**A broadscale test of host-symbiont cophylogeny reveals widespread phylogenetic congruence**

**Symbioses are extremely common and exert substantial biological influence, with great evolutionary and ecological relevance for disease4,5, driving major evolutionary transitions6-8, and affecting the structure and function of ecological communities9,10. Symbioses are also of considerable applied importance, due to the benefits provided by ecosystem services such as pollination and biocontrol, and the costs associated with harmful pests and pathogens11,12. Yet, much remains unknown about the patterns and processes that characterise symbioses. A major unanswered question is the degree to which symbiont phylogenies mirror those of their hosts. Currently, it is unclear whether symbiont evolutionary trees are typically congruent with those of their hosts, or if patterns differ for parasites and mutualists. Here, we perform a meta-analysis of host-symbiont phylogenetic congruence considering mode of symbiosis, host-symbiont taxonomy, and life-history, encompassing 232 host-symbiont cophylogenetic analyses from the primary literature. Our analysis represents an advancement from qualitative studies, toward a systematic and quantitative framework to investigate host-symbiont cophylogeny. We show that symbiont phylogeny reflects host phylogeny, and that the signature of congruence extends across host and symbiont diversity and life-history, demonstrating a general tendency of symbionts to track host phylogeny over evolutionary time. We identify two aspects of symbiont life-history that appear to promote closer ties between host and symbiont: vertical transmission and mutualism. We find that mode of symbiosis and mode of transmission are intimately interlinked, but we demonstrate that vertical transmission is the dominant factor in promoting host-symbiont phylogenetic congruence. Given the pervasiveness of symbioses across ecosystems and the tree of life, these findings provide fundamental insights into the processes responsible for generating the Earth’s rich biodiversity.**

**Main**

Symbioses exist across all taxonomic levels and are a common feature of life (Fig. 1).

A key unanswered question in the study of symbiosis is the extent to which symbiont phylogenies track those of their hosts. Given an ancestral host-symbiont association, multiple rounds of strict cospeciation will result in a symbiont phylogeny that perfectly mirrors host phylogeny, and thus phylogenetic congruence (Fig. 2a). In practice, perfect congruence is considered to be rare, due to the influence of disruptive events such as host switching (Fig. 2b), extinction (Fig. 2c), independent speciation (Fig. 2d), or failure to speciate (Fig. 2e), which lead to incongruence in host-symbiont phylogenies13 (Fig. 2f). The idea that symbionts track their hosts over evolutionary timescales, cospeciating in synchrony, is encapsulated by ‘Fahrenholz’s Rule’, which states that parasite phylogeny reflects host phylogeny14,15. Fahrenholz’s Rule was formulated over one hundred years ago, yet a persistent assumption of host-specialization and accompanying host-parasite phylogenetic congruence remains within the field of host-symbiont interactions16, despite apparently limited support from the literature17. Given the availability of statistical methods to quantify host-symbiont phylogenetic congruence (e.g.18,19), and a recent accumulation of studies that apply these approaches, opportunities now exist to examine the generality of Fahrenholz’s Rule within a formal quantitative framework.

We apply meta-analytical methods to analyse a large body of published studies that quantify phylogenetic congruence for particular symbioses. We consider reported test statistics from the two most widely applied approaches for estimating host-symbiont phylogenetic congruence: one based on estimations of shared discrete macroevolutionary events (i.e. 'TreeMap'20), and one based on branch-length comparisons to estimate overall similarity (i.e. 'Parafit'21).

Firstly, we examine the extent to which symbiont phylogeny tracks host phylogeny, providing a broadscale analysis of cophylogeny. We then test the validity of Fahrenholz’s Rule specifically, by testing the generality of the prediction that parasite phylogeny mirrors host phylogeny across multiple host and parasite taxa. If parasites are specialized and tightly coevolved to single host species22, we expect a strong signal of phylogenetic congruence between host and parasite phylogenies. Alternatively, if parasites commonly shift to new host species, either with parasite speciation following host-switching events23,24, or without speciation25, we expect a weak or absent signal of phylogenetic congruence.

Next, we compare the findings for parasites to those for mutually beneficial symbiotic interactions *sensu* Bronstein26. Mutualism can be viewed within the framework of ‘reciprocal exploitation’27. Within this framework, the incentive to cheat28,29 may destabilise the longevity of mutualisms over protracted evolutionary timescales, resulting in no greater overall phylogenetic congruence between hosts and mutualists than that observed for parasites. Conversely, mutualisms may be robust to such challenges and thus be evolutionarily persistent30,31, which would result in a pattern of tight host-mutualist phylogenetic congruence. To distinguish between these alternatives, we test host-mutualist phylogenetic congruence across host and mutualist taxonomic diversity, while simultaneously providing a general comparison of host-symbiont phylogenetic congruence between mutualism and parasitism.

Given the paucity of formal testing of the drivers of host-symbiont phylogenetic congruence, we extend our analyses beyond considering the type of symbiosis, to examine the influence of several classic traits of relevance for host-symbiont interactions. Host specificity is a central aspect of symbiont life history with widespread ecological and evolutionary implications9,32, and may exert an independent effect on host-symbiont phylogenetic congruence beyond the mutualist-parasite divide. If specialist symbionts are evolutionarily or ecologically ‘tied-in’ to their host associations, undergoing few or no host shifts33-35, they are expected to display high phylogenetic congruence with their hosts. However, if specialists possess an ability to make host-shifts of varying frequency and magnitude (while remaining associated with one or few hosts)36,37, congruence may be low. Meanwhile, truly generalist symbionts are expected to show low phylogenetic congruence with their hosts, unless dominant interactions occur within a subset of total host range38.

We also consider the influence of endosymbiosis versus ectosymbiosis. Endosymbionts are fully enclosed within the host, and are considered to have a more intimate interaction with host physiology, biochemistry and immunity than ectosymbionts5,32, which may translate into tighter associations, and greater host-symbiont phylogenetic congruence. Lastly, we examine the relevance of mode of transmission, to test the general expectation that vertical transmission promotes greater phylogenetic congruence39-41. If a symbiont is vertically transmitted (whether it has positive, neutral, or negative effects on the host), this should automatically decrease the likelihood of host-switching, and increase the likelihood of cospeciation. Therefore, cophylogenetic congruence should emerge as a consequence. In contrast, horizontal transmission should facilitate exposure to novel hosts, potentially leading to host-switching, and decreased host-symbiont phylogenetic congruence.

Considering 232 published host-symbiont cophylogeny studies (Extended Data Tab. 1), spanning a wide spectrum of host and symbiont taxa, we found support that host and symbiont phylogeny show a tendency to reflect one another, with only moderate variation in the strength of phylogenetic congruence among studies (*Zr*[all] = 0.345, *I*2 = 59%; Fig. 3a and Supplementary Table 1). Furthermore, the strength of the association identified is likely to be an underestimate of the true pattern, given the limits of current approaches to quantify congruence between host and symbiont phylogenies (see Methods, ‘Sensitivity analysis’). Next, we examined parasitism and mutualism separately. Our results show that host and parasite phylogenies display greater similarity than expected by chance, with parasite phylogeny tending to mirror host phylogeny, consistent with a broad interpretation of Fahrenholz’s Rule (*Zr*[parasite] = 0.311; Fig. 3b and Supplementary Table 2). However, host and mutualist phylogenies show greater congruence than that observed between host and parasite phylogenies, suggesting a stronger tendency of mutualists to track host phylogeny (*Zr*[mutualist] = 0.411 and *Zr*[mutualist-parasite] = -0.100; Fig. 3b and Supplementary Table 2). A potential explanation for this pattern is that reciprocal benefits provide a more cohesive force to unite host and symbiont evolutionary trajectories, than the antagonistic interactions involved in parasitism.

To further dissect cophylogenetic patterns between symbiont and host phylogenies, we examined whether taxonomy exerted an effect by partitioning studies according to broad taxonomic groups for hosts and symbionts. We found that effect size was positive across all host taxonomic groupings considered, with host-symbiont associations involving microbial hosts showing greatest congruence, followed by invertebrate hosts, vertebrate hosts, and lastly plant hosts (*Zr*[microbe] = 0.557, *Zr*[invertebrate] = 0.412, *Zr*[vertebrate] = 0.327, *Zr*[plant] = 0.244 and *R*2 = 0.168; Fig. 3c and Supplementary Table 3). For symbiont taxa, effect size was also positive across all taxonomic groups, but variation in phylogenetic congruence was lower (*Zr*[microbe] = 0.353, *Zr*[invertebrate] = 0.324, *Zr*[vertebrate] = 0.291, *Zr*[plant] = 0.733 and *R*2 = 0.082; Fig. 3d and Supplementary Table 4). Host-symbiont cophylogenies involving plant symbionts displayed markedly higher congruence, primarily driven by results for mutualistic algal symbionts and their lichen hosts, but sample size for this category was small, reflecting the scarcity of studies focussing on these associations in relevant cophylogenetic literature.

We examined if host specificity is associated with host-symbiont phylogenetic congruence using two estimators: (i) host range – the mean number of links between hosts and symbionts per symbiont within a cophylogeny), and, (ii) host taxonomic breadth – an index of the number of higher host taxonomic ranks associated with each symbiont within a cophylogeny. No significant association was identified for either measure of host specificity (*b*[ln(host range)] = -0.057 and *b*[ln(taxonomic breath)] = -0.056; Supplementary Fig. 1-2 and Supplementary Table 5-6), demonstrating that host specificity is not an important general determinant of host-symbiont cophylogeny (at least, given the variation in host generalism observed in our data set).

We also tested the obvious hypothesis that the more intimate relationships associated with endosymbiosis may translate into greater congruence between host and symbiont phylogenies. However, contrary to this hypothesis, we find that the distinction between endosymbiosis and ectosymbiosis has no influence on the degree of phylogenetic congruence observed between hosts and their symbionts (*Zr*[endo-ecto] = 0.010; Fig. 3e and Supplementary Table 7).

A major prediction for host-symbiont cophylogeny is that vertical transmission (i.e. ‘intergenerational transmission’, as opposed to horizontal ‘infectious transmission’) should promote phylogenetic congruence39-41. In line with this prediction, we found that mode of transmission was a highly significant correlate of host-symbiont phylogenetic congruence, with the strongest effect observed for vertical transmission, followed by the effect observed for mixed modes of transmission (symbionts are transferred via either route), and with horizontal transmission showing the lowest effect size (*Zr*[vertical] = 0.496, *Zr*[both] = 0.371, and *Zr*[horizontal] = 0.285; Fig. 3f and Supplementary Table 8). An issue affecting our data is that all of the vertically transmitted symbionts included in our analysis are classified as mutualists. However, many of the parasitic symbionts included show a mixed mode of transmission and splitting by mode of symbiosis reveals that parasites with mixed modes of transmission show greater phylogenetic congruence with their hosts than horizontally transmitted parasites (*Zr*[both(parasite)] = 0.362 and *Zr*[horizontal(parasite)] = 0.284; Fig. 3g and Supplementary Table 9). Similarly, mutualistic symbionts show a stepwise increase in phylogenetic congruence with hosts, from horizontal to mixed, and from mixed to vertical transmission, with vertically transmitted mutualists displaying considerably greater phylogenetic congruence than horizontally transmitted mutualists (*Zr*[vertical] = 0.493 and *Zr*[horizontal] = 0.290; Fig. 3g and Supplementary Table 9). No significant interactions were present among modes of symbiosis and modes of transmission, highlighting that vertical transmission is the variable that explains the effect on phylogenetic congruence (more associated results, and the results of publication bias tests and sensitivity analyses are found in Supplementary Fig. 3-10 and Supplementary Table 10-24).

Employing a large quantitative and systematic review of the cophylogeny literature, we tested major hypotheses regarding the drivers of host-symbiont phylogenetic congruence. We found support for a general pattern of congruence between host and symbiont phylogenies, in line with a liberal interpretation of Fahrenholtz’s Rule. Significant congruence was observed both for hosts and their parasites and for hosts and their mutualists, but it was significantly stronger in the latter case. We also identified an effect of mode of transmission on host-symbiont phylogenetic congruence, with vertical transmission correlated with greater congruence. Thus, we suggest that: (i) mutualism promotes greater host-symbiont phylogenetic congruence, and, (ii) this is driven primarily by a predominance of vertical transmission among mutualists, as opposed to parasites.

The observation that strict vertical transmission is uncommon in parasites fits with predictions that vertical transmission should favour decreased virulence, since reducing host fitness ultimately reduces a symbiont’s own opportunities for transmission42,43. Accordingly, parasite lineages forced to express strict vertical transmission have been demonstrated to shift along the parasitism-mutualism continuum towards greater host benevolence, both empirically44,45, and comparatively46,47. Meanwhile, a key question remains whether mutualism facilitates the evolution of vertical transmission, or if the process typically proceeds as argued above. A study of bacterial symbionts concluded that horizontal transmission was the most primitive mode, and that vertical transmission is an inescapable evolutionary end point, given the mutational processes that effect a symbiont as a consequence of adopting strict vertical transmission48. However, these conclusions may be taxon-specific, and require examination across host-symbiont taxonomic diversity.

Elucidating the processes that drive symbiont diversification is fundamental to understanding the factors responsible for generating the Earth’s biodiversity, given that symbionts represent a considerable proportion of total species diversity49,50. Meanwhile, unravelling the factors that influence host-symbiont phylogenetic congruence is crucial for improving knowledge of host-switching, a major research focus in host-parasite interactions, with direct implications for the prediction and mitigation of zoonoses, emerging infections, and the control of agricultural pests51-53. To our knowledge, this study represents the first quantitative appraisal of host-symbiont cophylogeny, a central aspect of host-symbiont evolution. With this study, we hope to initiate a new direction in the study of symbiosis, towards formal quantitative and systematic analyses that seek to address diverse questions regarding the nature of host-symbiotic evolutionary relationships. Importantly, considerable variation in congruence exists among host phylogenies and both parasite and mutualist phylogenies. Therefore, a core challenge is to identify which factors are of importance in fostering close cophylogeny. As the number of individual cophylogenetic studies increases, the power of these analyses will increase, permitting more detailed approaches to tease apart patterns and underlying mechanisms. Crucially, meta-analyses are only as good as the studies upon which they are based. A continued accumulation of taxonomically well-sampled, multi-locus host and symbiont phylogenies, ideally taking phylogenetic uncertainty into account, will provide a powerful platform on which to base further analyses.

**Data availability**

A copy of the dataset analysed in this study is included in the supplementary information.

**Acknowledgements**

AH was awarded a travel grant from the Nilsson-Ehle-donation fund to support research in theoretical and applied genetics, by the Royal Physiographic Society in Lund, to establish the collaboration leading to this work. AH is currently supported by a Biotechnology and Biological Sciences Research Council (BBSRC) David Phillips Fellowship (grant number: BB/N020146/1).

SN is supported by an Australian Research Council (ARC) Discovery Fellowship (DP180100818).

**Author information**

**Affiliations**

Alexander Hayward1, Robert Poulin2, Shinichi Nakagawa3

1 Centre for Ecology and Conservation, University of Exeter, Penryn Campus, Penryn, TR10 9FE, Cornwall, UK.

2 Department of Zoology, University of Otago, P.O. Box 56, Dunedin, 9054, New Zealand.

3 Evolution & Ecology Research Centre and School of Biological, Earth & Environmental Sciences, University of New South Wales, Sydney NSW 2052, Australia.

**Author contributions**

RP conceived the study, all authors designed the study. SN performed the analyses. AH collected the data and drafted the manuscript. RP and SN provided comments and contributed to the final manuscript.

**Competing interests**

The authors declare no competing interests.

**Corresponding author**

Correspondence to: alex.hayward@exeter.ac.uk, robert.poulin@otago.ac.nz, s.nakagawa@unsw.edu.au

**Supplementary Information**

**Figure legends**

**Fig. 3 | Phylogenetic congruence between hosts and symbionts.** A plot showing the group-wise mean(s) with their 95% confidences intervals (thick lines) and 95% prediction intervals (thin lines) with observed effect sizes based on various sample sizes for **a**, overall; **b**, types of symbiosis **c**, host taxa; **d**, symbiont taxa; **e**, places of symbiosis; **f**, transmission mode; **g**, types of symbiosis x transmission mode, associated values for each plot are shown in Supplementary Table 1-4 and 7-9.

**For figure caption: Additionally, the effect size for mutualism is ~0.4 (Fig. 3b), and the effect size for vertical transmission is ~0.5 (Fig. 3i), while the effect size for horizontally transmitted mutualists is just ~0.28 (Fig. 3j), which is similar to the observed effect size of ~0.31 for parasitism (Fig. 3b). Taken together, we argue that mode of transmission is the most important overall driver of phylogenetic congruence between hosts and symbionts. Forest plots the group-wise means with their 95% confidences interval (thick lines) and 95% prediction intervals (thin lines) with observed effect sizes based on various sample sizes.**

**References**

1 Wilkinson, D. M. At cross purposes. *Nature* **412**, 485, doi:10.1038/35087676 (2001).

2 Estrela, S., Kerr, B. & Morris, J. J. Transitions in individuality through symbiosis. *Current Opinion in Microbiology* **31**, 191-198 (2016).

3 Leung, T. & Poulin, R. Parasitism, commensalism, and mutualism: exploring the many shades of symbioses. *Vie et Milieu* **58**, 107 (2008).

4 Hopkins, S. R., Wojdak, J. M. & Belden, L. K. Defensive Symbionts Mediate Host&#x2013;Parasite Interactions at Multiple Scales. *Trends in Parasitology* **33**, 53-64, doi:10.1016/j.pt.2016.10.003 (2016).

5 Schmid Hempel, P. *Evolutionary parasitologythe integrated study of infections, immunology, ecology, and genetics*. (2011).

6 Margulis, L. & Fester, R. *Symbiosis as a source of evolutionary innovation: speciation and morphogenesis*. (Mit Press, 1991).

7 Szathmáry, E. & Smith, J. M. The major evolutionary transitions. *Nature* **374**, 227-232 (1995).

8 Kiers, E. T. & West, S. A. Evolving new organisms via symbiosis. *Science* **348**, 392-394 (2015).

9 Thrall, P. H., Hochberg, M. E., Burdon, J. J. & Bever, J. D. Coevolution of symbiotic mutualists and parasites in a community context. *Trends in Ecology & Evolution* **22**, 120-126, doi:<https://doi.org/10.1016/j.tree.2006.11.007> (2007).

10 Reynolds, H. L., Packer, A., Bever, J. D. & Clay, K. Grassroots ecology: plant–microbe–soil interactions as drivers of plant community structure and dynamics. *Ecology* **84**, 2281-2291, doi:10.1890/02-0298 (2003).

11 Haines-Young, R. & Potschin, M. The links between biodiversity, ecosystem services and human well-being. *Ecosystem Ecology: a new synthesis*, 110-139 (2010).

12 Gunn, A. & Pitt, S. J. *Parasitology: an integrated approach*. (John Wiley & Sons, 2012).

13 Paterson, A. M., Palma, R. L. & Gray, R. D. Drowning on arrival, missing the boat, and x-events: How likely are sorting events. *Tangled trees: Phylogeny, cospeciation, and coevolution*, 287-309 (2003).

14 Fahrenholz, H. Ectoparasiten und Abstammungslehre. *Zoologischer Anzeiger* **41**, 371–374 (1913).

15 Eichler, W. Die Entfaltungsregel und andere Gesetzmäßigkeiten in den parasitogenetischen Beziehungen der Mallophagen und anderer ständiger Parasiten zu ihren Wirten. *Zool. Anz* **137**, 77-83 (1942).

16 Nylin, S. *et al.* Embracing Colonizations: A New Paradigm for Species Association Dynamics. *Trends Ecol Evol* **33**, 4-14, doi:10.1016/j.tree.2017.10.005 (2018).

17 de Vienne, D. M. *et al.* Cospeciation vs host-shift speciation: methods for testing, evidence from natural associations and relation to coevolution. *New Phytologist* **198**, 347-385, doi:10.1111/nph.12150 (2013).

18 Brooks, D. R. Hennig's Parasitological Method: A Proposed Solution. *Systematic Zoology* **30**, 229-249, doi:10.2307/2413247 (1981).

19 Page, R. D. M. COMPONENT ANALYSIS: A VALIANT FAILURE? *Cladistics* **6**, 119-136, doi:10.1111/j.1096-0031.1990.tb00532.x (1990).

20 Page, R. D. Parallel phylogenies: reconstructing the history of host‐parasite assemblages. *Cladistics* **10**, 155-173 (1994).

21 Legendre, P., Desdevises, Y. & Bazin, E. A statistical test for host–parasite coevolution. *Systematic biology* **51**, 217-234 (2002).

22 Summers, K. *et al.* Parasitic exploitation as an engine of diversity. *Biol Rev* **78**, 639-675, doi:10.1017/S146479310300616x (2003).

23 Giraud, T., Gladieux, P. & Gavrilets, S. Linking the emergence of fungal plant diseases with ecological speciation. *Trends in Ecology & Evolution* **25**, 387-395, doi:10.1016/j.tree.2010.03.006 (2010).

24 Rundle, H. D. & Nosil, P. Ecological speciation. *Ecol Lett* **8**, 336-352, doi:10.1111/j.1461-0248.2004.00715.x (2005).

25 Clayton, D. H., Bush, S. E. & Johnson, K. P. *Coevolution of life on hosts: integrating ecology and history*. (University of Chicago Press, 2015).

26 Bronstein, J. L. *Mutualism*. (Oxford University Press, USA, 2015).

27 Herre, E. A., Knowlton, N., Mueller, U. G. & Rehner, S. A. The evolution of mutualisms: exploring the paths between conflict and cooperation. *Trends in Ecology & Evolution* **14**, 49-53, doi:Doi 10.1016/S0169-5347(98)01529-8 (1999).

28 Trivers, R. L. The Evolution of Reciprocal Altruism. *The Quarterly Review of Biology* **46**, 35-57, doi:10.1086/406755 (1971).

29 Leigh, E. G., Jr. The evolution of mutualism. *J Evol Biol* **23**, 2507-2528, doi:10.1111/j.1420-9101.2010.02114.x (2010).

30 Douglas, A. E. Conflict, cheats and the persistence of symbioses. *New Phytologist* **177**, 849-858, doi:10.1111/j.1469-8137.2007.02326.x (2008).

31 Ferriere, R., Gauduchon, M. & Bronstein, J. L. Evolution and persistence of obligate mutualists and exploiters: competition for partners and evolutionary immunization. *Ecol Lett* **10**, 115-126, doi:10.1111/j.1461-0248.2006.01008.x (2007).

32 Poulin, R. *Evolutionary ecology of parasites*. (Princeton university press, 2007).

33 Hafner, M. S. *et al.* Disparate rates of molecular evolution in cospeciating hosts and parasites. *Science* **265**, 1087-1090 (1994).

34 Hafner, M. S., Demastes, J. W., Spradling, T. A. & Reed, D. L. Cophylogeny between pocket gophers and chewing lice. *Tangled trees: phylogeny, cospeciation, and coevolution. University of Chicago Press, Chicago*, 195-218 (2003).

35 Clayton, D. H. & Johnson, K. P. Linking coevolutionary history to ecological process: doves and lice. *Evolution* **57**, 2335-2341 (2003).

36 Hall, A. A. *et al.* Codivergence of the primary bacterial endosymbiont of psyllids versus host switches and replacement of their secondary bacterial endosymbionts. *Environmental microbiology* **18**, 2591-2603 (2016).

37 Krumbholz, A., Bininda-Emonds, O. R., Wutzler, P. & Zell, R. Phylogenetics, evolution, and medical importance of polyomaviruses. *Infection, Genetics and Evolution* **9**, 784-799 (2009).

38 Charleston, M. & Robertson, D. Preferential host switching by primate lentiviruses can account for phylogenetic similarity with the primate phylogeny. *Systematic biology* **51**, 528-535 (2002).

39 Moran, N. A., McCutcheon, J. P. & Nakabachi, A. Genomics and Evolution of Heritable Bacterial Symbionts. *Annu Rev Genet* **42**, 165-190, doi:10.1146/annurev.genet.41.110306.130119 (2008).

40 Ebert, D. The Epidemiology and Evolution of Symbionts with Mixed-Mode Transmission. *Annu Rev Ecol Evol S* **44**, 623-+, doi:10.1146/annurev-ecolsys-032513-100555 (2013).

41 Nieberding, C. M. & Olivieri, I. Parasites: proxies for host genealogy and ecology? *Trends in Ecology & Evolution* **22**, 156-165 (2007).

42 Ewald, P. W. Transmission modes and evolution of the parasitism-mutualism continuum. *Ann N Y Acad Sci* **503**, 295-306, doi:10.1111/j.1749-6632.1987.tb40616.x (1987).

43 Yamamura, N. Vertical transmission and evolution of mutualism from parasitism. *Theoretical Population Biology* **44**, 95-109 (1993).

44 Bull, J. J., Molineux, I. J. & Rice, W. R. Selection of Benevolence in a Host-Parasite System. *Evolution* **45**, 875-882, doi:10.1111/j.1558-5646.1991.tb04356.x (1991).

45 Stewart, A. D., Logsdon, J. M. & Kelley, S. E. An empirical study of the evolution of virulence under both horizontal and vertical transmission. *Evolution* **59**, 730-739 (2005).

46 Herre, E. A. Population structure and the evolution of virulence in nematode parasites of fig wasps. *Science* **259**, 1442-1445, doi:10.1126/science.259.5100.1442 (1993).

47 Clayton, D. H. & Tompkins, D. M. Ectoparasite virulence is linked to mode of transmission. *Proceedings of the Royal Society of London. Series B: Biological Sciences* **256**, 211-217 (1994).

48 Sachs, J. L., Skophammer, R. G. & Regus, J. U. Evolutionary transitions in bacterial symbiosis. *Proc Natl Acad Sci U S A* **108 Suppl 2**, 10800-10807, doi:10.1073/pnas.1100304108 (2011).

49 Windsor, D. A. Most of the species on Earth are parasites. *International Journal for Parasitology* **28**, 1939-1941, doi:Doi 10.1016/S0020-7519(98)00153-2 (1998).

50 Poulin, R. Parasite biodiversity revisited: frontiers and constraints. *Int J Parasitol* **44**, 581-589, doi:10.1016/j.ijpara.2014.02.003 (2014).

51 Woolhouse, M. E., Haydon, D. T. & Antia, R. Emerging pathogens: the epidemiology and evolution of species jumps. *Trends Ecol Evol* **20**, 238-244, doi:10.1016/j.tree.2005.02.009 (2005).

52 Morens, D. M., Folkers, G. K. & Fauci, A. S. The challenge of emerging and re-emerging infectious diseases. *Nature* **430**, 242-249, doi:10.1038/nature02759 (2004).

53 Gortazar, C. *et al.* Crossing the interspecies barrier: opening the door to zoonotic pathogens. *PLoS Pathog* **10**, e1004129, doi:10.1371/journal.ppat.1004129 (2014).

54 Zug, R. & Hammerstein, P. Bad guys turned nice? A critical assessment of Wolbachia mutualisms in arthropod hosts. *Biol Rev Camb Philos Soc* **90**, 89-111, doi:10.1111/brv.12098 (2015).