopsylla caucasica*  
*Palaeopsylla kohauti*  
*Palaeopsylla soricis*  
*Doratopsylla dasyncnema*  
*Corrodopsylla birulai*

#### Family Coptopsyllidae

*Coptopsylla lamellifer*  
*Coptopsylla arax*  
*Coptopsylla olgae*  
*Coptopsylla bairamalensis*

#### Family Hystrichopsyllidae II

*Catallagia fetisovi*  
*Catallagia striata*  
*Catallagia ioffi*  
*Catallagia dacenkoi*  
*Paraneopsylla ioffi*  
*Paraneopsylla tiflovi*  
*Neopsylla mana*  
*Neopsylla teratura*  
*Neopsylla meridiana*  
*Neopsylla setosa*  
*Neopsylla pleskei*  
*Neopsylla acanthina*  
*Neopsylla democratica*  
*Neopsylla bidentatiformis*  
*Neopsylla galea*  
*Neopsylla abagaitui*  
*Hystrichopsylla microti*  
*Hystrichopsylla satunini*  
*Hystrichopsylla orientalis*  
*Hystrichopsylla talpae*  
*Atyphloceras nuperus*  
*Wagnerina longicauda*  
*Wagnerina tuvensis*



*Wagnerina schelkovnikovi*  
*Stenoponia tripectinata*  
*Stenoponia ivanovi*  
*Stenoponia suknevi*  
*Stenoponia conspecta*  
*Stenoponia vlasovi*  
*Stenoponia montana*  
*Stenoponia sidimi*  
*Rhadinopsylla (Actenophthalmus) dahurica*  
*Rhadinopsylla (Actenophthalmus) altifrons*  
*Rhadinopsylla (Actenophthalmus) pentacantha*  
*Rhadinopsylla (Actenophthalmus) insolita*  
*Rhadinopsylla (Actenophthalmus) rothschildi*  
*Rhadinopsylla (Actenophthalmus) isacantha*  
*Rhadinopsylla (Actenophthalmus) altaica*  
*Rhadinopsylla (Actenophthalmus) ioffi*  
*Rhadinopsylla (Actenophthalmus) angusta*  
*Rhadinopsylla (Actenophthalmus) pseudodahurica*  
*Rhadinopsylla (Actenophthalmus) integella*  
*Rhadinopsylla (Ralipsylla) li*  
*Rhadinopsylla (Rhadinopsylla) bivirgis*  
*Rhadinopsylla (Rhadinopsylla) ucrainica*  
*Rhadinopsylla (Rhadinopsylla) socia*  
*Rhadinopsylla (Rhadinopsylla) cedestis*

## Mammals

### Order Rodentia

#### Family Dipodidae

##### Subfamily Allactaginae

*Allactaga elater*  
*Pygeretmus pumilio*  
*Allactaga sibirica*  
*Allactaga severtzovi*

##### Subfamily Dipodinae

*Dipus sagitta*  
*Stylodipus telum*

##### Subfamily Sicistinae

*Sicista betulina*  
*Sicista subtilis*

#### Family Spalacidae

*Spalax nehringi*

#### Family Muridae

##### Subfamily Murinae

*Apodemus agrarius*  
*Apodemus mystacinus*  
*Apodemus sylvaticus*

*Apodemus flavicollis*  
*Apodemus fulvipectus*  
*Mus musculus*  
*Micromys minutus*  
*Rattus norvegicus*

Subfamily Gerbillinae  
*Meriones tamariscinus*  
*Meriones unguiculatus*  
*Meriones meridianus*  
*Meriones vinogradovi*  
*Meriones libycus*  
*Meriones tristrami*  
*Meriones persicus*  
*Rhombomys opimus*

Family Cricetidae

Subfamily Arvicolinae

*Lagurus lagurus*  
*Alticola argentatus*  
*Clethrionomys rutilus*  
*Clethrionomys glareolus*  
*Clethrionomys rufocanus*  
*Lemmus sibiricus*  
*Myopus schisticolor*  
*Arvicola terrestris*  
*Ellobius talpinus*  
*Microtus maximowiczii*  
*Microtus oeconomus*  
*Microtus agrestis*  
*Microtus juldaschi*  
*Microtus arvalis*  
*Microtus schidlovskii*  
*Microtus socialis*  
*Microtus subterraneus*  
*Lasiopodomys brandtii*  
*Microtus gregalis*  
*Chionomys nivalis*

Subfamily Cricetinae

*Allocricetulus evermanni*  
*Cricetus cricetus*  
*Cricetulus migratorius*  
*Cricetulus barabensis*  
*Phodopus campbelli*  
*Phodopus sungorus*

Family Calomyscidae

*Calomyscus mystax*

Family Sciuridae

*Marmota baibacina*

*Urocitellus undulatus*  
*Urocitellus parryii*  
*Spermophilus fulvus*  
*Spermophilus pygmaeus*  
*Spermophilus suslicus*  
*Tamias sibiricus*

Family Gliridae

*Dryomys nitedula*  
*Muscardinus avellanarius*  
*Myoxus glis*

Order Lagomorpha

Family Ochotonidae

*Ochotona daurica*

Order Soricomorpha

Family Talpidae

*Talpa europaea*

Family Soricidae

*Crocidura leucodon*

*Crocidura suaveolens*

*Sorex alpinus*

*Sorex araneus*

*Sorex minutus*

*Sorex cinereus*

*Neomys anomalus*

*Neomys fodiens*