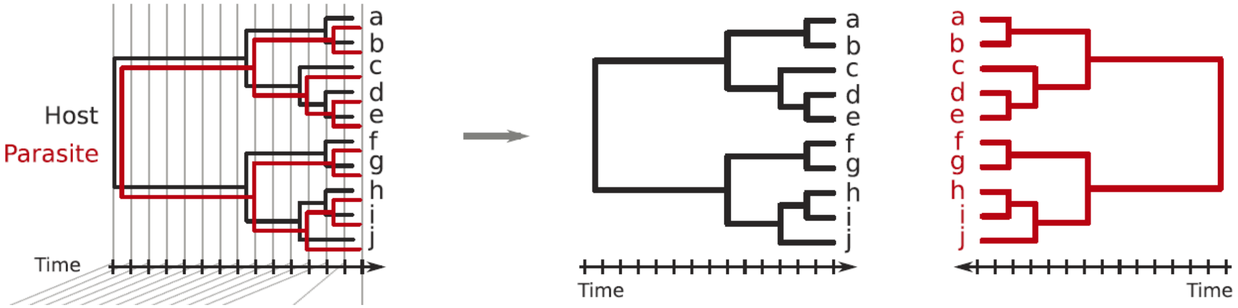
Evolution of plant-herbivore relationships

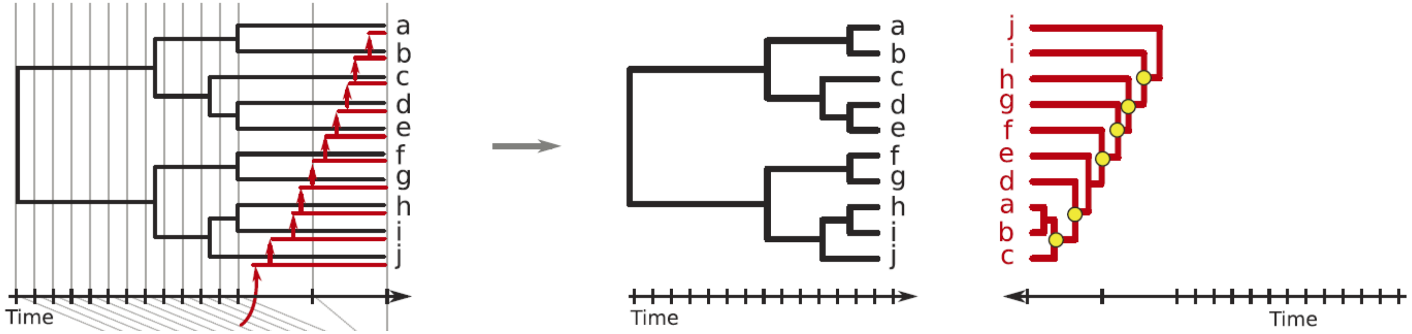

Photo G. Weiblen

VOJTECH NOVOTNY:
COMMUNITY ECOLOGY
LECTURE NO 3
University of S. Bohemia

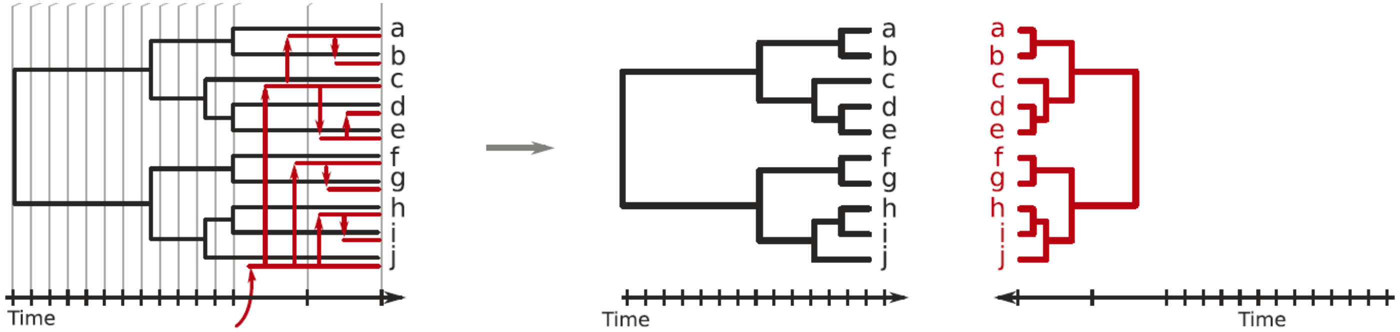


Host lineage
Parasite lineage
Cospeciation
Host shift
● Conflicting nodes

Cospeciation resulting in congruent phylogenies.



Host-shift speciation resulting in congruent phylogenies, but with shorter branches in the parasite lineages



Host-shift speciations, resulting in incongruent phylogenies.

de Vienne et al. New Phytologist (2013)
doi: 10.1111/nph.12150

Where to find genuine plant - insect coevolution?

The plant - insect mutualisms where
- the insect pollinates flowers
- then oviposits to some of them so that the larval survival depends on successful pollination

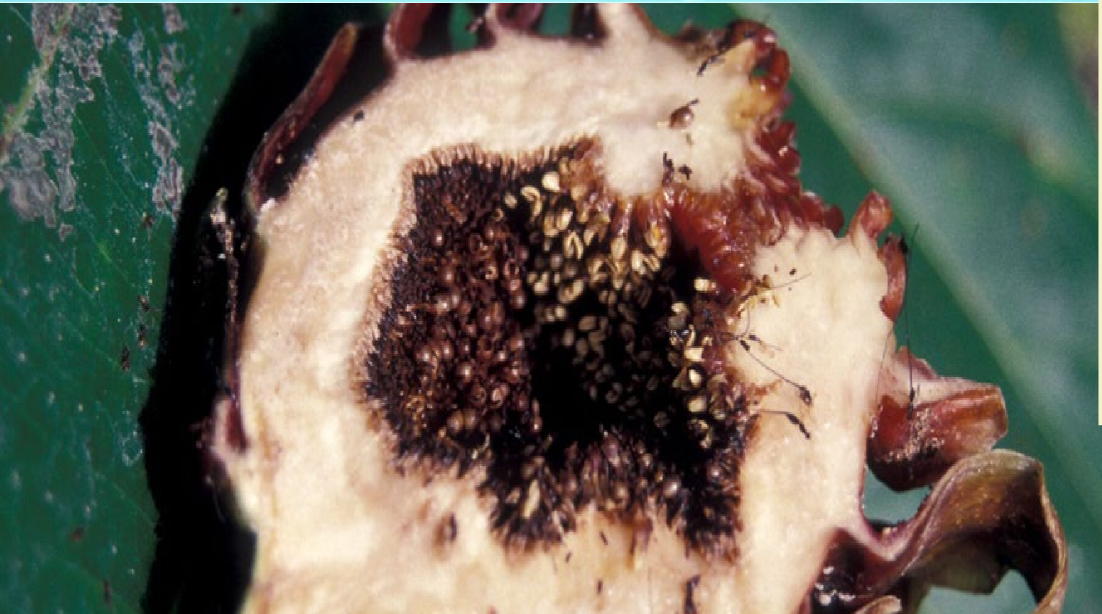
Ficus - Agaonidae wasps

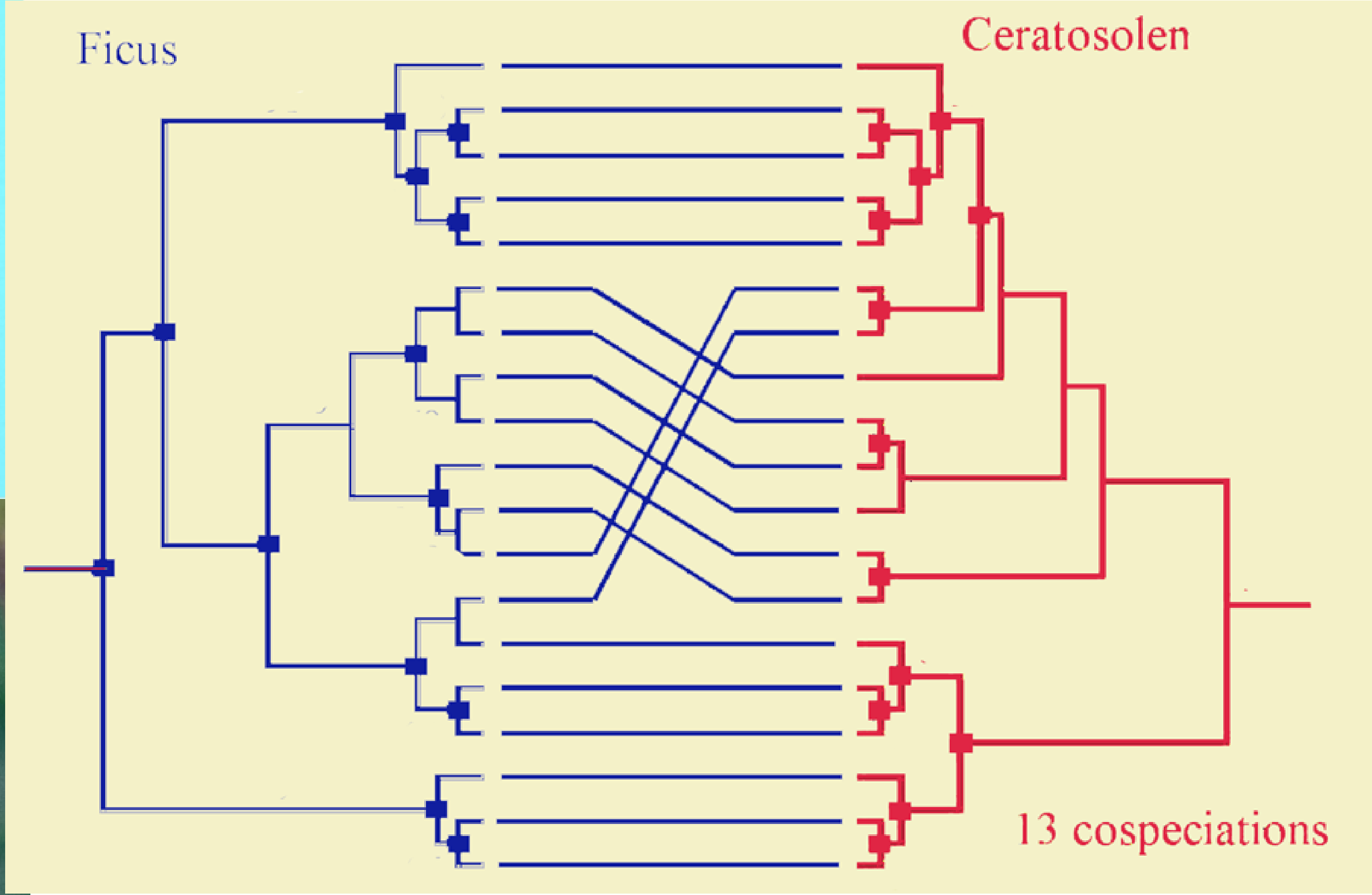
Yucca - Tegeticula moths (Yponomeutidae)

Trollius - Chiastocheta (Anthomyiidae) flies

Glochidium - Epicephala (Gracillariidae) moths

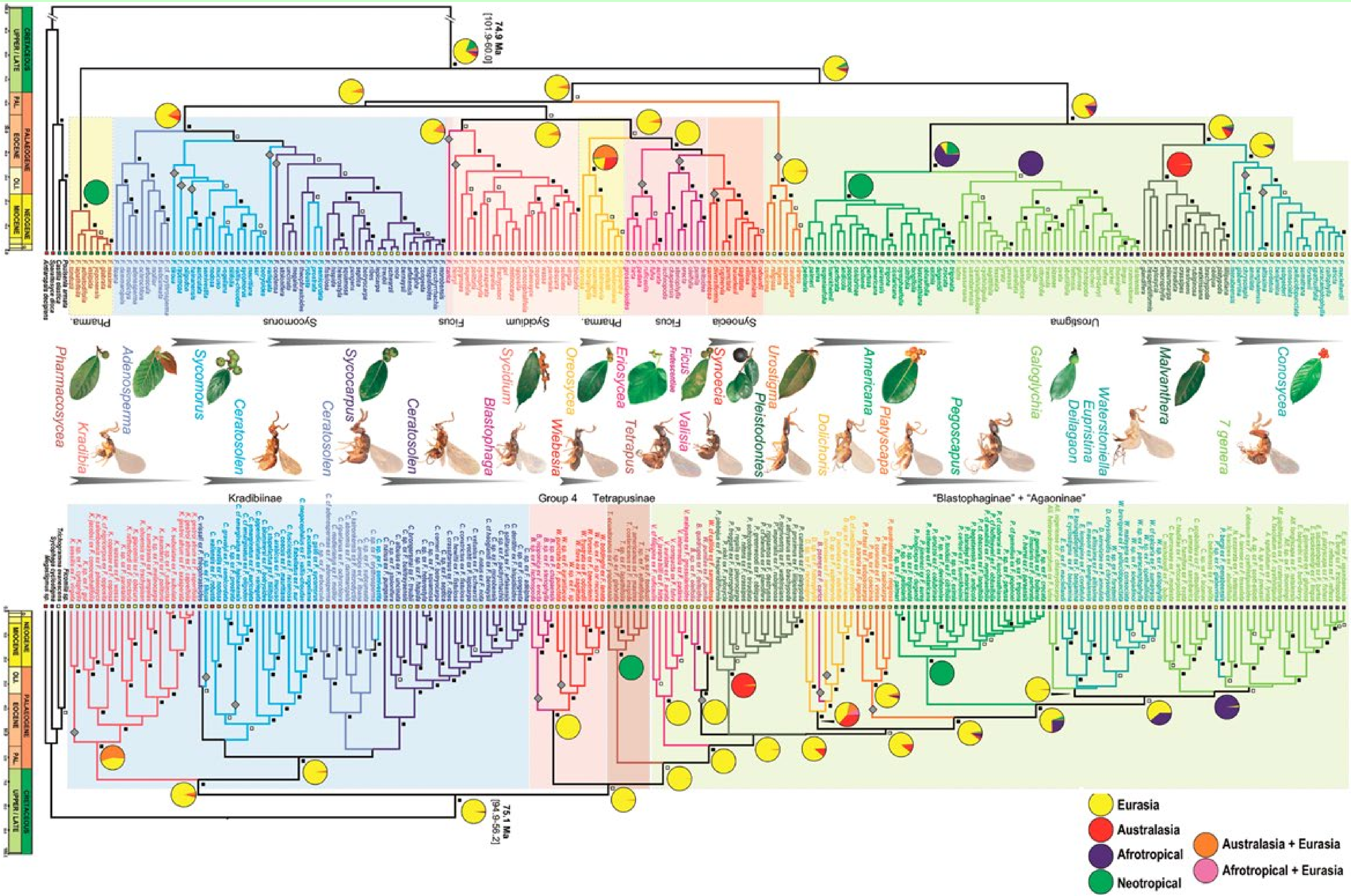
Ficus and their pollinating wasps





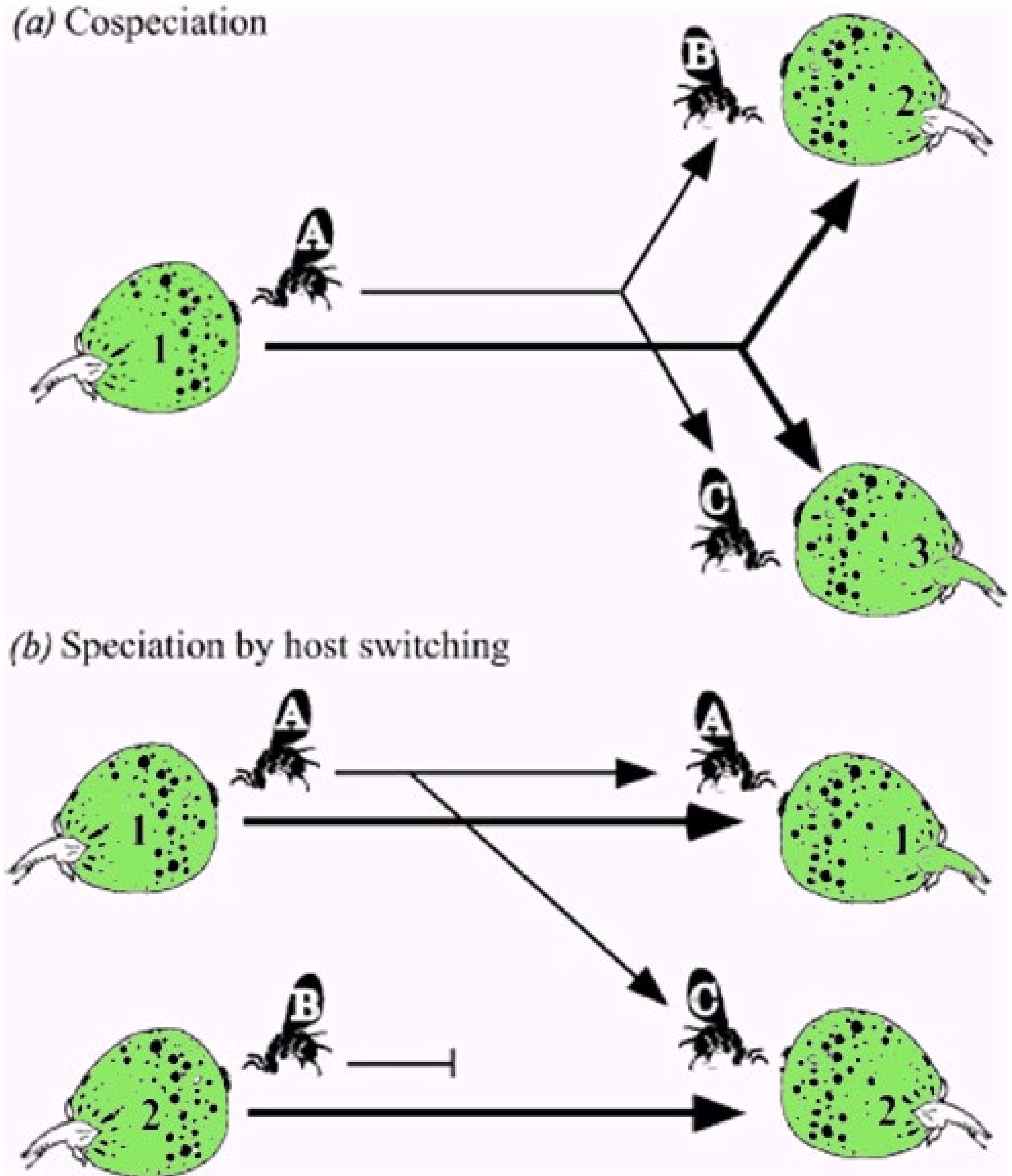
13 cospeciations

Ficus – pollinator wasp evolution

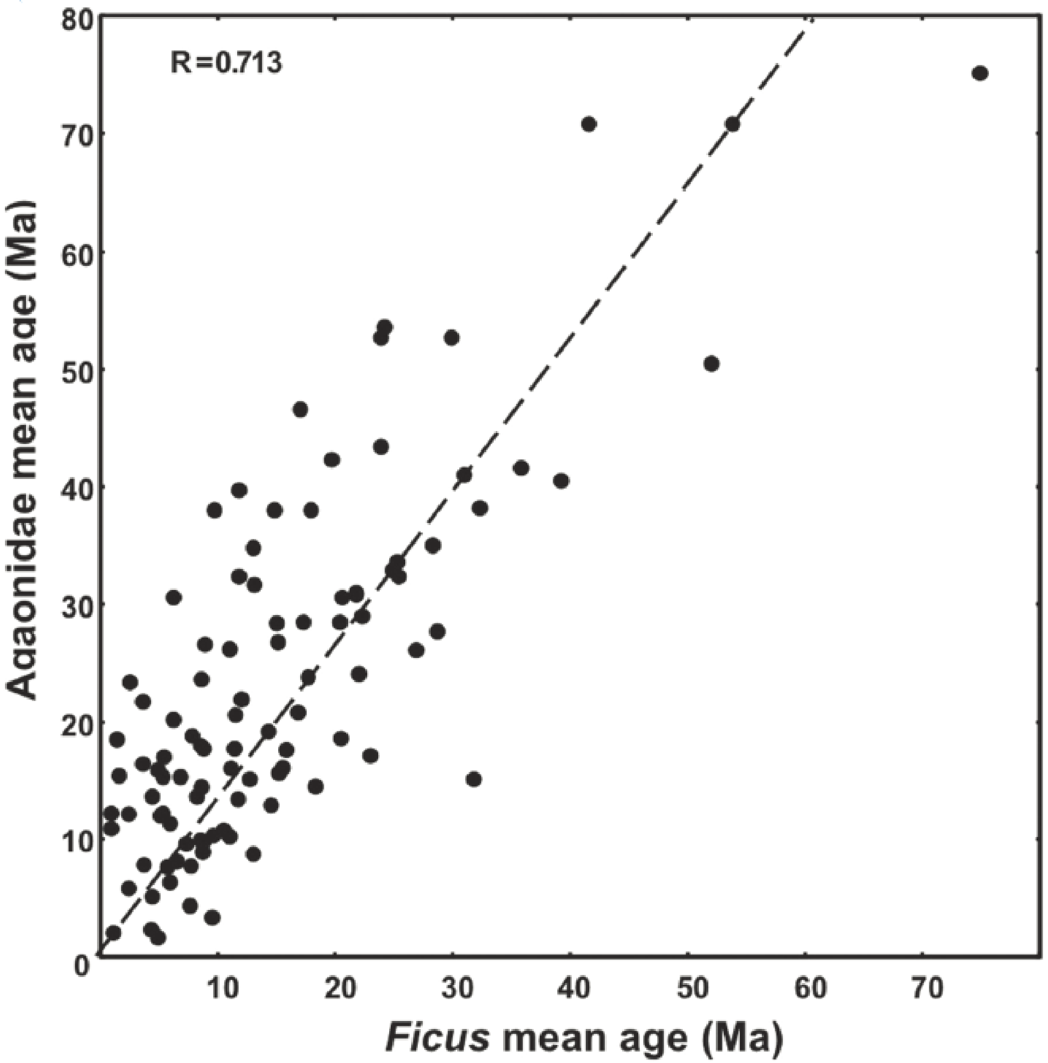


Cruaud et al. *Syst. Biol.* 61(6):1029–1047, 2012

How the fig - wasp relationships evolved?



Temporal congruence of the 198 cospeciation events

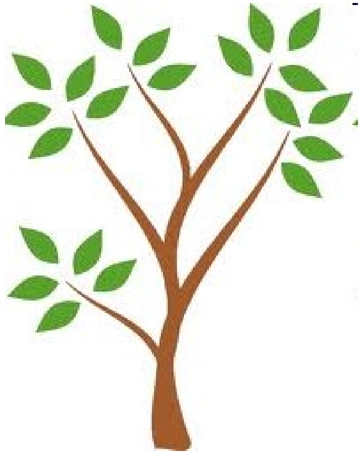


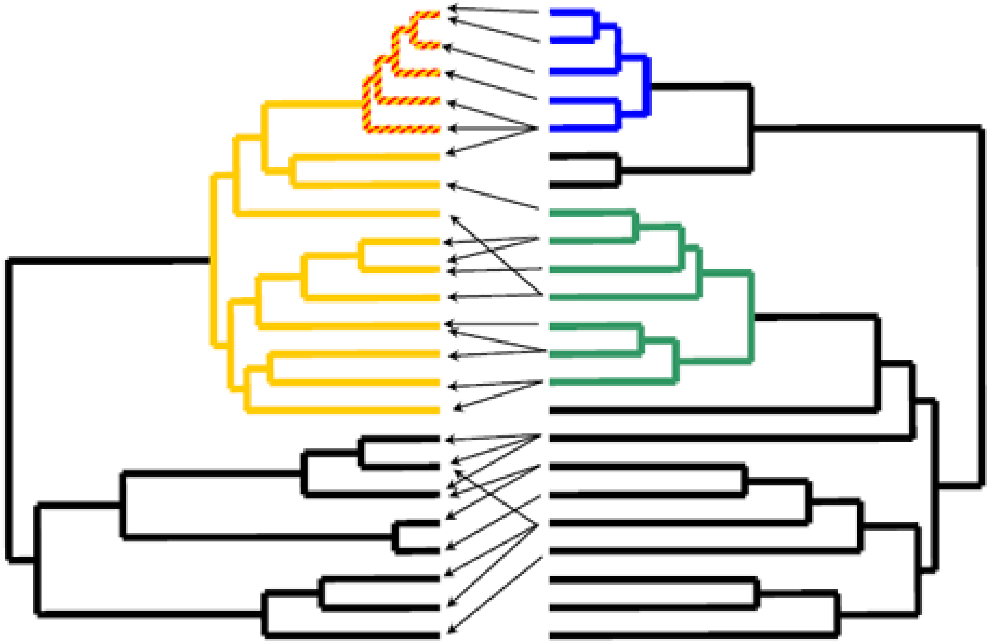
Cruaud et al. *Syst. Biol.* 61(6):1029–1047, 2012 Weiblen 2002

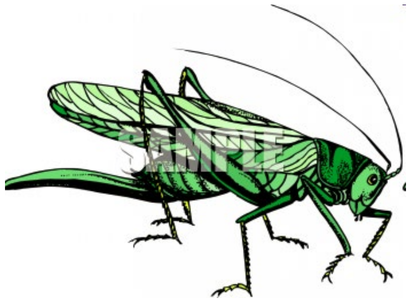
Coevolution: reciprocal evolutionary change in interacting species

Escape-and-radiate coevolution

1. Plants evolve (via mutation, recombination) a new toxin/deterrent.
2. New chemical leads to protection from herbivores.
3. Protected plants enter a new adaptive zone, in which they are free to radiate.
4. Herbivores evolve (via mutation, recombination) ways to deal with new toxin.
5. Herbivores enter a new adaptive zone and are free to radiate.
6. The cycle is repeated.

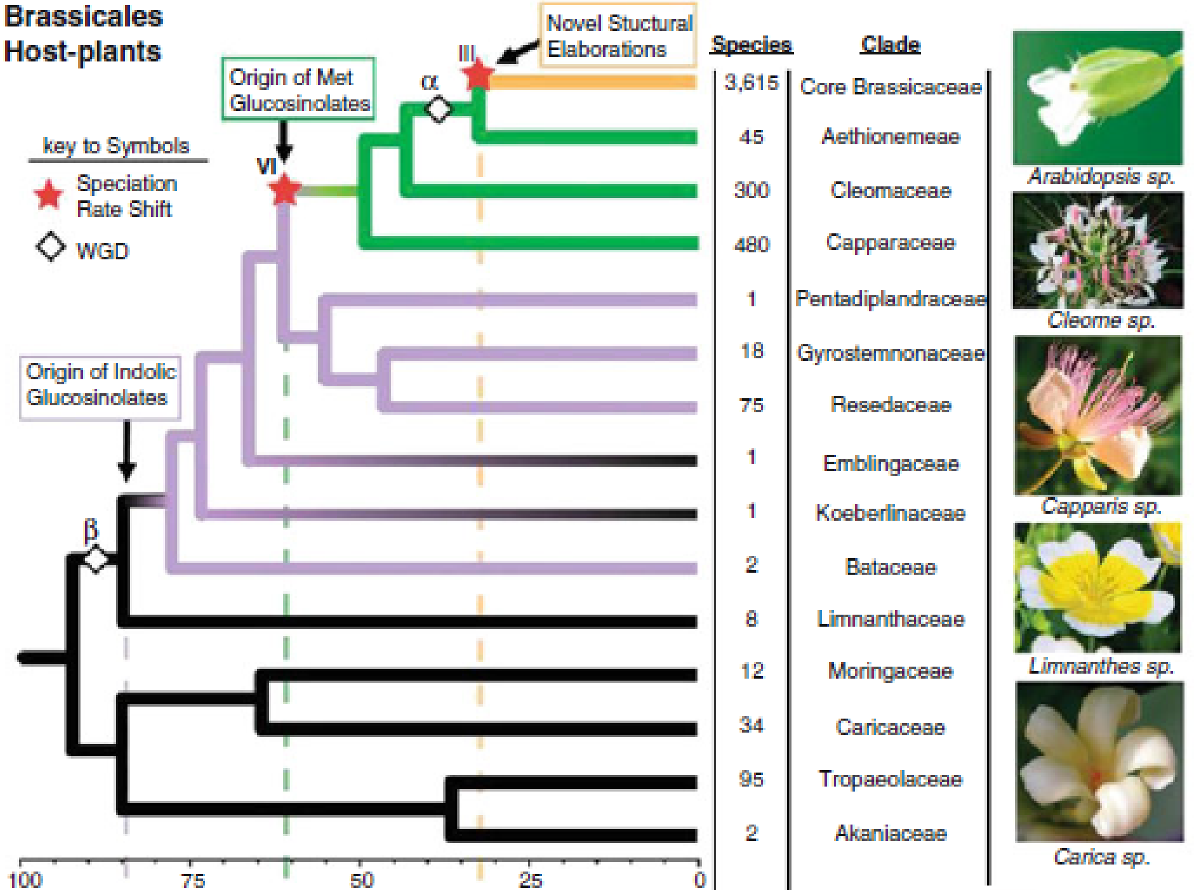


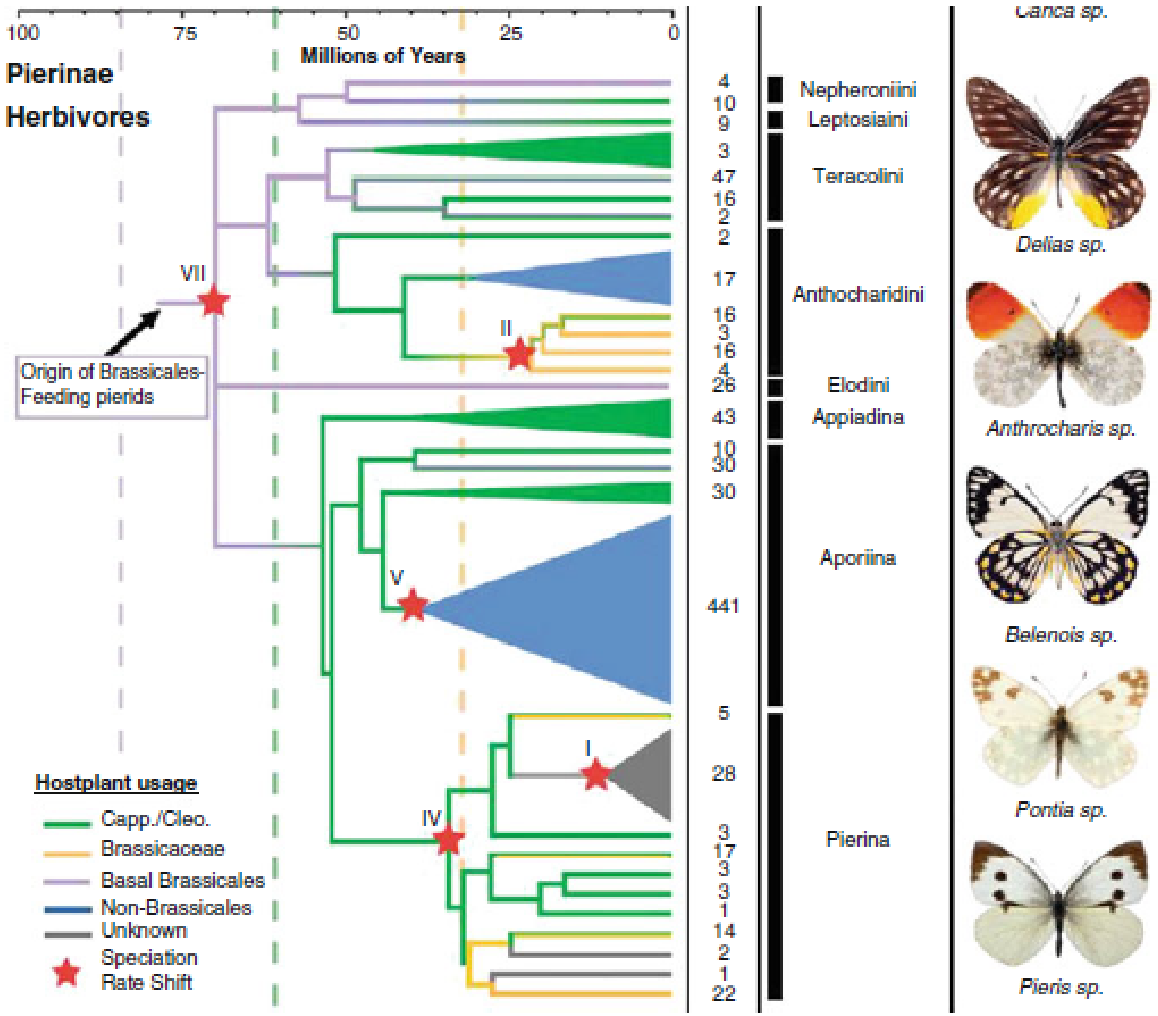


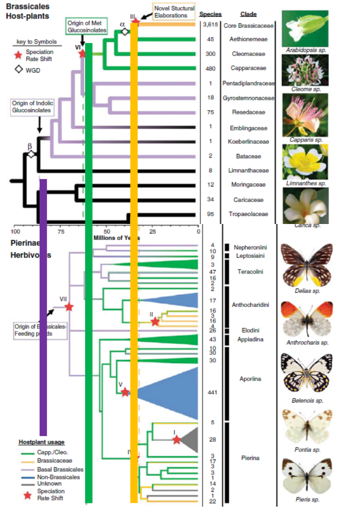


Escape and radiation concept: plants develop new defence [yellow, orange], their speciation rate increases, herbivores develop counter-defence [green, blue] colonize them and then speciate faster

Escape and radiate dynamics of Brassicales – Pierinae interactions

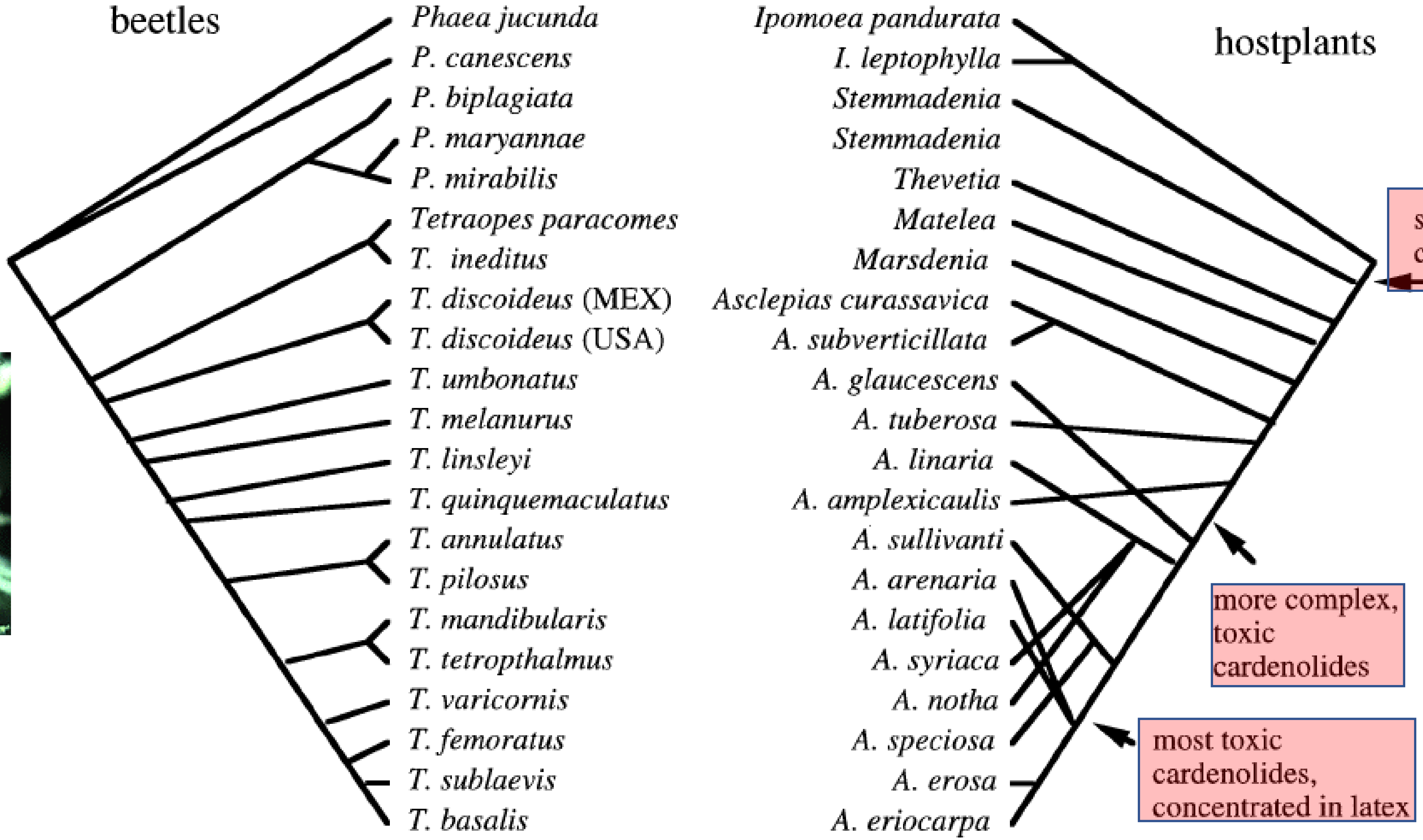






Eunice Kariñho-Betancourt 2019. J.-M. Mérillon, K. G. Ramawat (eds.), Co-Evolution of Secondary Metabolites

Tetraopes beetles and *Asclepias* hosts: evolutionary defence escalation



beetles

- *Phaea jucunda*
- *P. canescens*
- *P. biplagiata*
- *P. maryannae*
- *P. mirabilis*
- *Tetraopes paracomes*
- *T. ineditus*
- *T. discoideus* (MEX)
- *T. discoideus* (USA)
- *T. umbonatus*
- *T. melanurus*
- *T. linsleyi*
- *T. quinquemaculatus*
- *T. annulatus*
- *T. pilosus*
- *T. mandibularis*
- *T. tetropthalmus*
- *T. varicornis*
- *T. femoratus*
- *T. sublaevis*
- *T. basalis*

hostplants

- *Ipomoea pandurata*
- *I. leptophylla*
- *Stemmadenia*
- *Stemmadenia*
- *Thevetia*
- *Matelea*
- *Marsdenia*
- *Asclepias curassavica*
- *A. subverticillata*
- *A. glaucescens*
- *A. tuberosa*
- *A. linaria*
- *A. amplexicaulis*
- *A. sullivanti*
- *A. arenaria*
- *A. latifolia*
- *A. syriaca*
- *A. notha*
- *A. speciosa*
- *A. erosa*
- *A. eriocarpa*

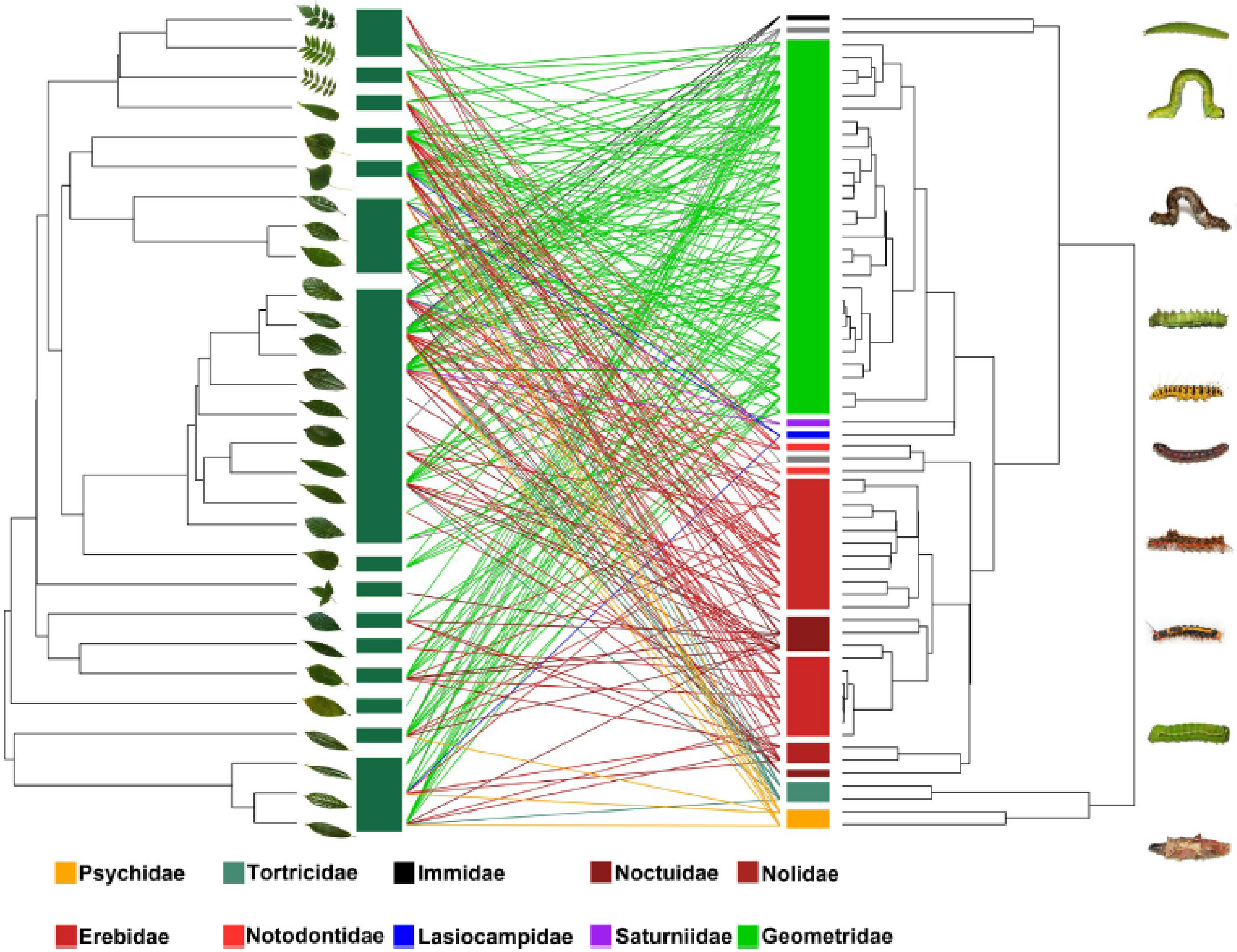
simple cardenolides

more complex, toxic cardenolides

most toxic cardenolides, concentrated in latex

Farrell & Mitter
1998

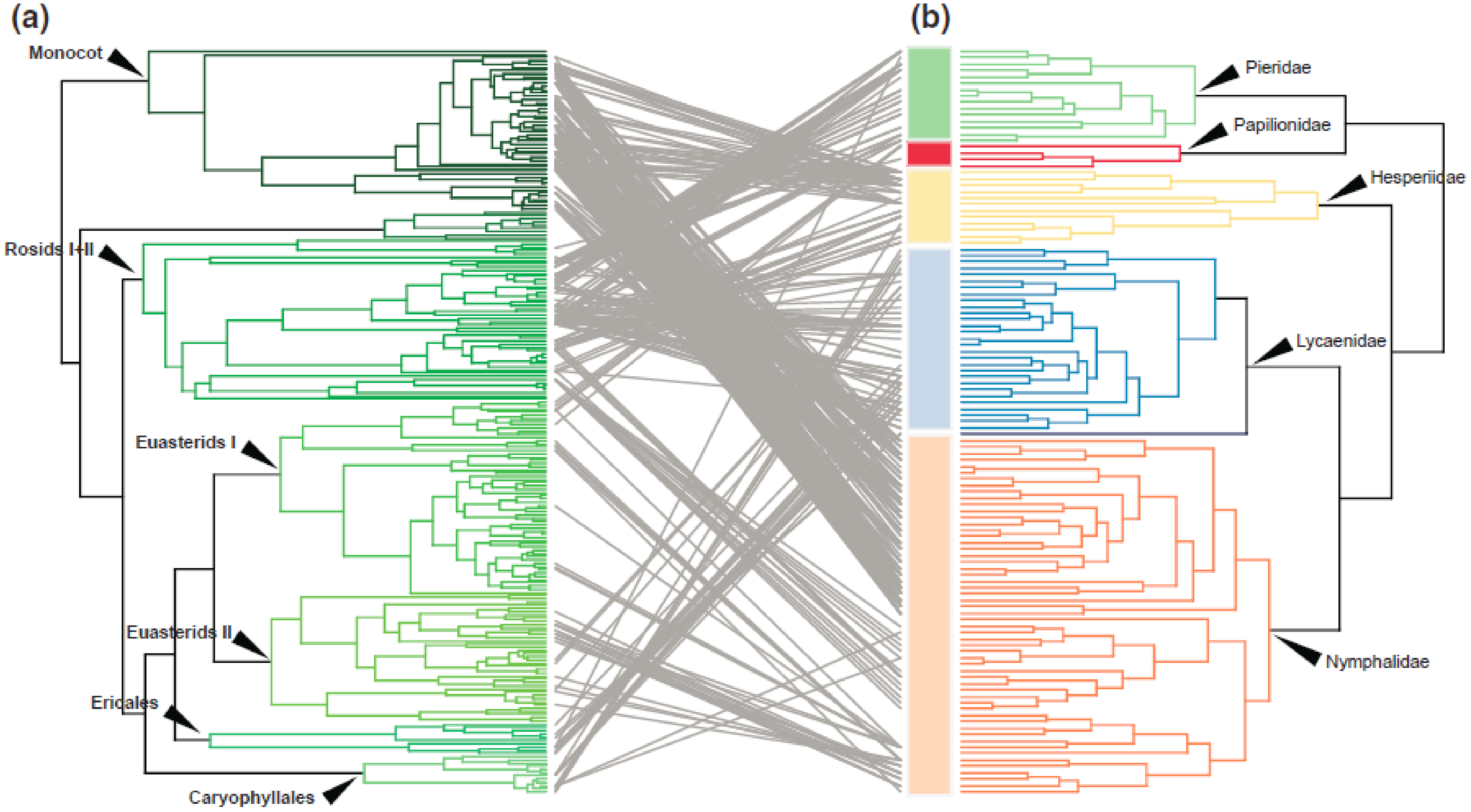
Phylogenetic signal in a forest plant-caterpillar food web

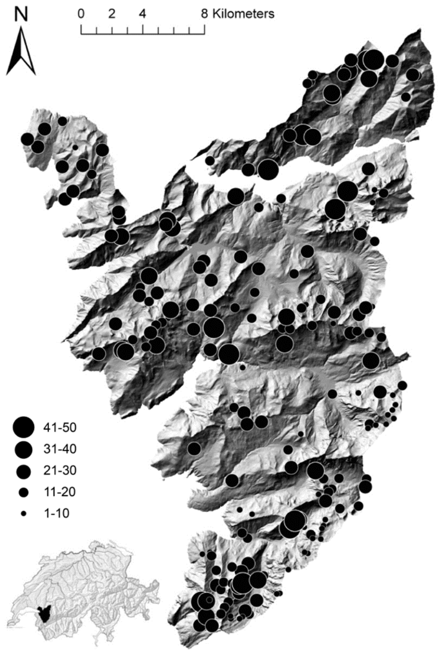


Subtropical forest in S China
(BEF Experiment)

Phylogenetic congruence for the most abundant lepidopteran species and plant species. Each rectangle represents a family for tree species; colours indicate different lepidopteran superfamilies. The trophic network is nonrandomly structured.

Wang et al. Molecular Ecology. 2020;29:2747–2762



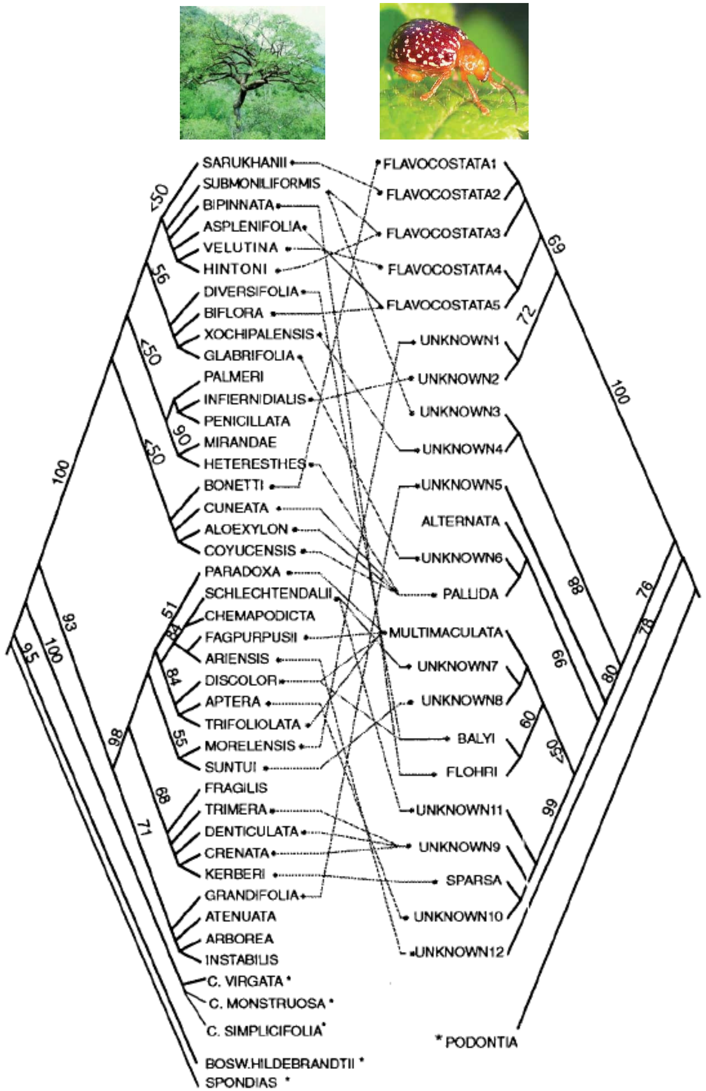


Swiss Alp meadows: 231 most abundant plant species vs. all butterfly species

Strong phylogenetic signal but a lot of phylogenetically unexplained variability

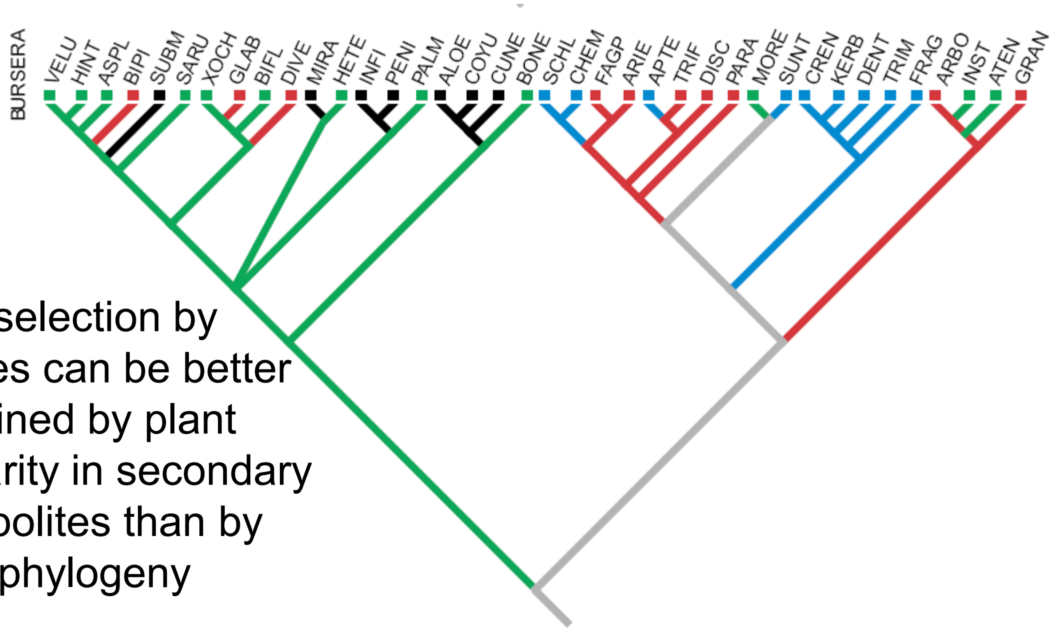
Pellissier et al. 2013, Ecology Letters

Blepharida beetles on *Bursera* plants: secondary chemistry has low phylogenetic signal, explains multiple host colonizations



Bursera phylogeny does not correspond with phylogeny of its beetles

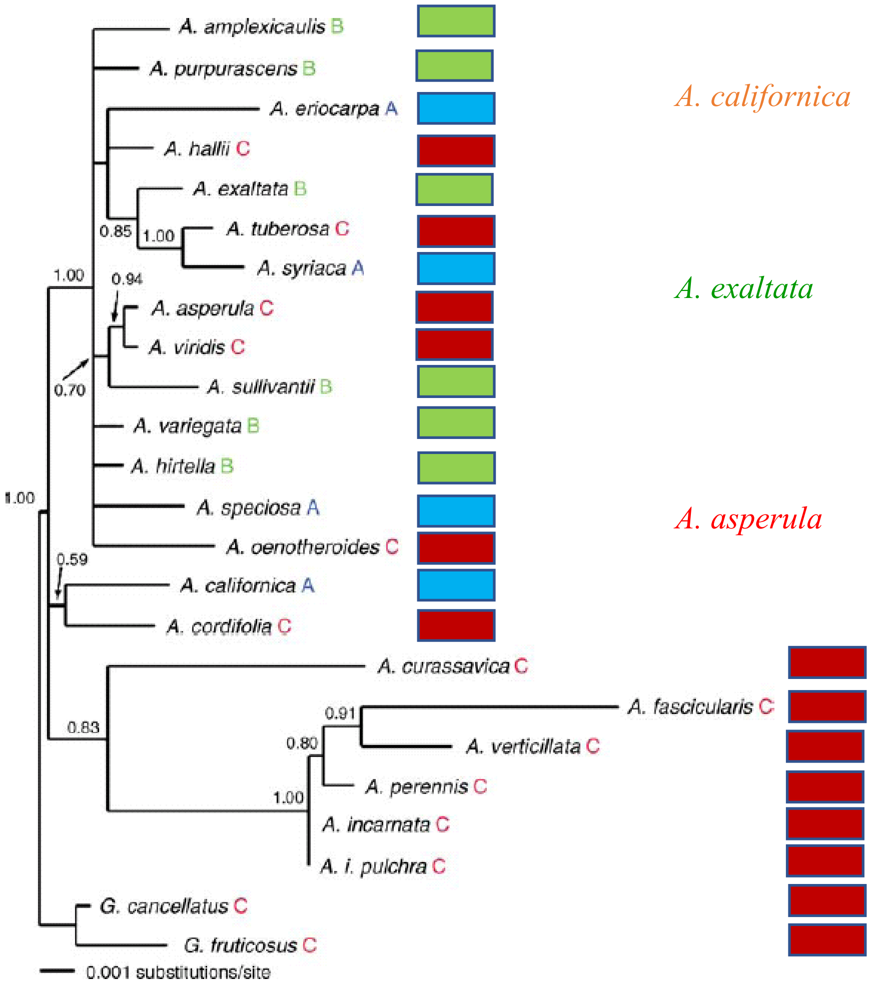
different secondary chemistry marked by different colour on Bursera phylogeny



Host selection by beetles can be better explained by plant similarity in secondary metabolites than by plant phylogeny

Becerra 1997

Asclepias defense strategies: life history traits and phylogeny

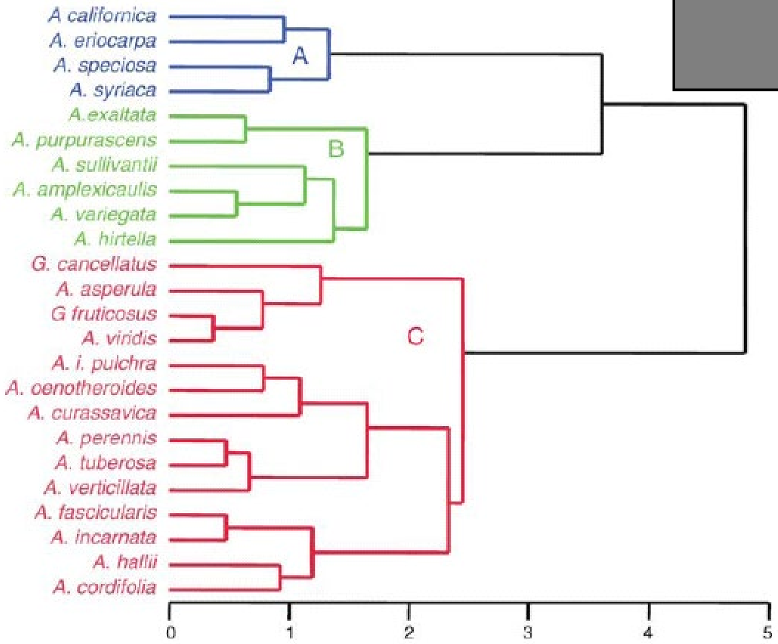


Distribution of defense strategies on *Asclepias* phylogeny

A. californica

A. exaltata

A. asperula



Phenogram recognizing three defense strategies based on 7 traits:

Putative defense trait
Latex (mg)
Cardenolides (% dry mass)
Trichomes (no. hairs/cm^2)
Toughness (g)
C:N
Water content (%)
Specific leaf area (mm^2/mg)

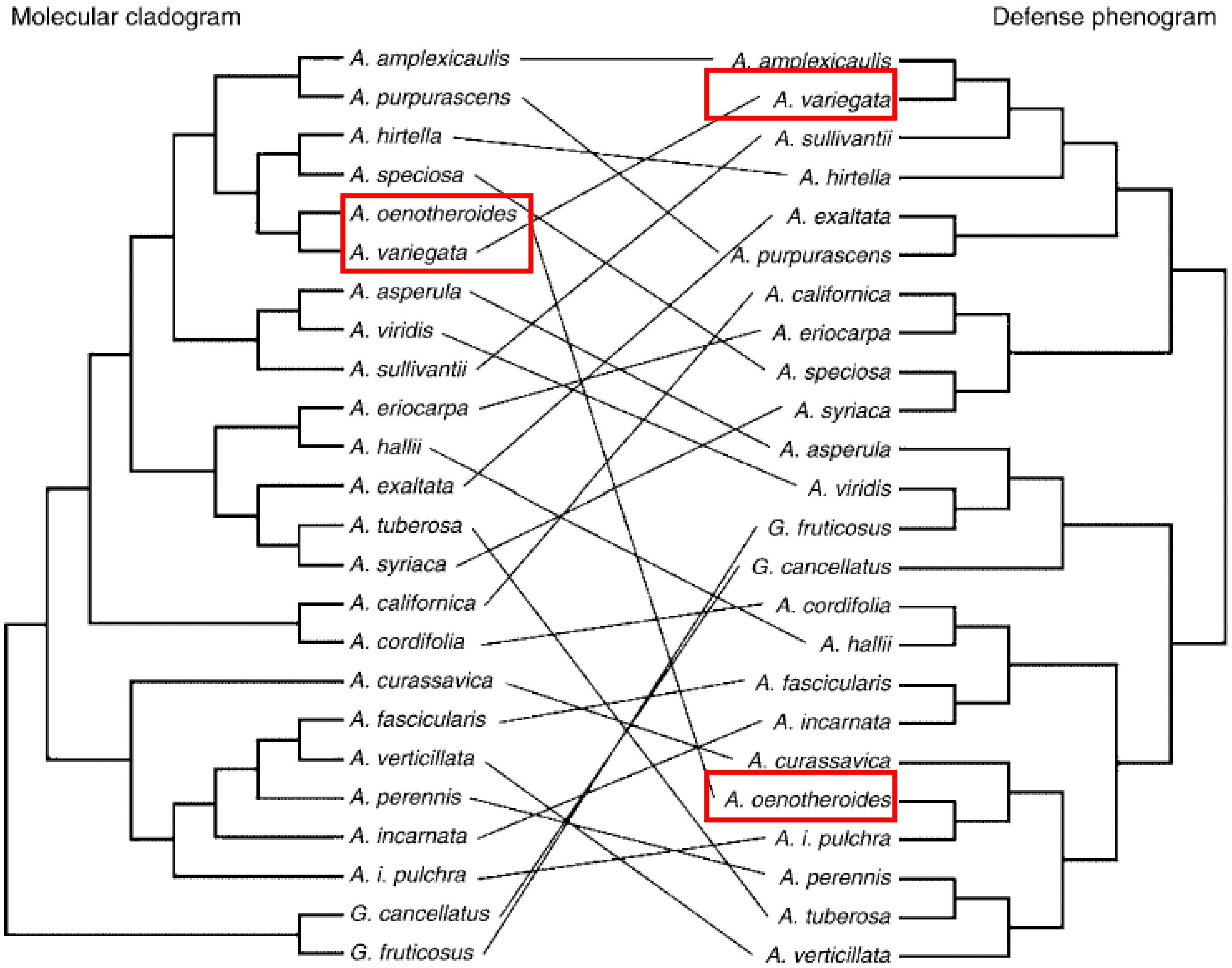
A: soft leaves, many trichomes, high latex

B: tough leaves, low water content, medium latex

C: soft leaves, low latex, high cardenolides

Agrawal & Fishbein, Ecology, 87 Suppl., 2006, S132–S149

Asclepias defense strategies: phylogenetically unstable

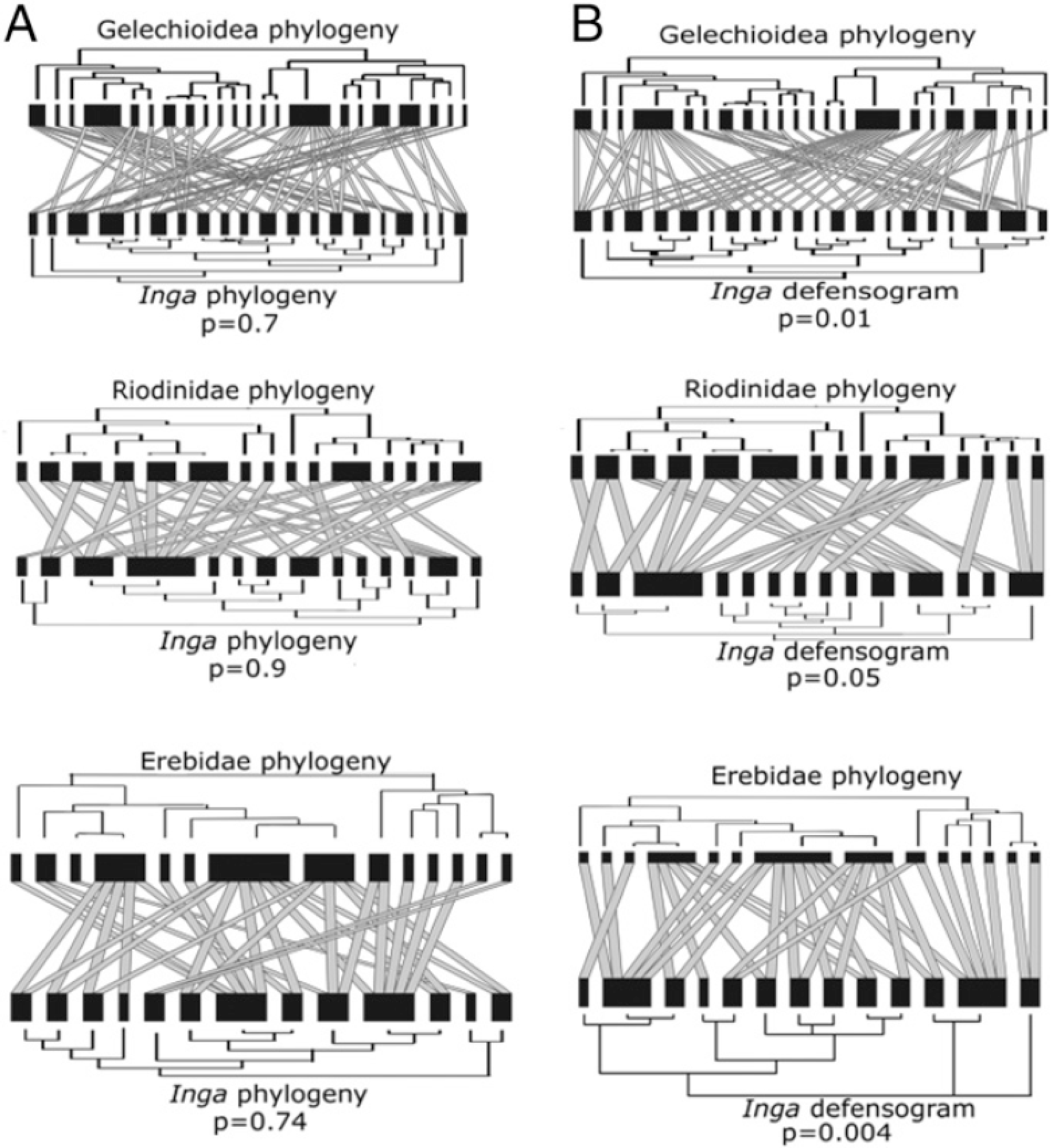


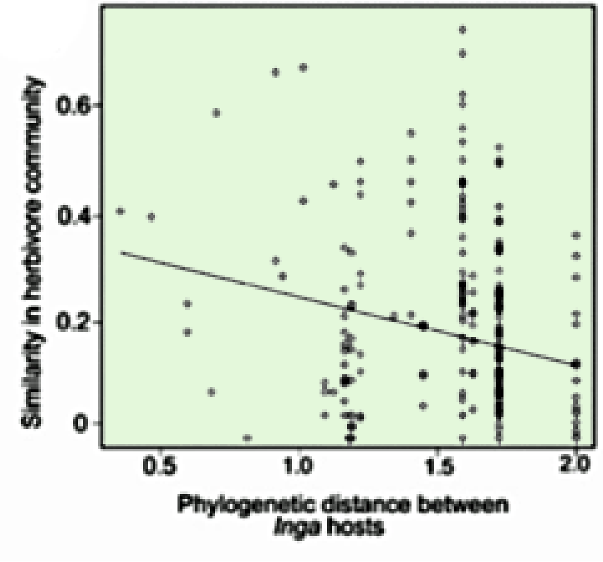
B: tough leaves, low water content, medium latex

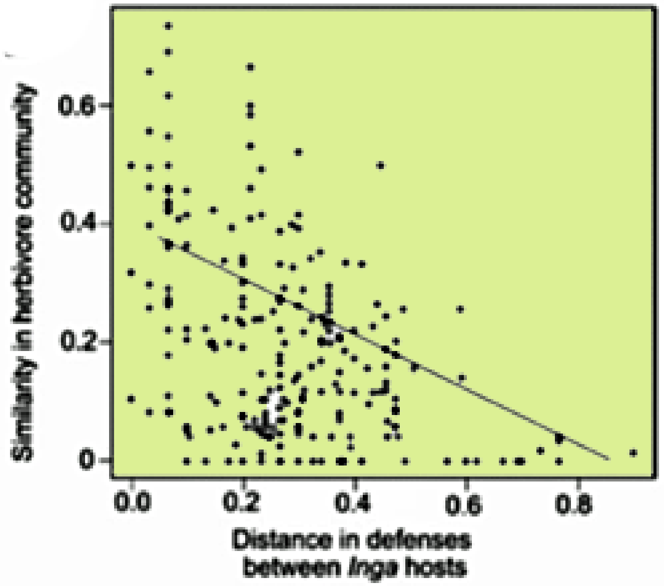
C: soft leaves, low latex, high cardenolides

Agrawal & Fishbein, Ecology, 87 Suppl., 2006, S132–S149

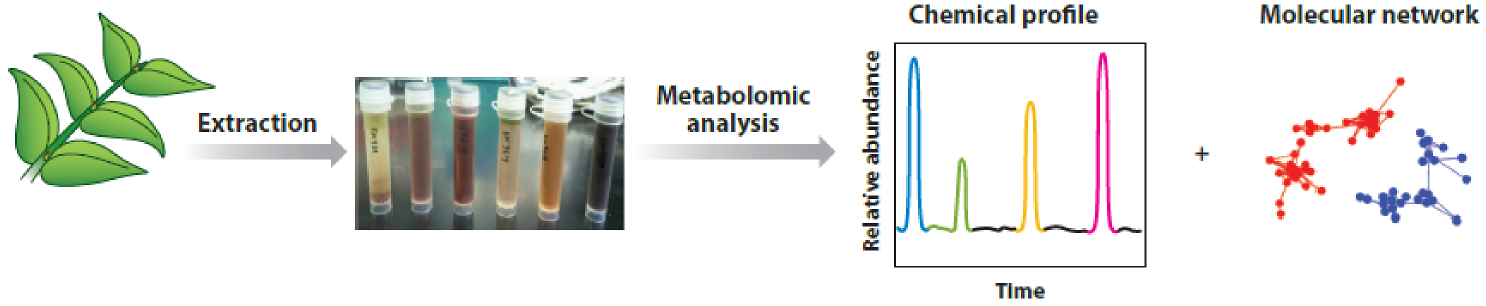
Inga spp.: chemistry, biotic protection by ants, trichomes, and leaf production seasonality, not phylogeny, correlate with the composition of herbivore communities



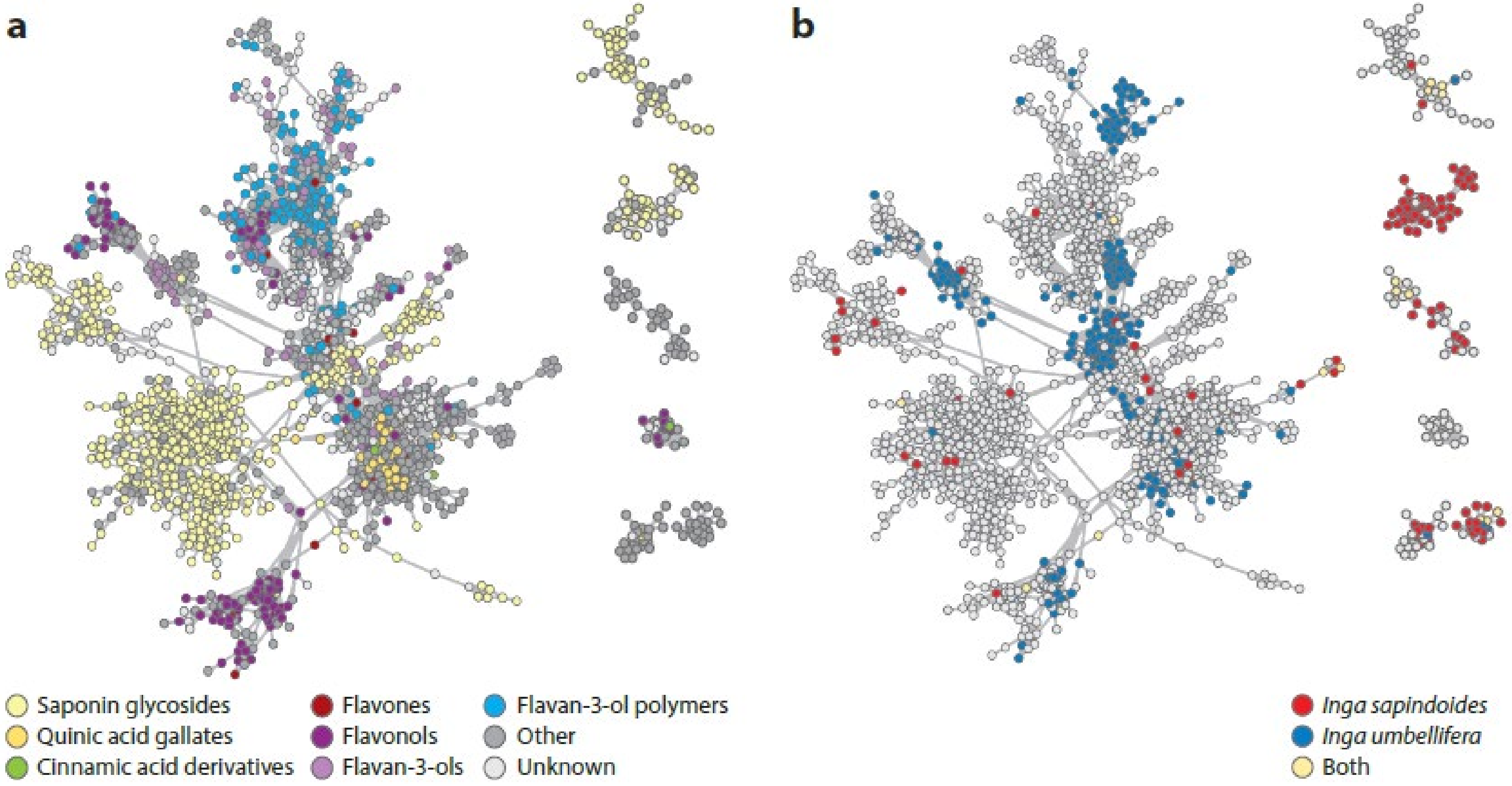




Endara et al. 2017, PNAS www.pnas.org/cgi/doi/10.1073/pnas.1707727114



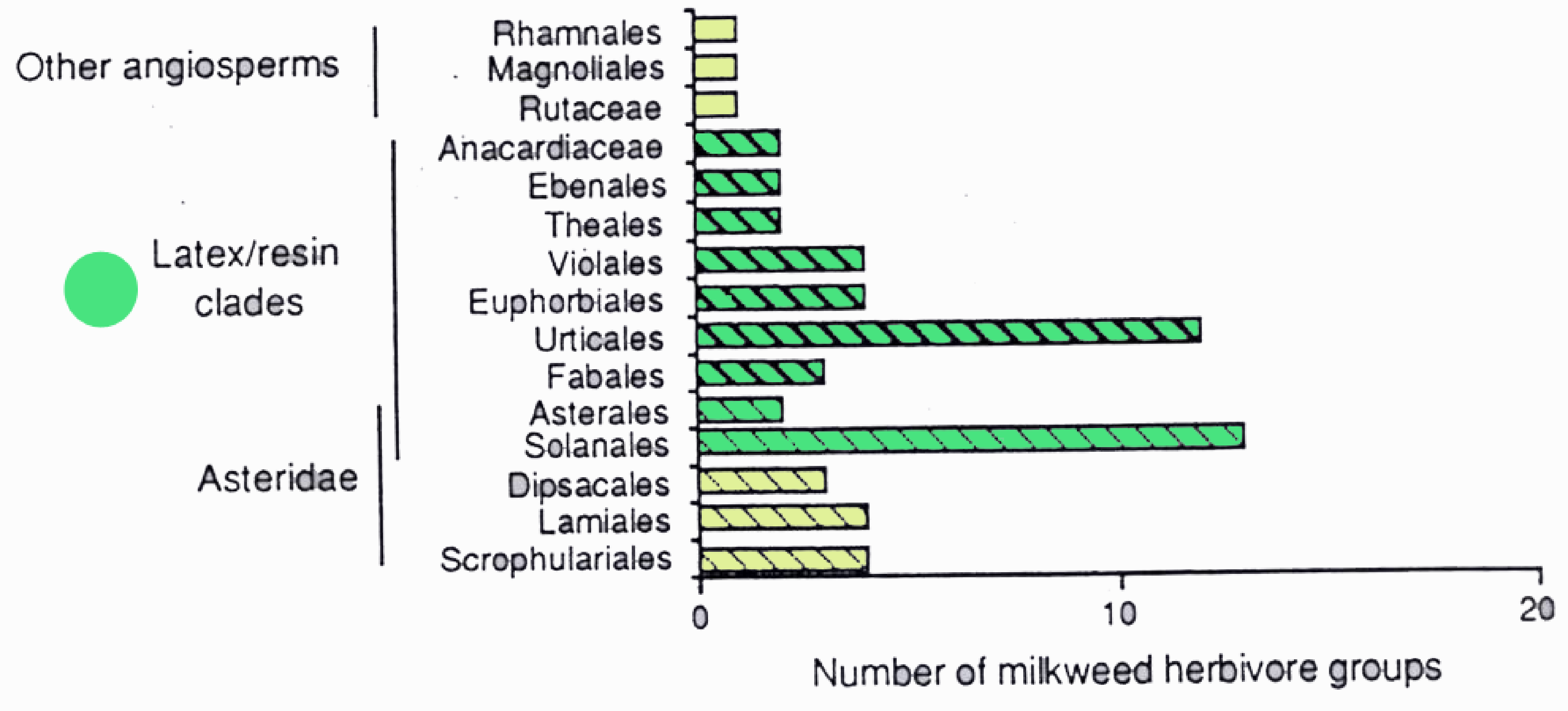
Molecular networks of metabolites



98 tropical species of Inga (Fabaceae).

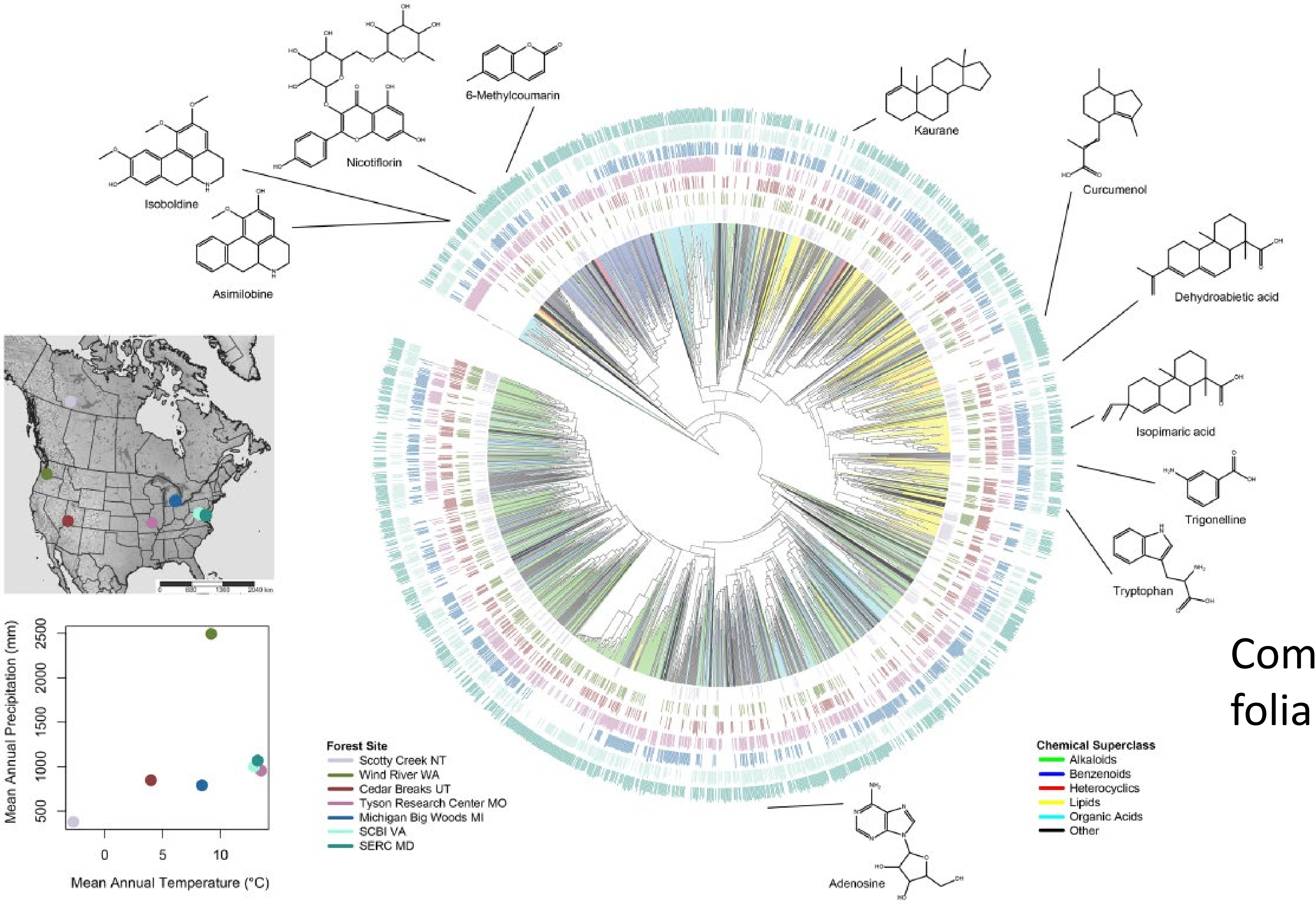
Endara et al Annu. Rev. Ecol. Evol. Syst. 2023. 54:107–27

Herbivores feeding on latex-rich Asclepiadaceae - Apocynaceae colonize preferably other latex plant lineages



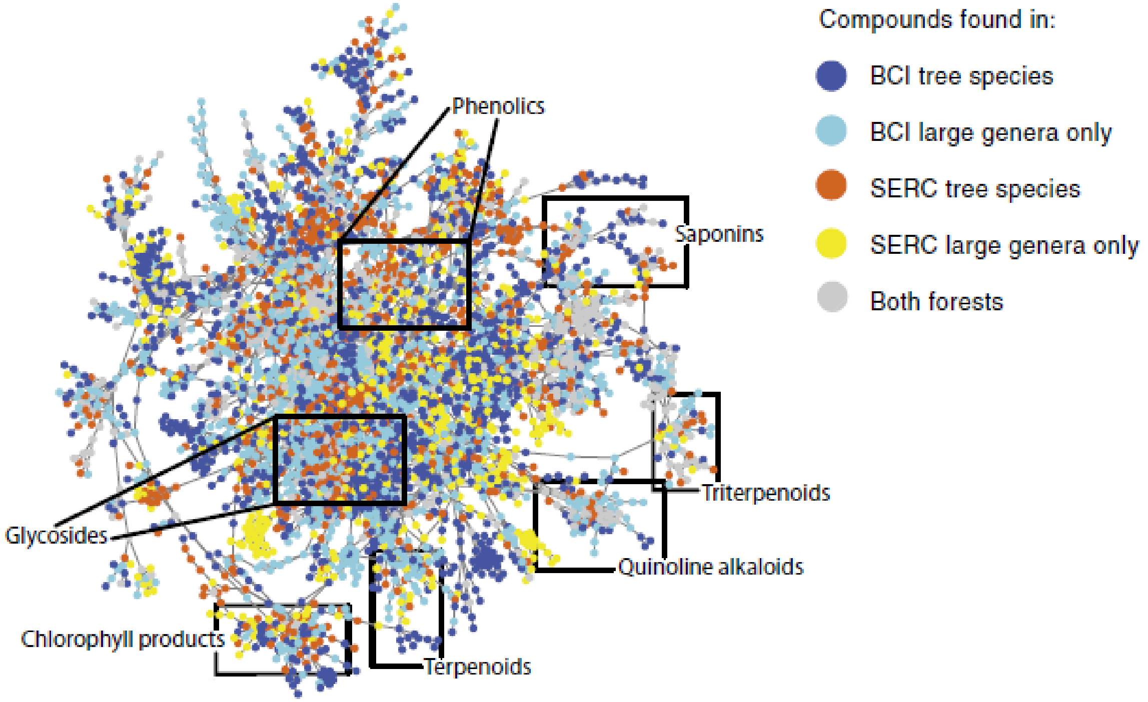
Number of colonization of plants from various orders by herbivores feeding on latex-rich Asclepiadaceae - Apocynaceae plants: insects retain their taste for latex

Complexity of plant foliar metabolites

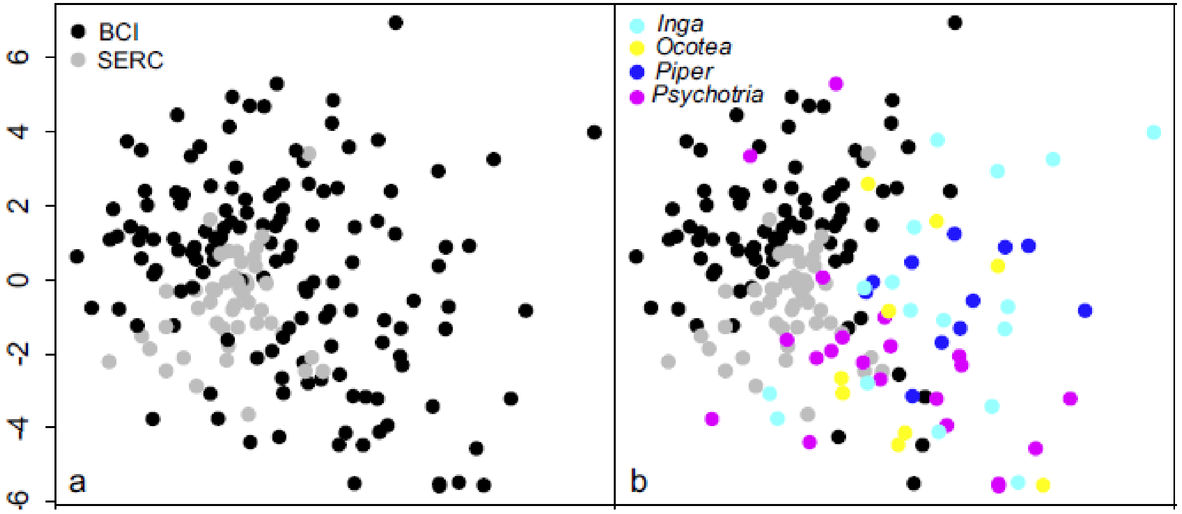


Hierarchical dendrogram of 13,480 foliar metabolites by their structural similarity. Branch color = chemotaxonomic classification Concentric bars represent abundance of metabolites in seven forest plots.

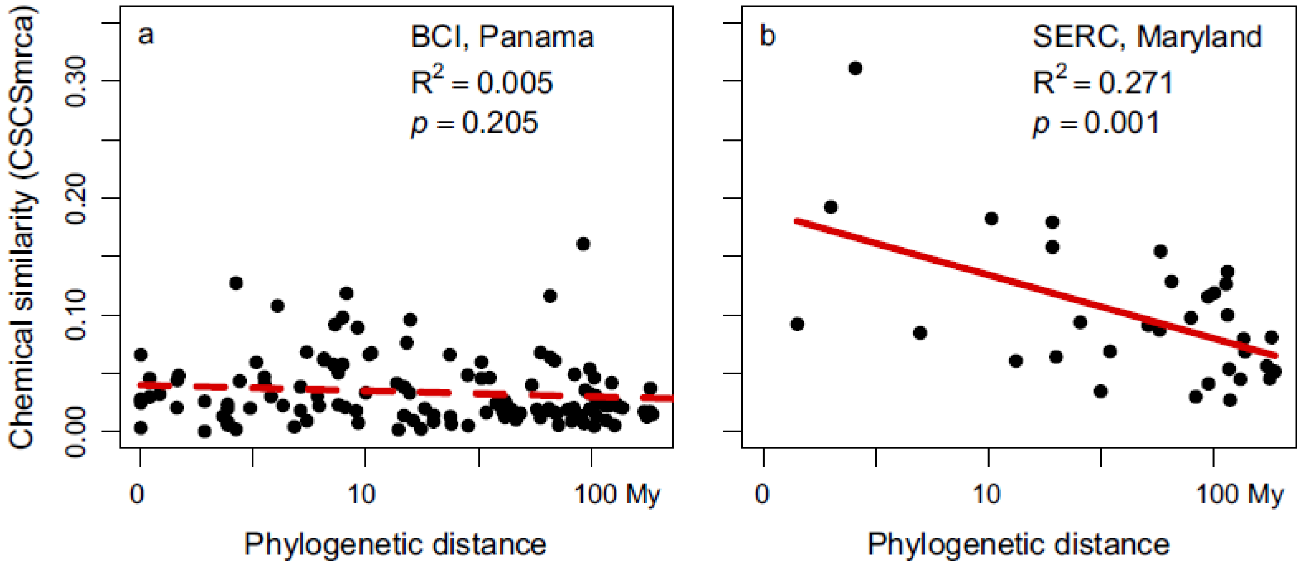
Sedio et al. 2021. Front. Ecol. Evol. 9: 679638.



36,223 compounds in leaves of tree and shrub species from Maryland and Panama. Nodes represent compounds. Links between nodes represent structural similarity between compounds.

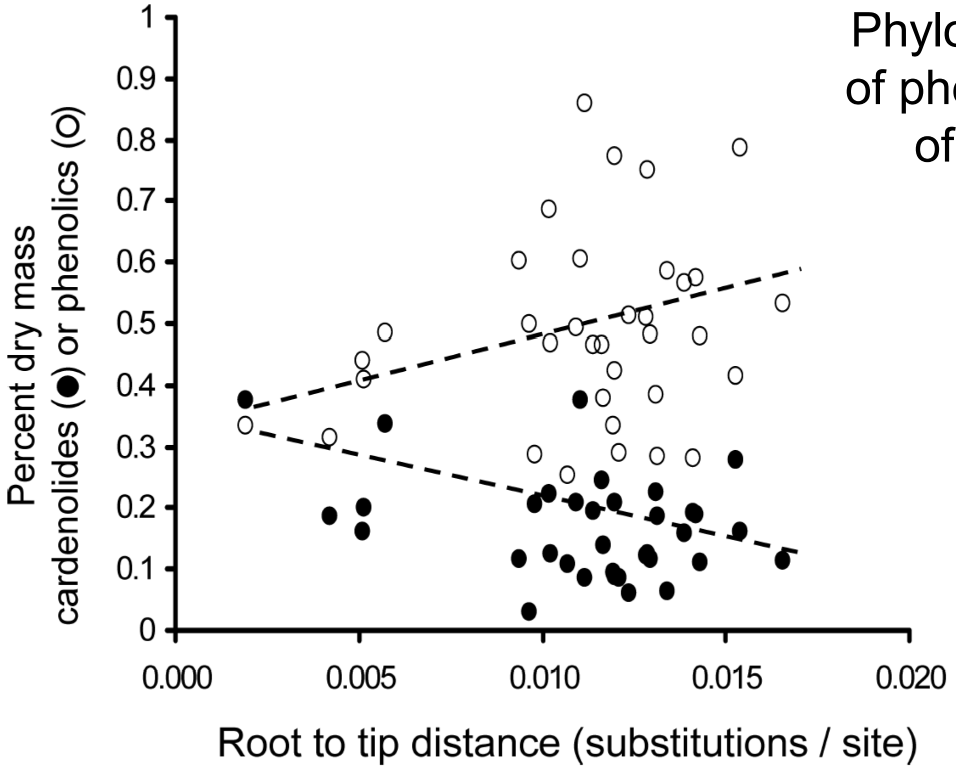


185 tree and shrub species from Maryland (SERC) and Panama (BCI) NMDS chemical similarity

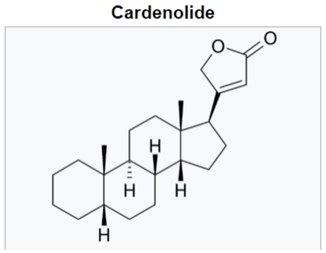


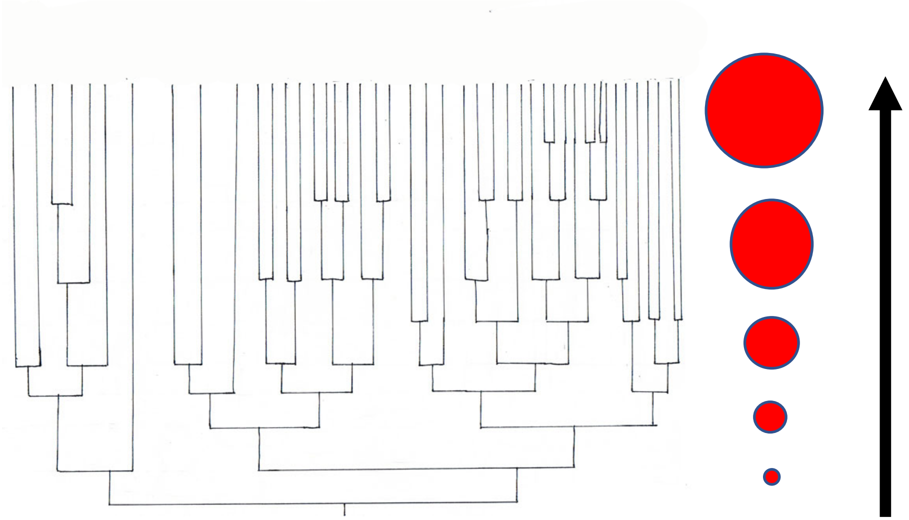
Sedio et al., Ecology, 99, 2018, 2647–2653

Escalation: the trait value increases in the course of evolution



Phylogenetic escalation of phenolics and decline of cardenolides in *Asclepia* spp.

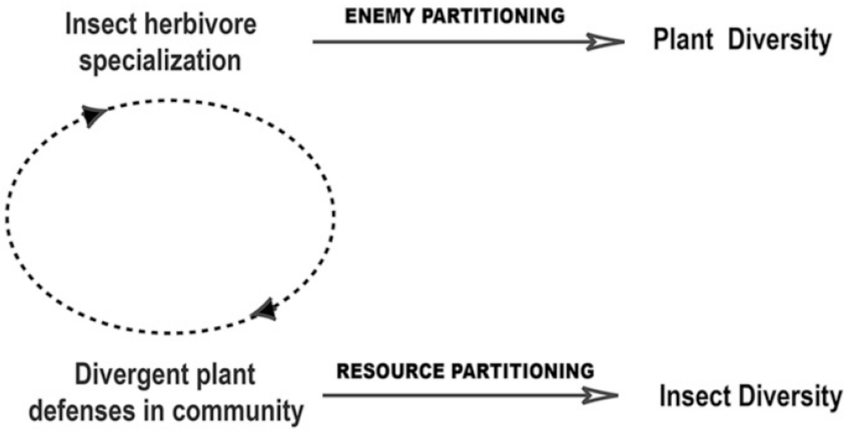




Trait value in evolution

Divergent plant defences:

traits more dissimilar between close relatives than expected under a conserved model of evolution



Insect herbivore specialization

ENEMY PARTITIONING

Plant Diversity

Divergent plant defenses in community

RESOURCE PARTITIONING

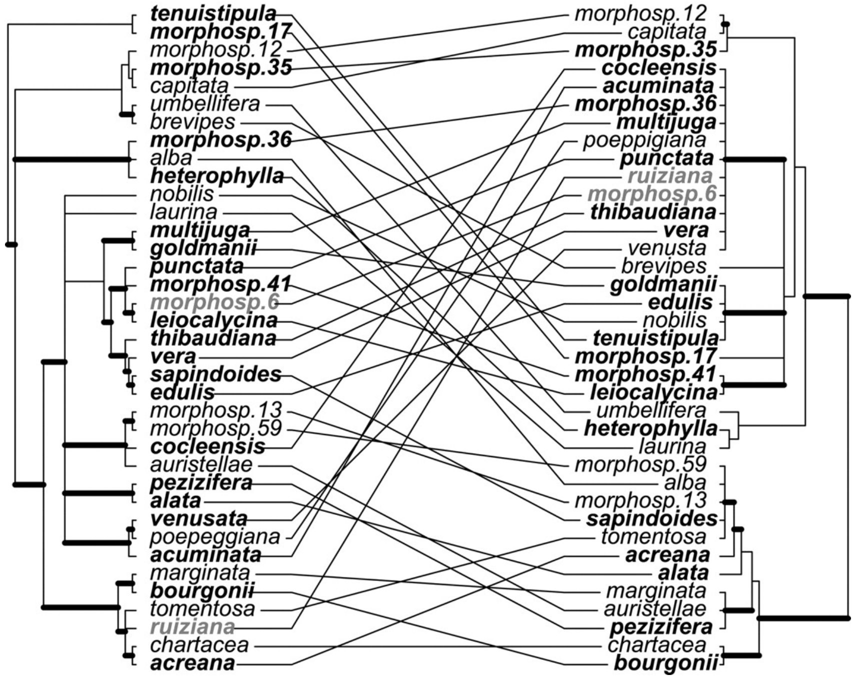
Insect Diversity

Becerra JX 2015: PNAS 112, 6098

Agrawal et al. 2009, Evolution 63-3: 663–673

Futuyma & Agrawal, 2009, PNAS 106: 18054–18061

Defence divergence in a species-rich genus: *Inga*

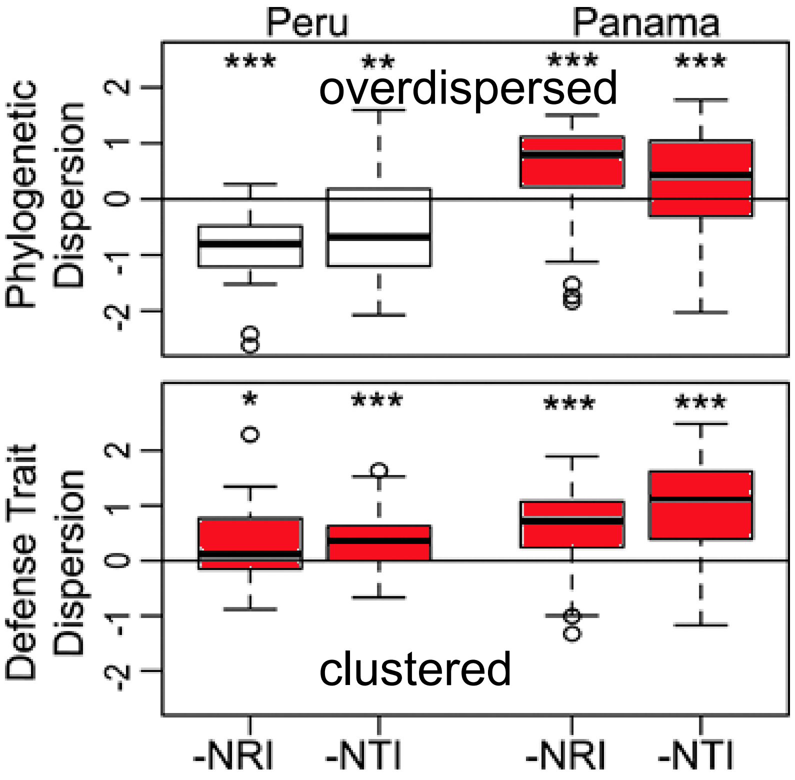


Inga spp.

phylogeny
cladogram

chemistry
dendrogram

Inga species co-occurring as neighbors are more different in anti-herbivore defenses than random, suggesting that possessing a rare defense phenotype increases fitness.



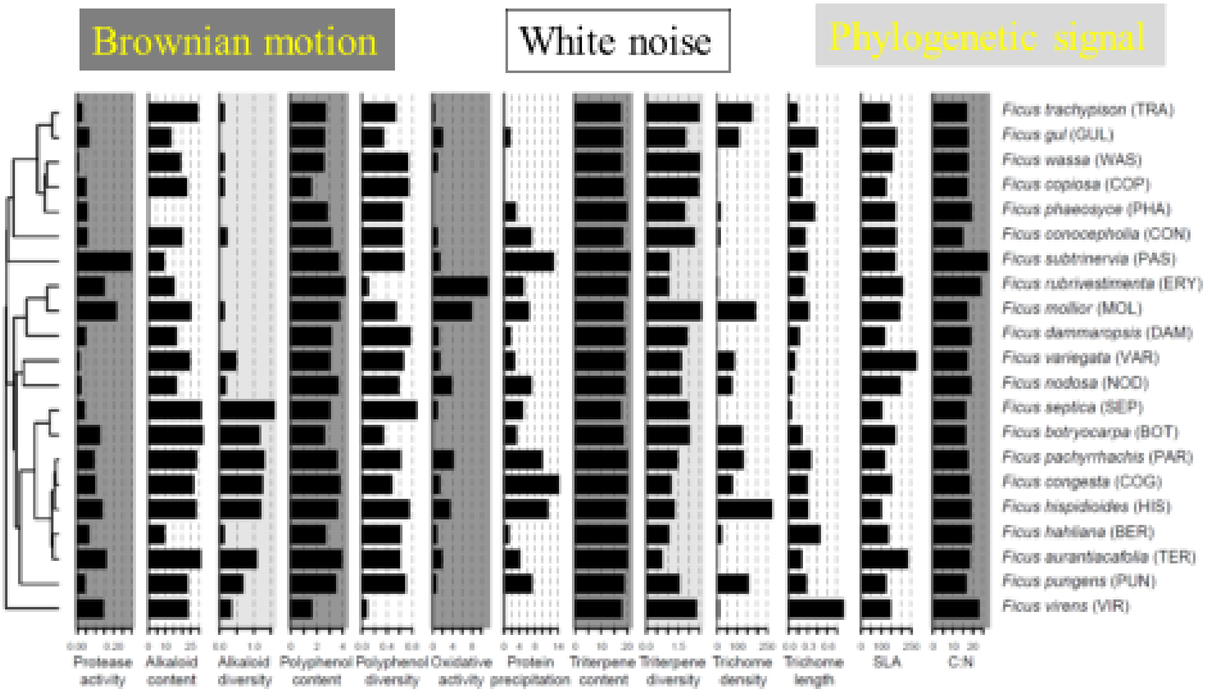
NRI: net relatedness index, NTI: nearest taxon index

Community species composition phylogenetically clustered in Peru and over-dispersed in Panama, defence traits over-dispersed in both locations

Kursar et al. PNAS 2009. 106:18073

Defence divergence in a species-rich genus: *Ficus*

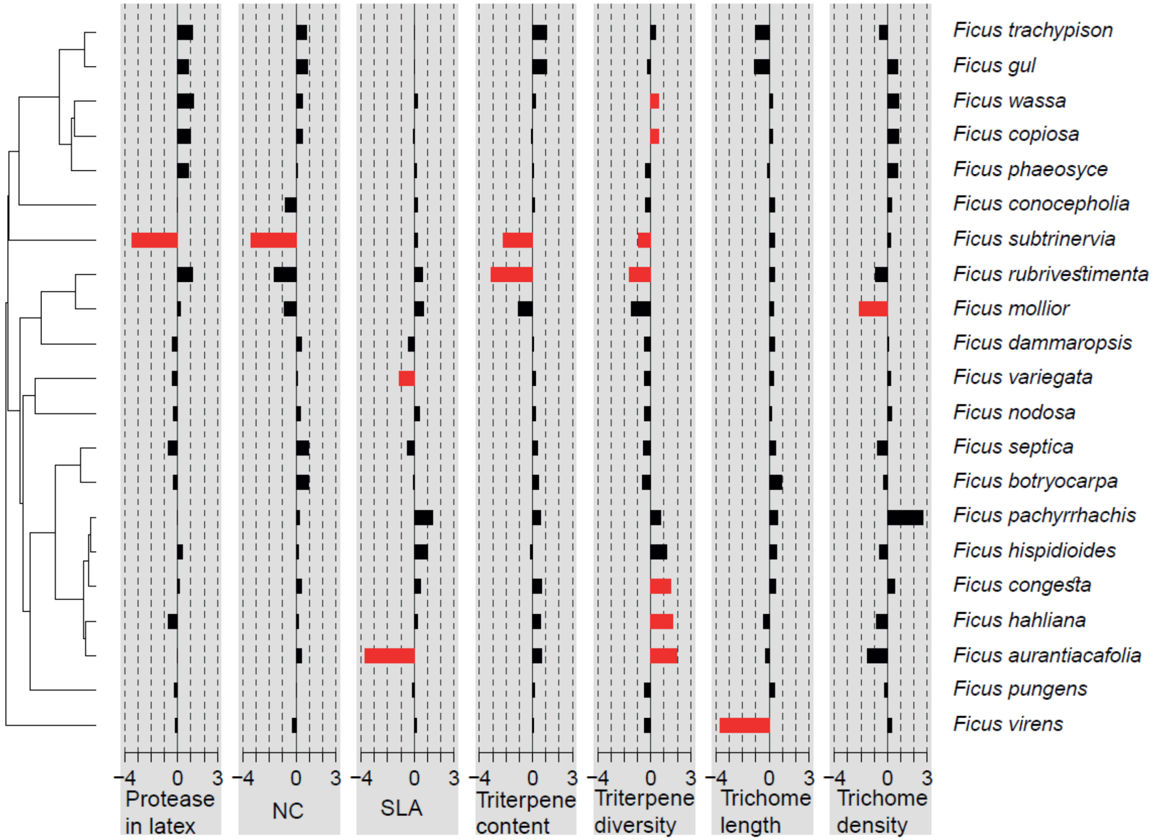
Phylogenetic distribution of plant defence traits on *Ficus* trees



Volf, Segar et al. Ecology Letters in press

Volf et al. 2017 Ecology Letters

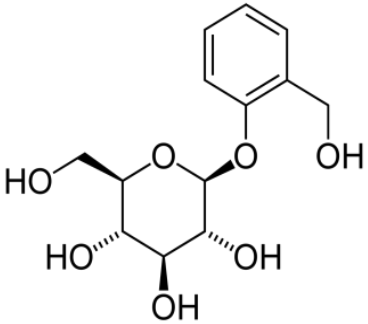
Species significantly dissimilar to their relatives in defensive traits

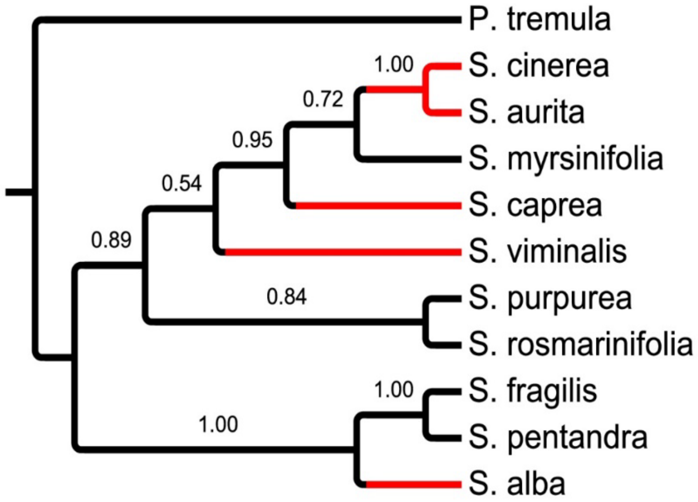


When anti-herbivore secondary metabolites become useless

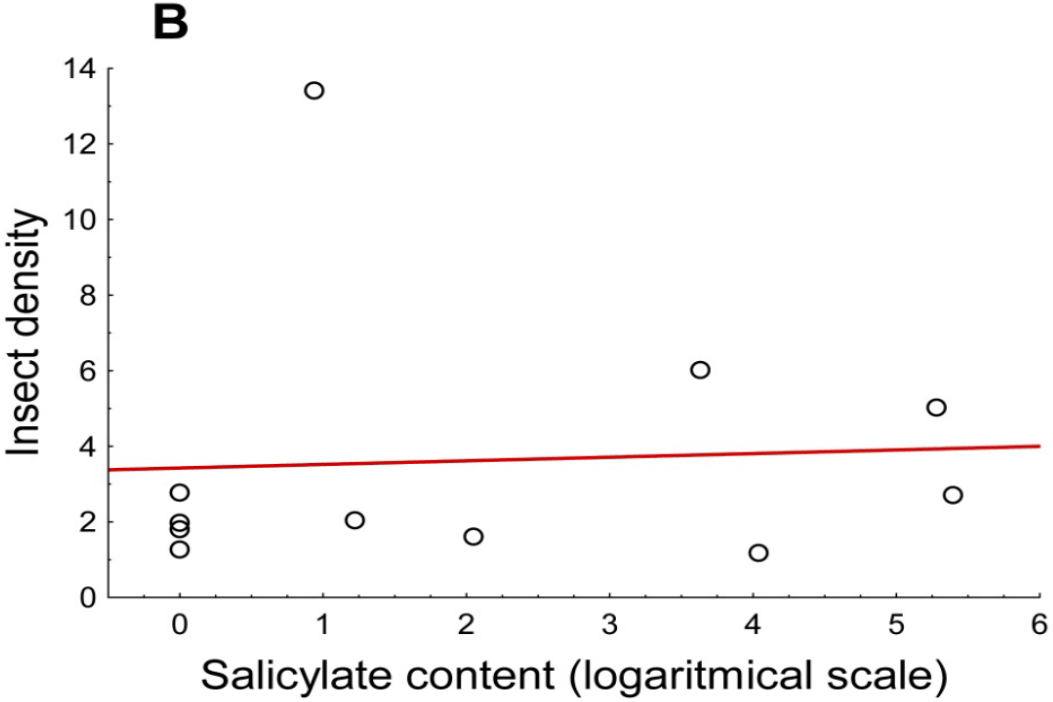
Willows: protected by salicylates

- some species invest large resources (represent up to 20% of plant biomass)
- salicylates only work against generalist herbivores
- overall herbivore density not correlated with salicylate content
- some species lost salicylates





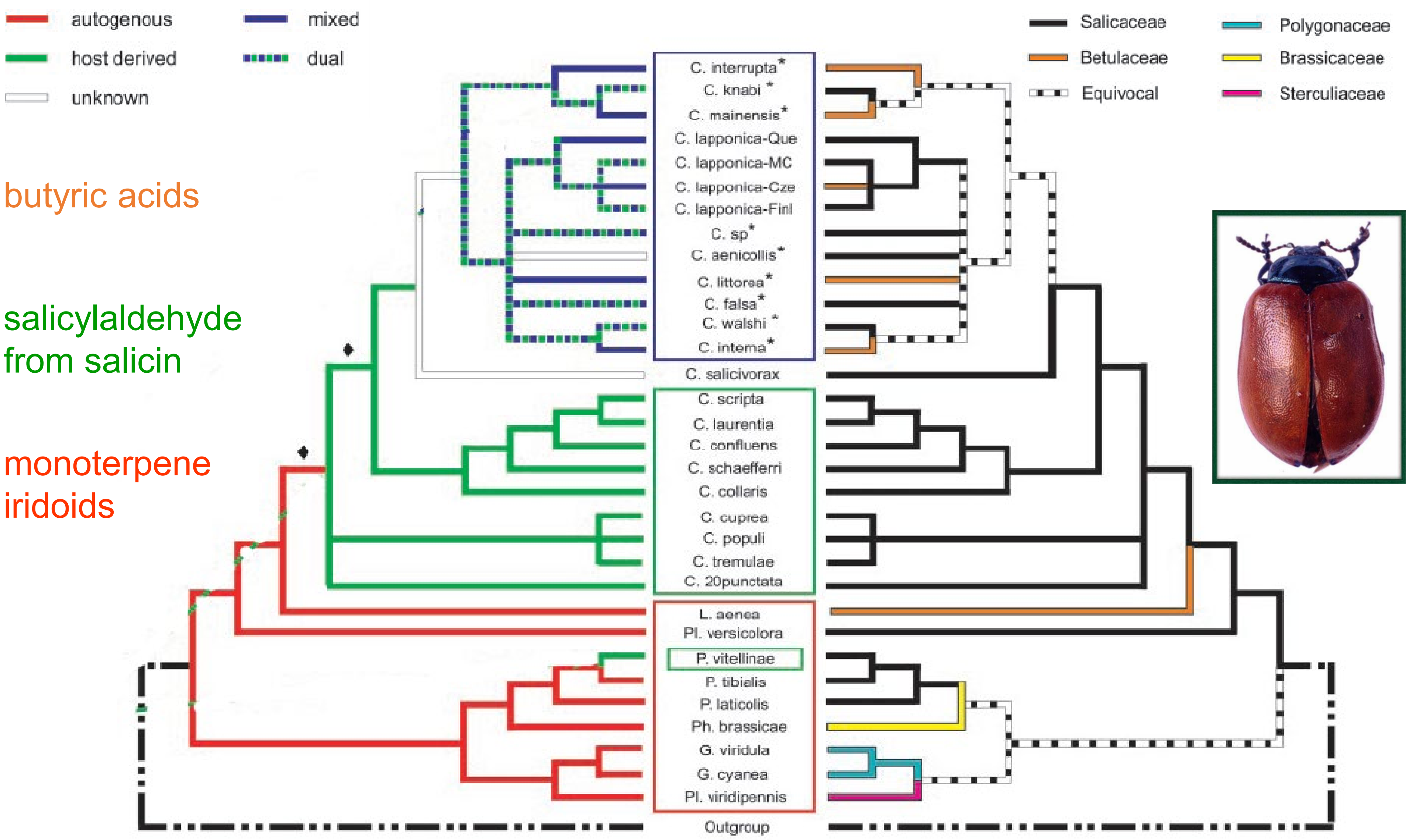
Species that lost salicylates



Volf, et al 2015. *J. Anim. Ecol.* **84**, 1123, and 2015 *Ent. Exp. Appl.* **156**, 88

Is narrow host specialization an evolutionary dead-end?

Chrysomela beetles dependent for anti-predator defence on salicylates from Salicaceae hosts develop a new defense, butyric acid, that allows expansion of their host range to Betulaceae



butyric acids

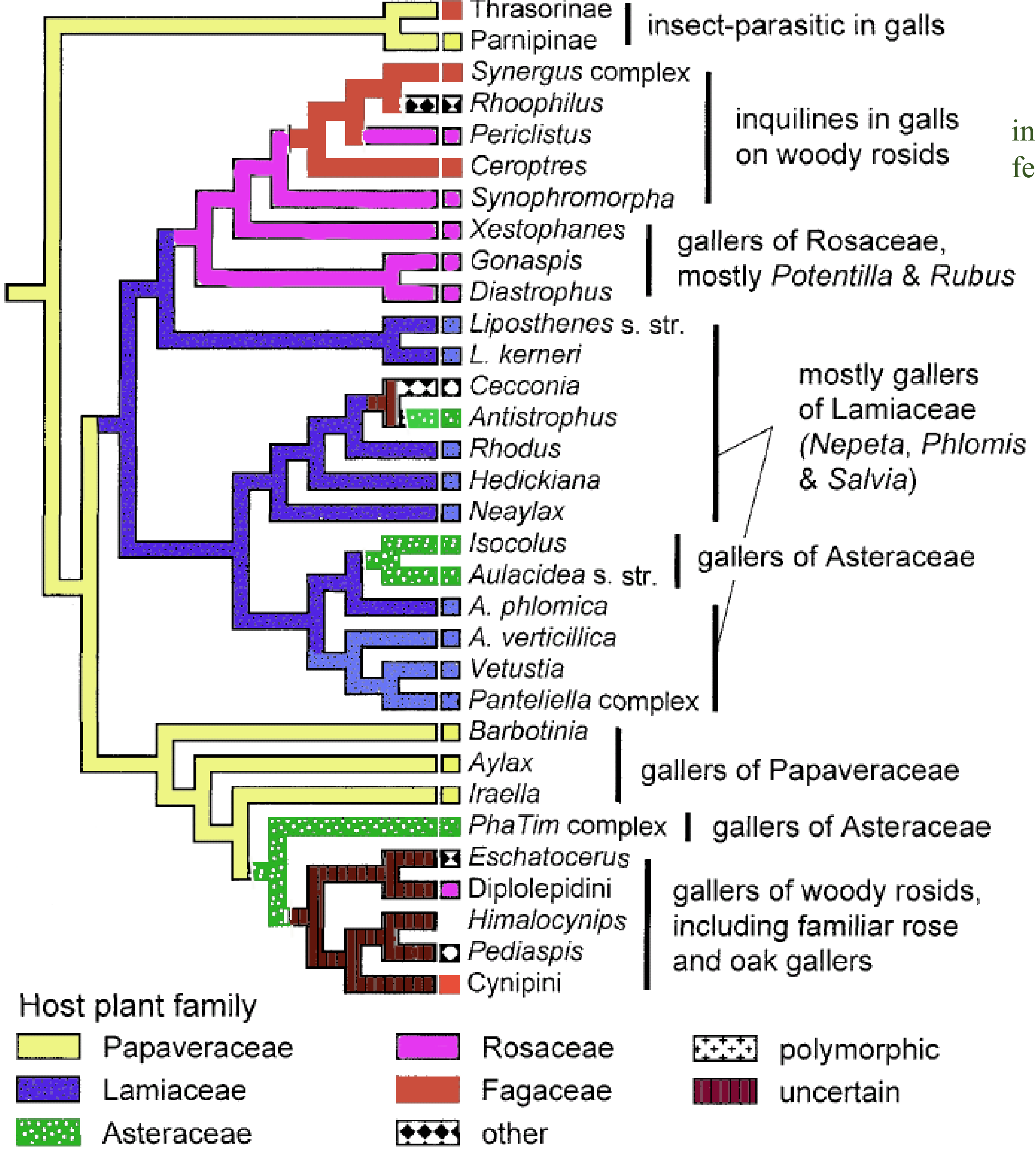
salicylaldehyde
from salicin

monoterpene
iridoids

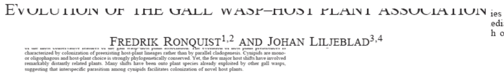
Termonia et al. 2001

Host plants of galling cynipid wasps: numerous transitions

inquilines do not induce their own galls, feed inside galls of other spp.



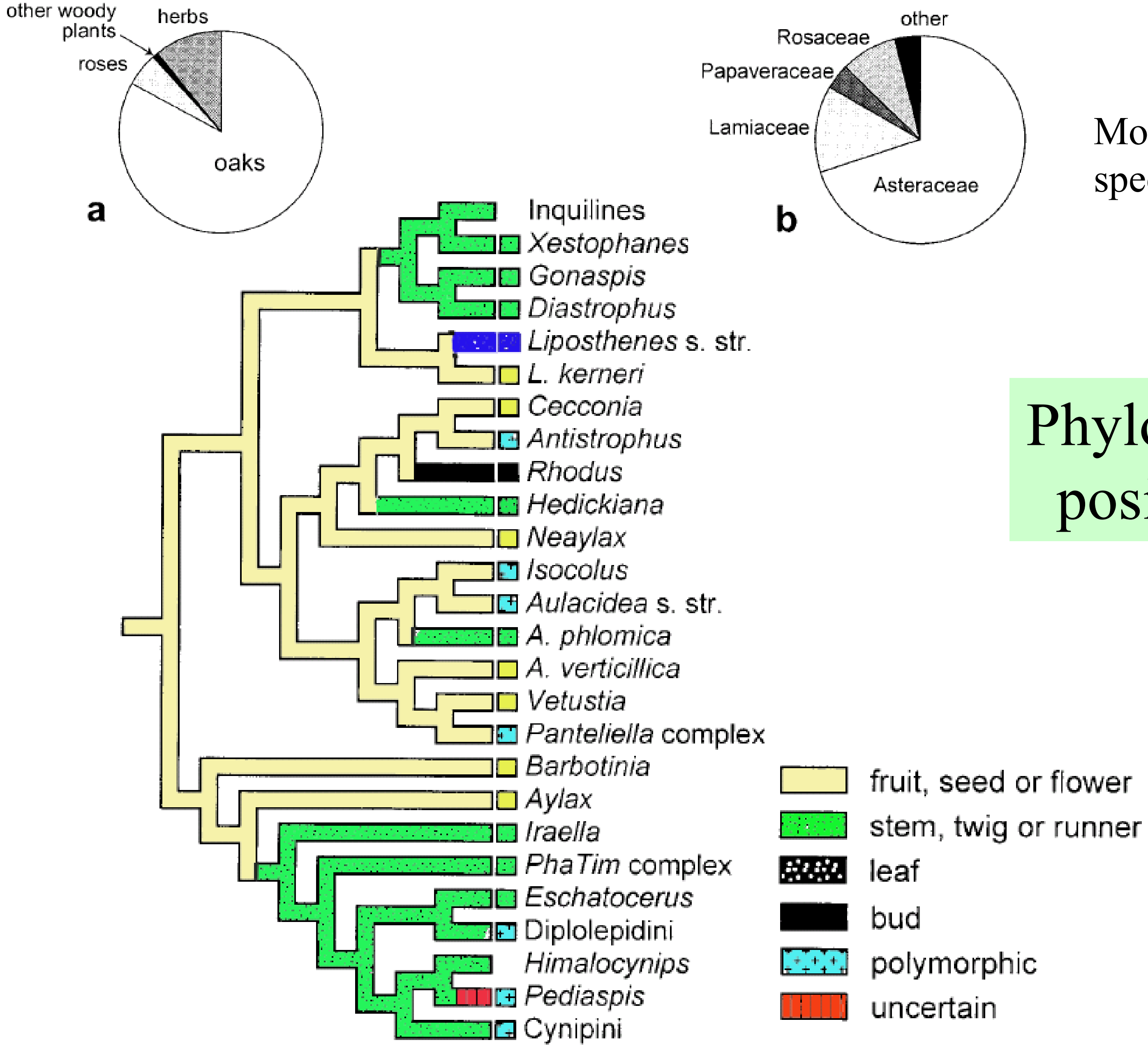
Evolution, 55(12), 2001, pp. 2503–2522



EVOLUTION OF THE GALL WASP–HOST PLANT ASSOCIATIONS

FREDRIK RONQUIST[1,2] AND JOHAN LILJEBLAD[3,4]

Gall wasps (Cynipidae): second largest radiation of gallers, 1300 spp.



Most of species on woody plants, particularly oaks (a), species on herbaceous plants mostly on Asteraceae (b)

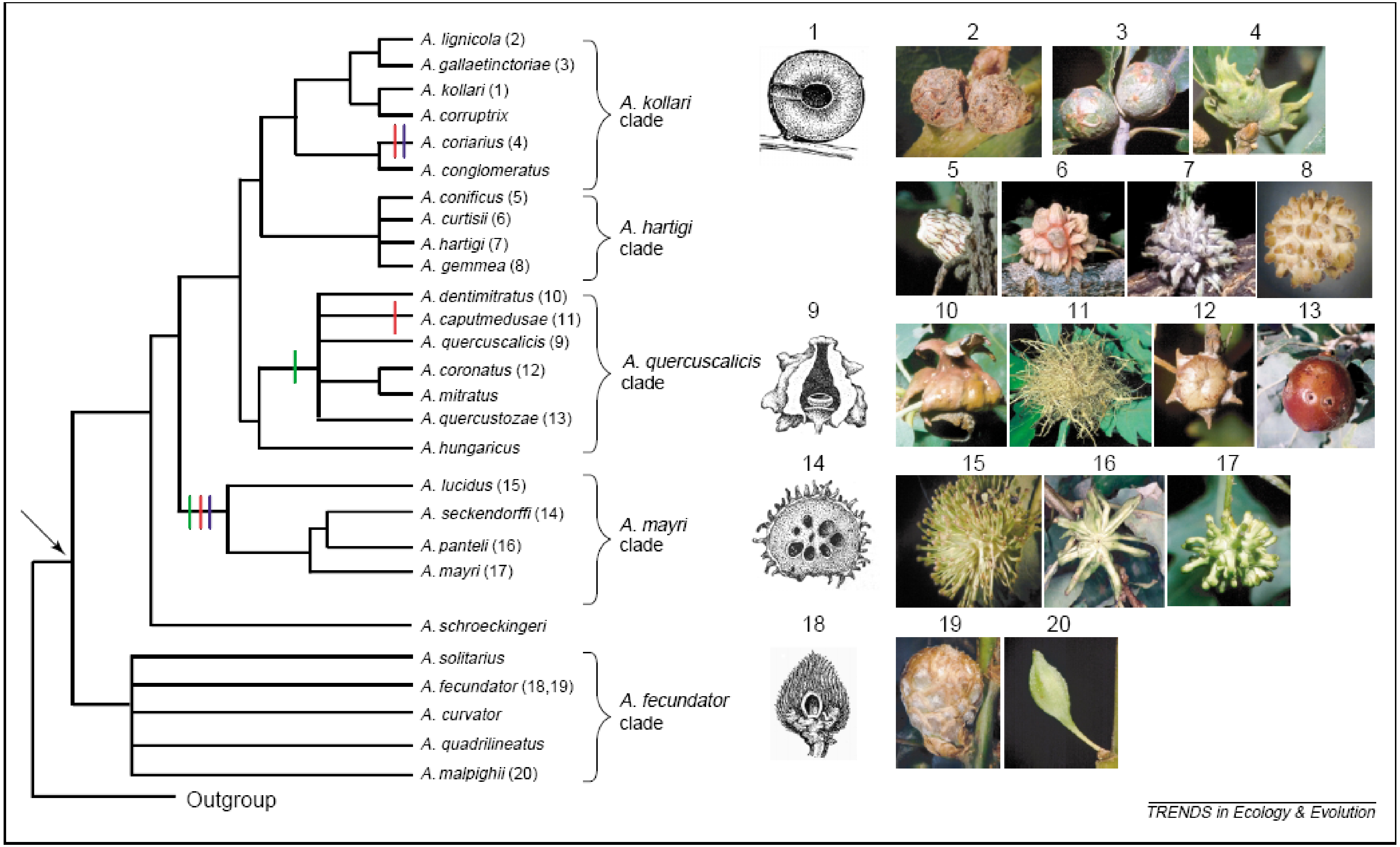
Phylogenetic conservatism in the position of galls on host plants

Evolution, 55(12), 2001, pp. 2503–2522

EVOLUTION OF THE GALL WASP–HOST PLANT ASSOCIATION

FREDRIK RONQUIST[1,2] AND JOHAN LILJEBLAD[3,4]

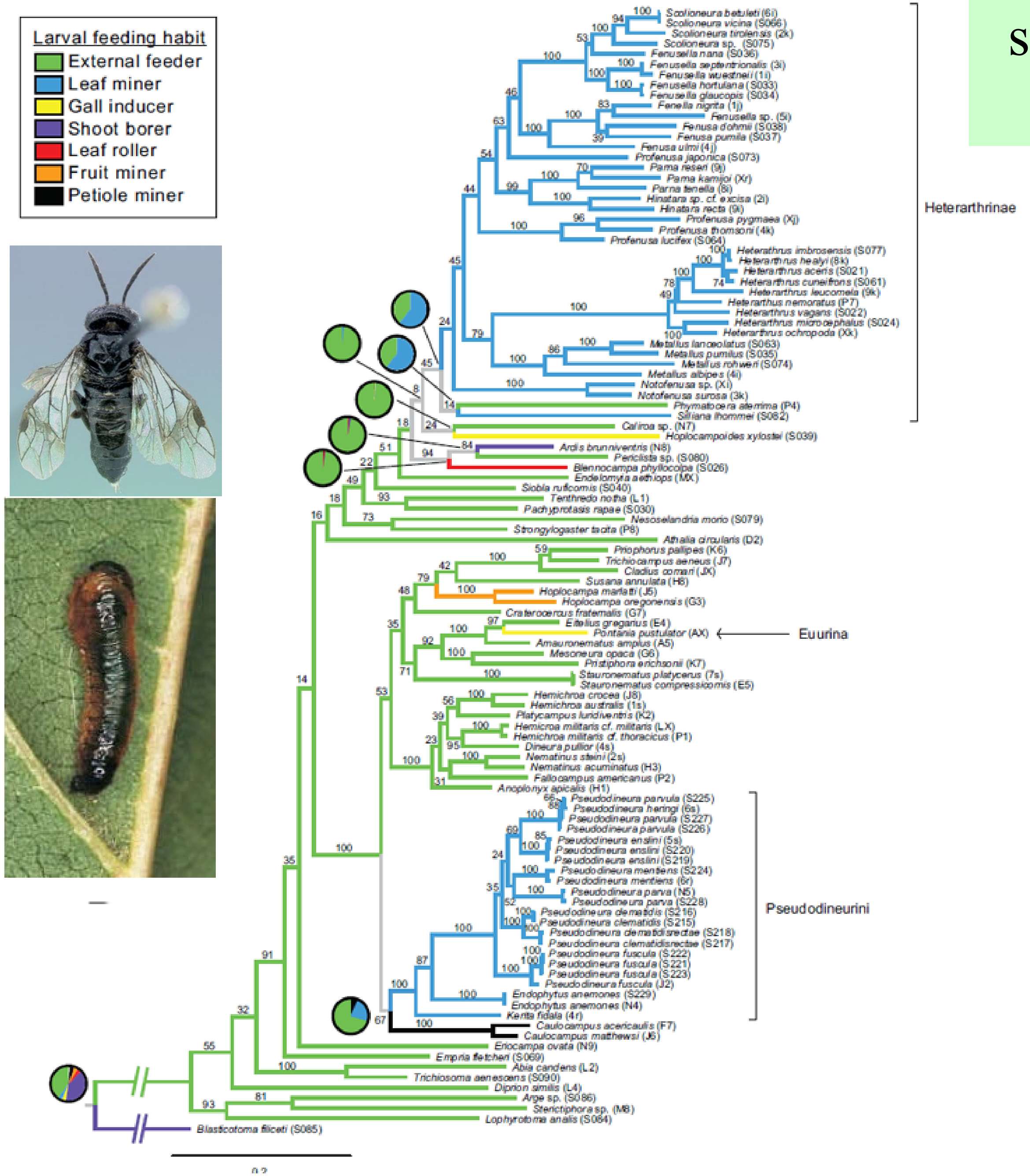
Cynipid gallers *Andricus* on oaks in Europe: evolutionary conservatism in gall type



TRENDS in Ecology & Evolution

Figure 4. Patterns in the evolution of oak cynipid gall morphology for European members of the genus *Andricus*, traced over a phylogeny generated from DNA sequence data [19,20]. Numbered images correspond to species identified by the same numbers in the phylogeny. Members of each clade commonly share similar gall traits (solid woody galls in the *A. kollari* clade; an internal airspace, and an external coat of sticky resin in the *A. quercuscalicis* clade; spiny, many-chambered galls coated in sticky resin in the *A. mayri* clade). Spiny galls have evolved convergently from unspined ancestors three times (red bars), galls with many larval chambers have evolved convergently from galls containing a single larva twice (blue bars), and coatings of sticky resin have evolved convergently from non-sticky ancestors twice (green bars) during radiation from a common ancestor (marked with an arrow) that induced galls that lacked spines or resin, and contained a single larva. Images 3–5, 7,10–12, 17 reproduced with permission from György Csóka.

Guilds of sawflies: surprising phylogenetic flexibility [for such complex change]



External feeder

Leaf miner

Galler

Shoot borer

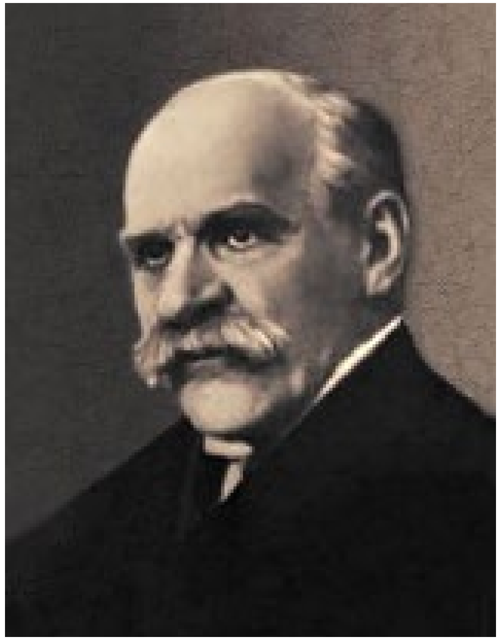
Leaf roller

Fruit miner

Petiole miner

Leppanen 2014

When the British biologist J. B. S. Haldane was asked by a group of theologians what one could conclude as to the nature of the Creator from a study of His creation, Haldane is said to have answered, "An inordinate fondness for beetles" (*1*). Haldane's remark reflects the



"Inordinate Fondness" Explained: Why Are There So Many Beetles?

Brian D. Farrell

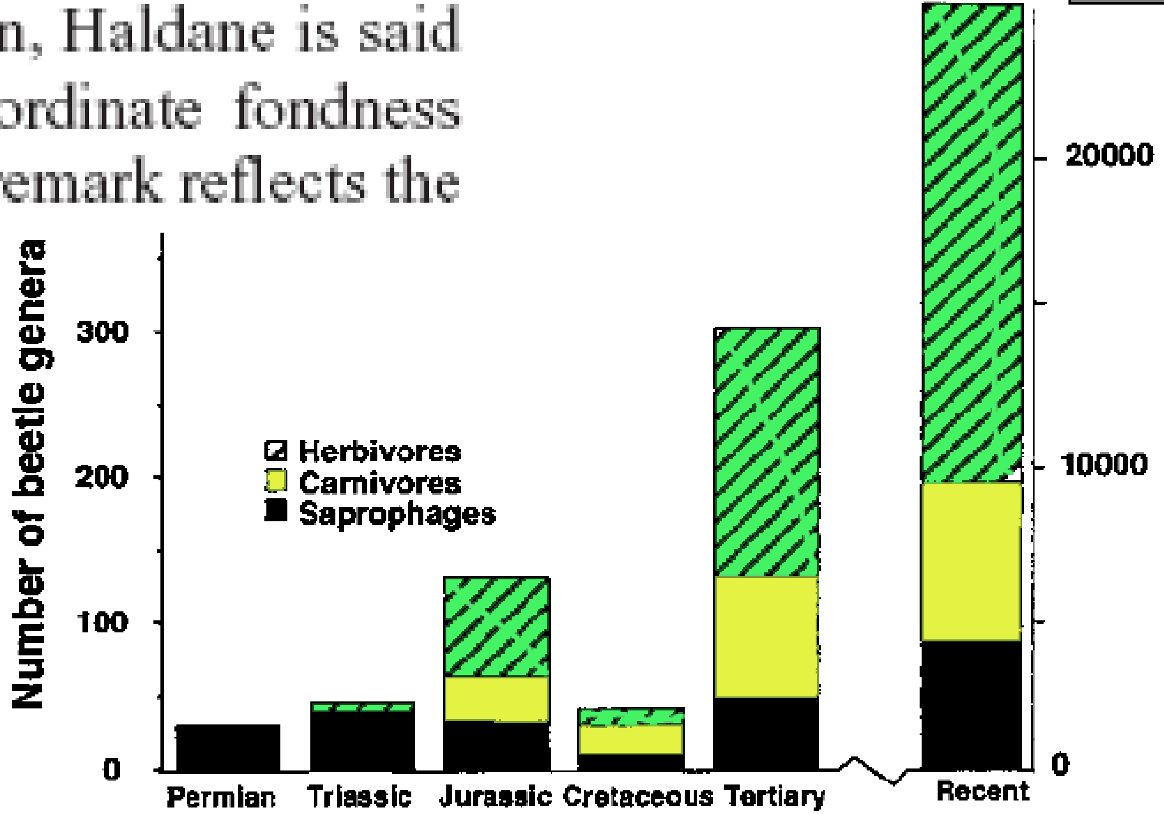
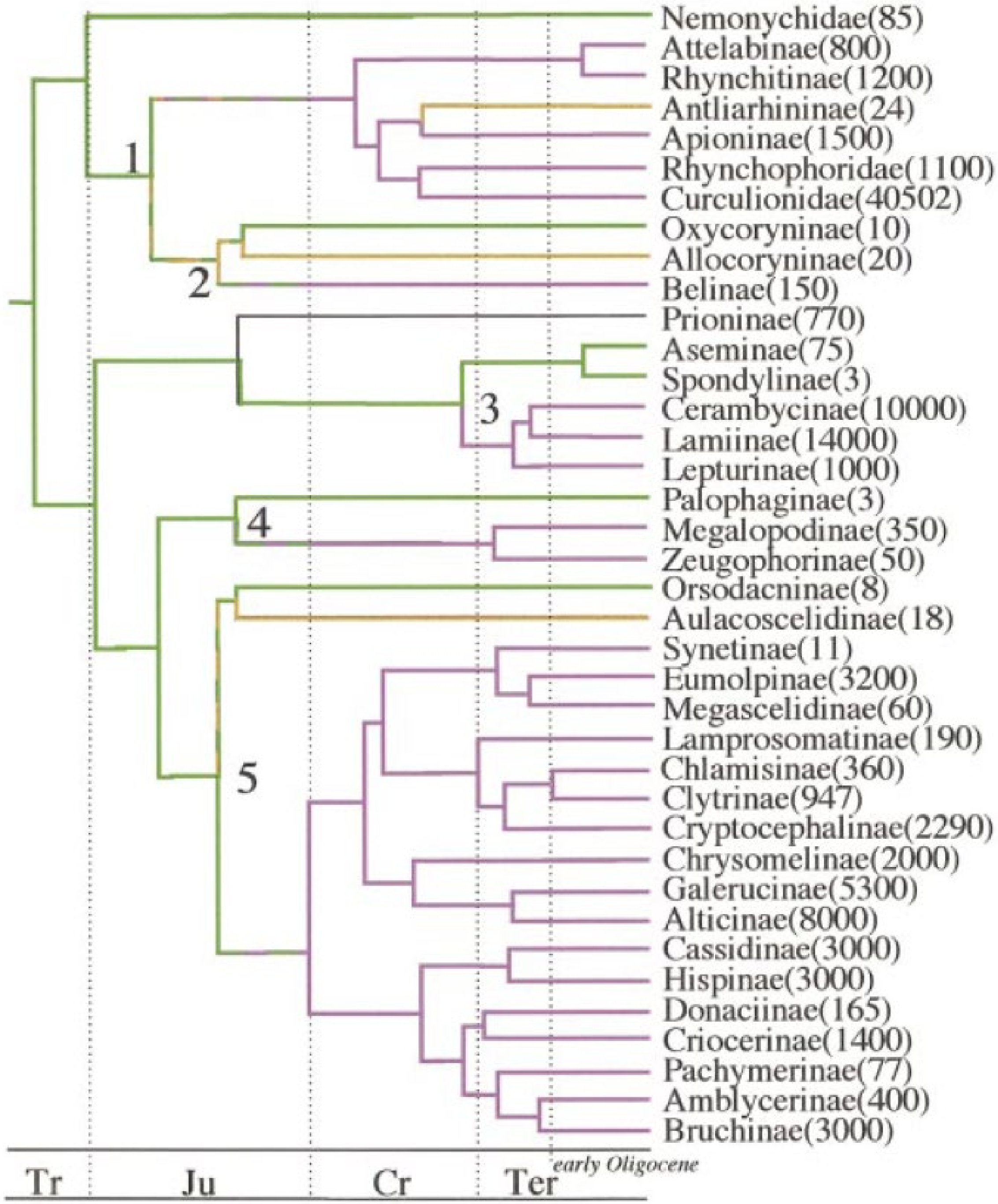


Fig. 1. The number of beetle genera of each of three trophic levels (*34*) per geological period (Permian to Tertiary) and epoch (Recent) (*5*, *35*). Permian fossils are entirely of the saprophagous Archostemmata (*5*), and the first Adephaga and Polyphaga (the curculionoid Obrienidae) appear in the Triassic (*9*). Low diversity in the Cretaceous likely reflects the paucity of studied strata. The proportions of fossil genera in each beetle series (defined by Crowson) in the Tertiary and Recent are significantly correlated ($P = 0.001$). The disproportionate rise in the diversity of the post-Cretaceous phytophagous beetles likely reflects the exponential rise in angiosperm diversity, particularly of herbaceous taxa.



Farrell 1998

angiosperms

conifers

Cycadales

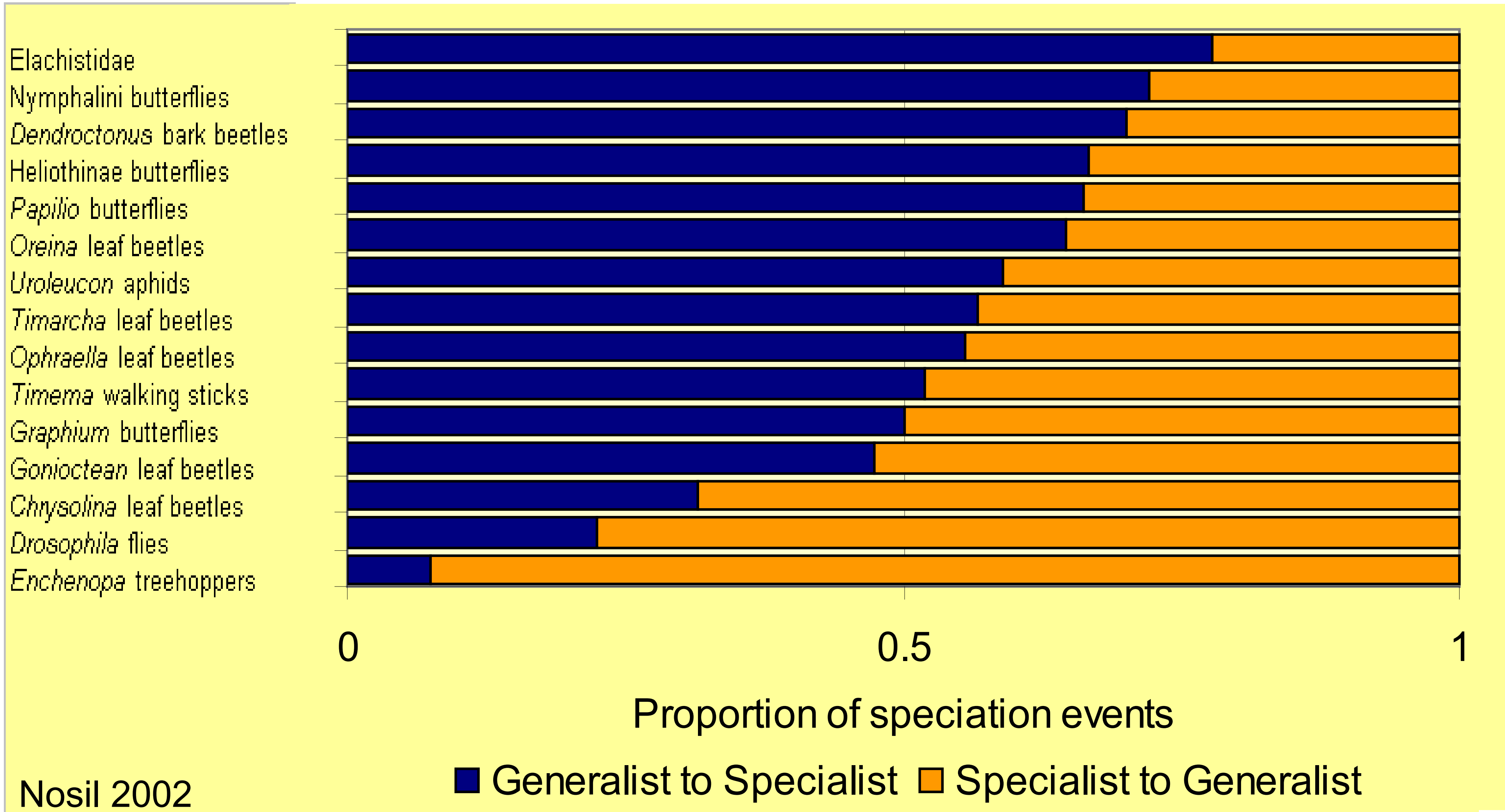
1 - 5: colonizations
of angiosperms

Beetles: high species diversity associated with feeding on angiosperms

Fig. 3. The phylogeny of the families and subfamilies of Phytophaga represented by genera in Fig. 2, with estimates of the number of current species in parentheses (36). Branches are colored by major host-plant group as in Fig. 2, but with purple indicating the collective use of angiosperms. The approximate age of each clade (estimated from the beetle fossil record) is indicated by the depth of the branches, with dotted lines superimposed for each period. The five origins of associations with angiosperms are numbered. In the Curculionoidea, an equally parsimonious interpretation would be an origin of angiosperm association at 1 followed by a reversal to cycad-*Araucaria* association at 2. However, this interpretation seems less plausible than two separate origins in the Cretaceo

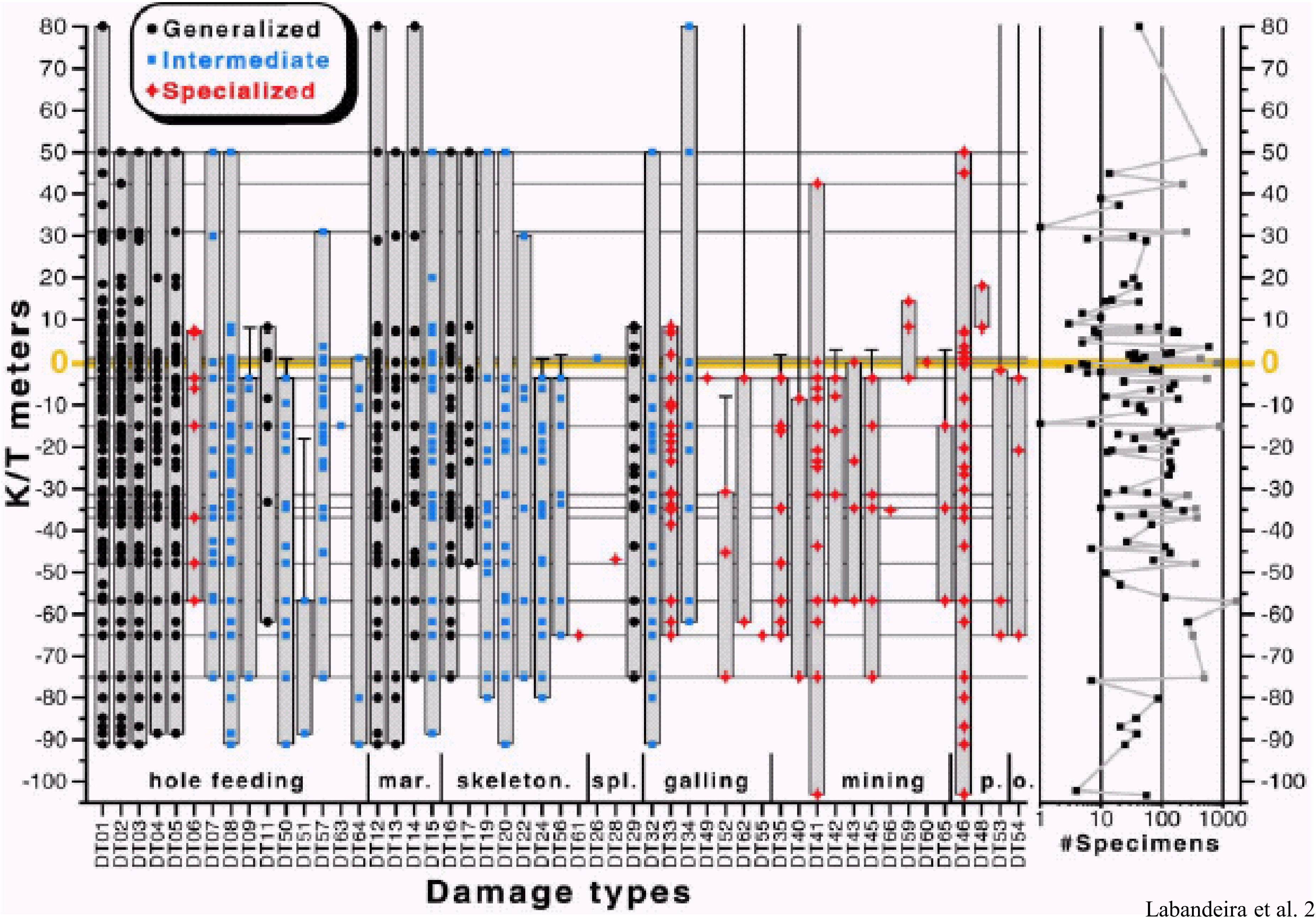
Host specificity:
is narrow specialization determined by speciation dynamics?

Transition from a generalist to a specialist is more likely than reverse transition

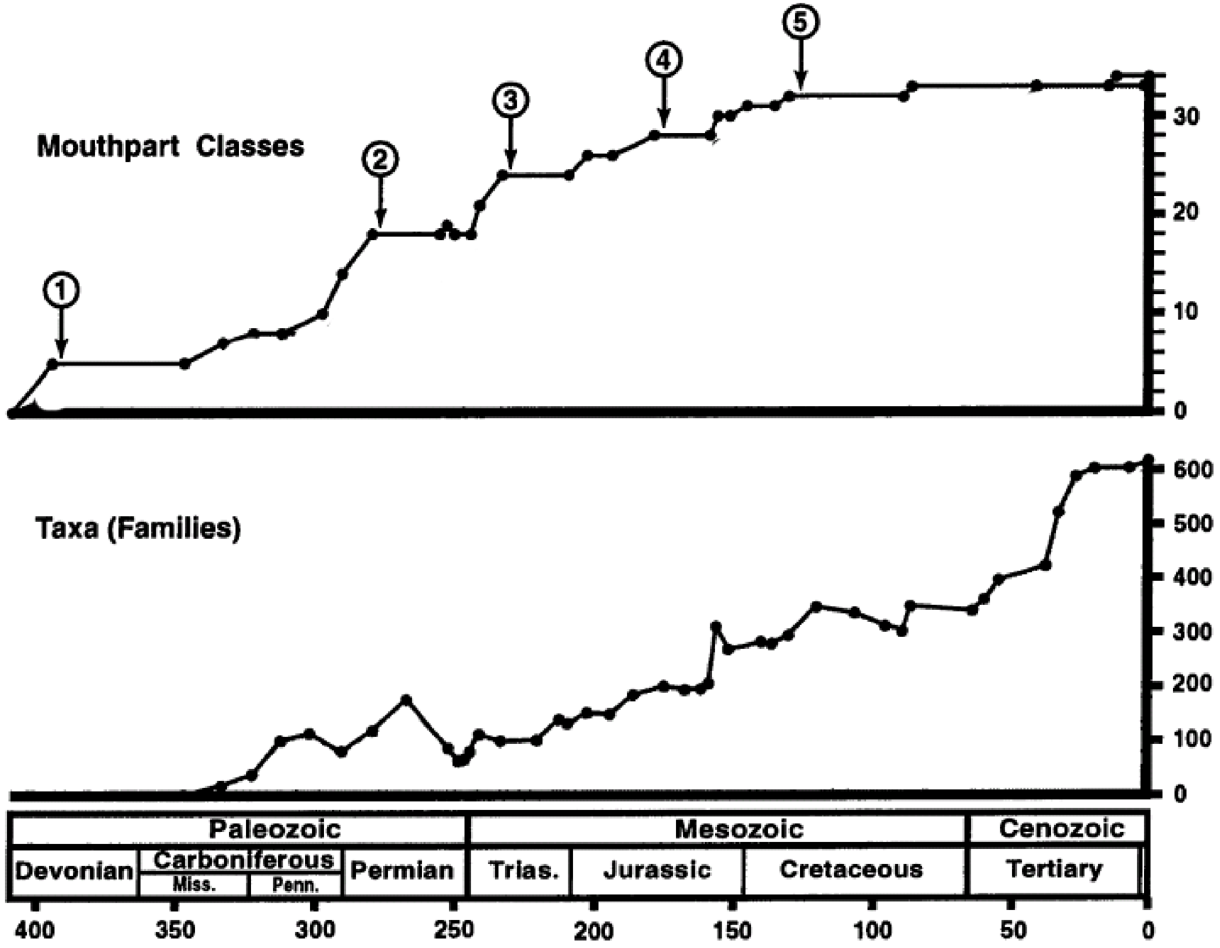


Nosil 2002

Mass extinction (Cretaceous-Tertiary boundary): specialists die first

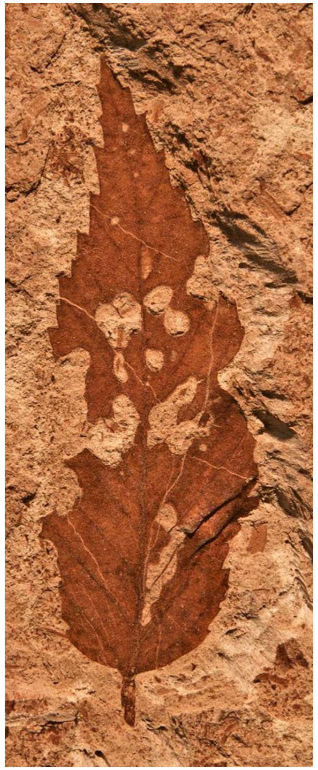


Labandeira et al. 2002 PNAS 99:2061



No. of mouthpart classes

No. of insect families



While number of insect families is steadily increasing through evolution, there has not been any major inovation in mouthparts dor almost 100 million years:
has everything been already invented?

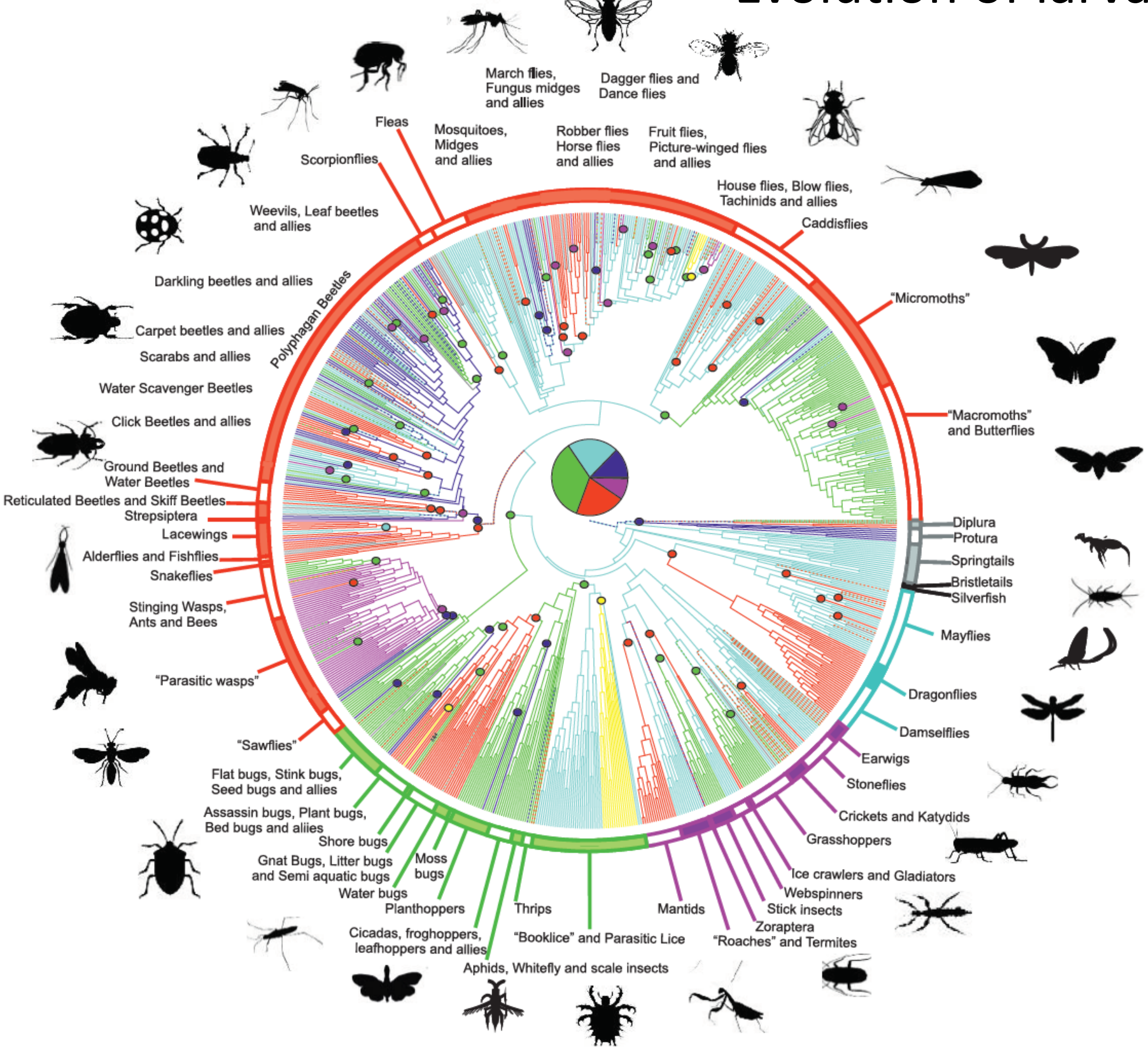
Biol. Rev. (2007), 82, pp. 425–454.
doi:10.1111/j.1469-185X.2007.00018.x

Why are there so many insect species? Perspectives from fossils and phylogenies

Peter J. Mayhew*

Fig. 5. Comparison of insect mouthpart diversity (upper panel) and family diversity (lower panel) over the fossil record. In the upper panel, the bottom curve and dark shading represents strong evidence for presence and the top curve less strong evidence. Numbered arrows represent equilibria following five phases in mouthpart diversification: 1, Early Devonian: primitive modes only. 2, Pennsylvanian innovations. 3, Early Permian innovations. 4, Late Triassic to Early Jurassic innovations. 5, Late Jurassic to early Cretaceous innovations. Reprinted, with permission, from Labandeira (1997), the Annual Review of Ecology and Systematics,

Evolution of larval feeding in insects



FUNGIVORY

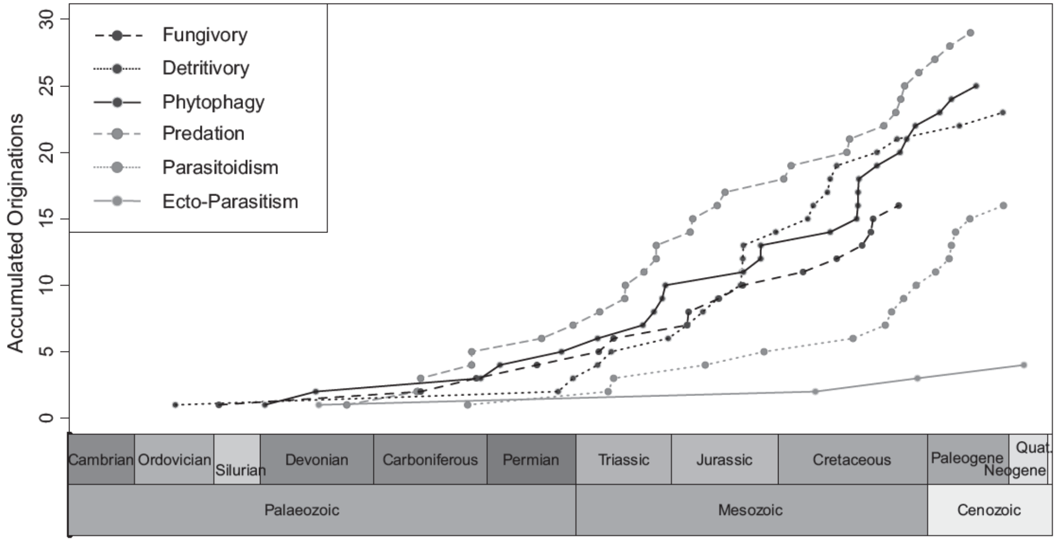
DETRITIVORY

PHYTOPHAGY

PREDATORY

PARASITOIDS

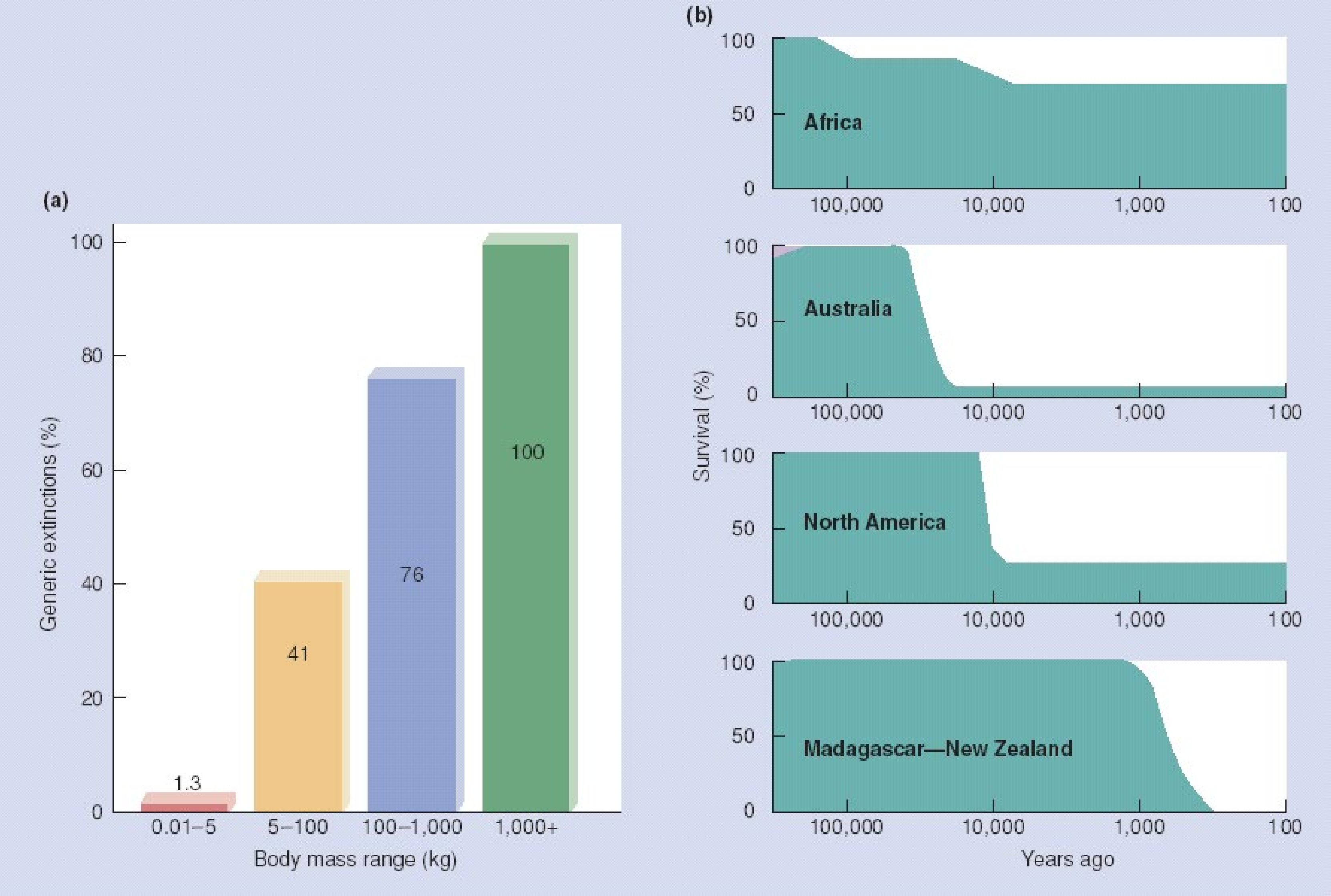
ECTOPARASITES



Rainford & Mayhew 2015, Amer Nat 186

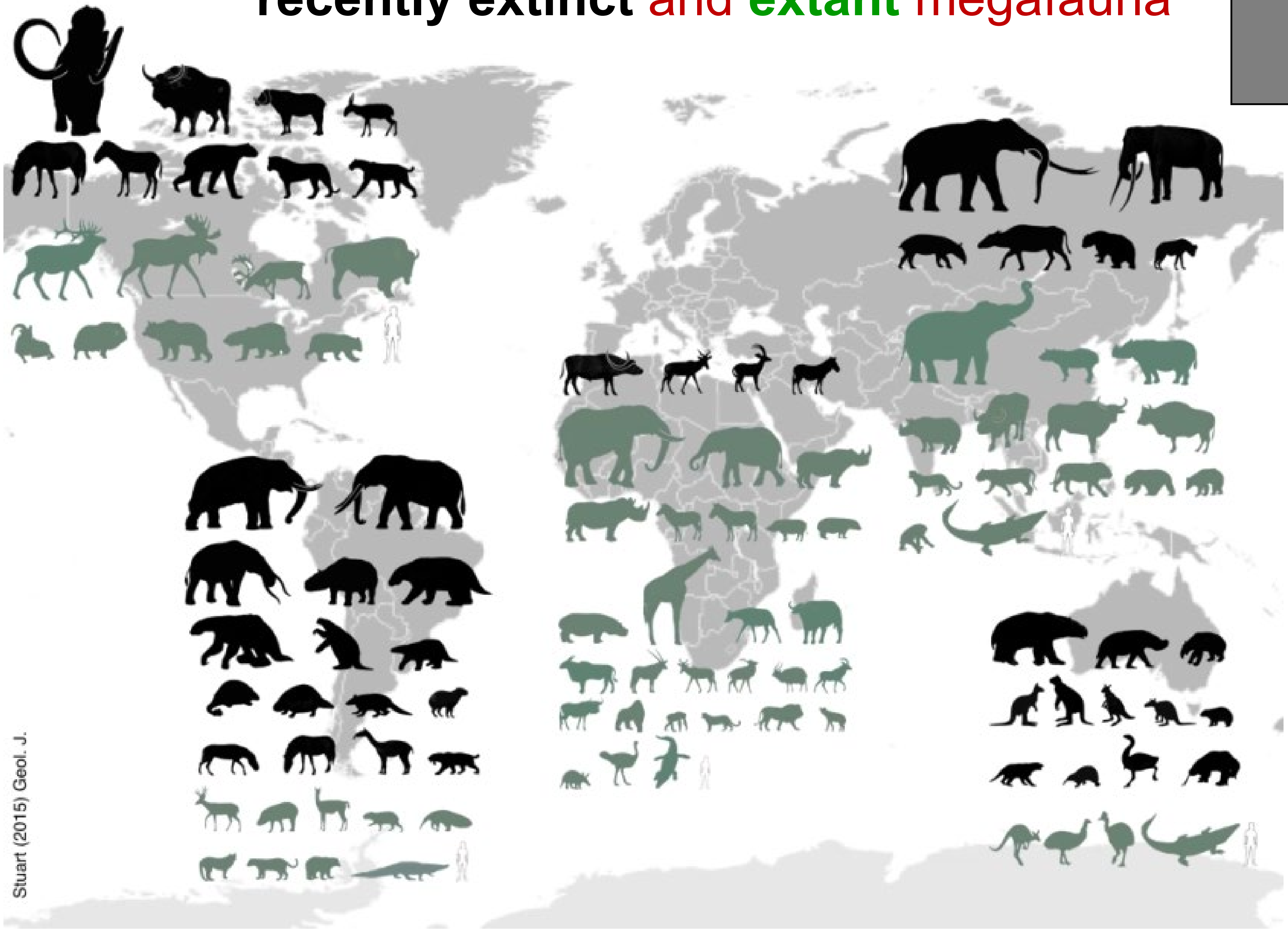
Figure 2: Reconstructed dietary ecologies for the larval raw data set under maximum likelihood. Ecologies are denoted as follows: dark blue = fungivory, cyan = detritivory, green = phytophagy, red = predatory, magenta = parasitoids, and yellow = ectoparasites. Taxa and nodes with mixed states are indicated by dashed lines. Taxa with unknown states are shown in gray. Colored dots denote the positions of sister-group comparisons (table 2). The coloration of the outer ring denotes major clades (gray = Entognatha, black = basal insects, cyan = Palaeoptera, purple = Polyneoptera, green = Paraneoptera, red = Holometabola). The pie chart (*inset*) gives the relative species richness associated with each dietary category, with taxa with mixed ecologies contributing to all relevant states; see data deposited in the Dryad Digital Repository: http://

Extinction of large mammalian herbivores in past 130,000 years: what are ecological consequences?



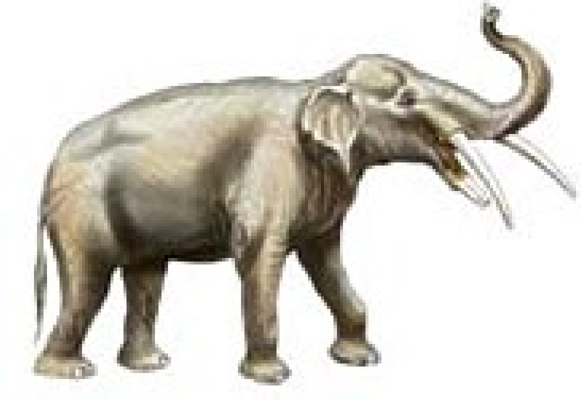
(a) The percentage of genera of large mammalian herbivores that have gone extinct in the last 130,000 years is strongly size dependent (data from North and South America, Europe, and Australia combined). (After Owen-Smith, 1987.) (b) Percentage survival of large animals on three continents and two large islands (New Zealand and Madagascar). (After Martin, 1984.)

recently extinct and extant megafauna



Stuart (2015) Geol. J.

What were ecological roles or recently extinct megafauna?



Janzen & Martin (1982) NEOTROPICAL ANACHRONISMS: The Fruits the Gomphoteres Ate

THE END

Large recently extinct fauna, such as gomphoteres in S. America, could be important consumers and dispersal agents of large fruits

Crescentia alata

Enterologium cyclocarpum

Similar role played by forest elephants in Africa