



Sciences biologiques,  
Écologie et Environnement  
**CONFÉRENCES  
JACQUES-MONOD**



# Open Questions in Disease Ecology and Evolution: from Basic Research to Evolutionary Medicine

## FINAL REPORT

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Roscoff, France  
30<sup>th</sup> October – 3 November 2017

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## Résumé

En 2004, Thierry RIGAUD (BioGeoSciences, Dijon) et Dieter EBERT (Bâle, Suisse) ont organisé la première conférence Jacques Monod sur l'écologie évolutive des relations hôte-parasite. Cette conférence a rencontré un tel succès que d'autres conférences ont eu lieu en 2007, 2011 et 2014. Voici le rapport final de la dernière conférence sur l'évolution des interactions hôte-parasite qui a eu lieu à Roscoff en octobre 2017, organisée par Ana RIVERO (MIVEGEC, Montpellier) et Andrea GRAHAM (Princeton, États-Unis).

Au fil de ces dernières années, les Conférences Jacques Monod sur l'évolution des interactions hôte-parasite ont acquis une renommée internationale auprès des chercheurs travaillant sur l'écologie et l'évolution des maladies infectieuses. Le caractère unique de ces CJM réside dans le fait qu'elles rassemblent une communauté multidisciplinaire et interactive de chercheurs travaillant sur un large éventail de systèmes (plantes à hôtes vertébrés, virus à parasites métazoaires) et d'approches (phénotypiques, génomiques, théoriques). Aucune autre conférence dans le monde ne réunit un tel éventail des chercheurs travaillant sur ces problématiques. Comme l'a souligné l'un des conférenciers invités, les parasites ne respectent pas les frontières disciplinaires ou taxonomiques, mais la plupart de nos programmes de recherche sont étroitement axés sur un pathogène ou hôte donné (protozoaires, plantes, vertébrés, invertébrés). La force de cette conférence et ce qui la rend unique est qu'elle capte la diversité d'approches et des systèmes modèles, favorisant ainsi les échanges entre les différentes disciplines.

En conséquence, ces CJM attirent des chercheurs de tout premier plan, qui considèrent cette conférence comme une opportunité unique de se tenir au courant des dernières percées dans ce domaine vaste et cloisonné. Tous les conférenciers invités ont donc accepté notre invitation à y participer avec enthousiasme, et de nombreux autres chercheurs de premier plan dans le domaine ont postulé pour y participer. Les 75 participants non invités sont venus de 11 pays différents (France, Royaume-Uni, Allemagne, États-Unis, Suisse, Canada, Norvège, Finlande, Inde, Pays-Bas et Espagne). Le tiers ( $n = 25$ ) des participants étaient des étudiants en thèse. Comme les années précédentes, la qualité des abstracts des participants non invités était extrêmement élevée.

Le programme a été divisé en 7 sessions de communication orale et 2 sessions de posters. Les sessions de communication étaient les suivantes :

- I. Virulence parasitaire
- II. Dynamique inter- et intra-hôte
- III. Symbiotes et phénotype étendu
- IV. Plusieurs hôtes, plusieurs-parasites, changements d'hôtes
- V. Vecteurs (comportement, manipulation, transmission)
- VI. Coévolution hôte-parasite
- VII. Application des concepts : santé humaine, animale, et végétale

Les deux sessions de posters, d'une durée de deux heures chacune, ont été très suivies et ont donné lieu à des discussions animées entre les participants. La qualité des présentations d'affiches était extrêmement élevée.

La conférence a été particulièrement remarquable pour son sex-ratio équilibré: 52% des participants et 44% des conférenciers étaient des femmes. Les participants ont célébré cette tendance très positive qui augmente la visibilité des chercheuses dans le domaine. Il y a également eu une participation remarquable (et remarquable) de femmes, y compris de jeunes scientifiques, aux

questions et réponses, un point qui a récemment été souligné comme étant en cause dans les conférences internationales. Les participants ont également souligné que l'atmosphère de la conférence était extrêmement amicale et peu compétitive, la meilleure preuve étant que de nombreux exposés ont présenté des résultats et des idées non publiés.

Nous avons pris soin d'organiser le programme afin de laisser le plus de temps possible pour des discussions informelles: longues pauses déjeuner, un après-midi sur l'île de Batz, et une longue « soirée » après le banquet grâce à l'aimable autorisation du propriétaire du Gulf Stream, qu'a permis aux participants de discuter pendant quelques heures avant le départ du lendemain matin.

Il y a eu un accord unanime et enthousiaste pour le renouvellement de cette conférence en 2020 et pour qu'Andrea GRAHAM (Princeton, US <http://algraham.princeton.edu/>) et Oliver KALTZ (ISEM, Montpellier <http://www.eec.univ-montp2.fr/people/oliver-kaltz/>) soient les prochains président et vice-président. La complémentarité des sujets de recherche (Andrea est un immunologiste évolutionnaire avec une solide expérience dans la recherche empirique sur les mammifères, avec des applications immédiates en médecine; Oliver est un éco-évolutionniste expérimental travaillant sur le rôle de l'hétérogénéité environnementale dans l'épidémiologie des infections chez les protozoaires) sera un grand atout pour l'organisation de la prochaine conférence et aura probablement un accueil aussi enthousiaste que celui des conférences précédentes.

Le président et le vice-président, mais aussi les autres participants ont souligné le travail d'organisation fantastique réalisé par Nathalie BABIC, dont l'efficacité et la convivialité ont grandement contribué à ce que cette conférence soit un franc succès.

## Overview

In 2004 Thierry RIGAUD (BioGeoSciences, Dijon) and Dieter EBERT (Basel, Switzerland) organised a Jacques Monod Conference on the Evolutionary Ecology of Host-Parasite Relationships. This conference encountered such a degree of success that follow-up conferences took place in 2007, 2011 and 2014. The following is the final report for the latest of conferences on the topic of the evolution of host-parasite interactions, which took place in Roscoff in October 2017 hosted by Ana RIVERO (MIVEGEC, Montpellier), and Andrea GRAHAM (Princeton, US).

Over the years, the Jacques Monod Conferences on the evolution of host-parasite interactions have acquired international cult status amongst disease ecologists and evolutionary biologists. The uniqueness of these JMCs lies in the fact that they bring together a multidisciplinary and interactive community of disease ecologists and evolutionary biologists working on a wide range of systems (plant to vertebrate hosts, viruses to metazoan parasites) and approaches (phenotypic, genomic, theoretical). Arguably<sup>1</sup>, no other conference in the world brings together such a diverse spectrum of disease ecologists. As a result, these JM Conferences attract the most prominent researchers in the field, which see this meeting as an opportunity to be brought up to date on the latest breakthroughs in this large, and compartmentalized, field. Every single invited speaker in our “wish list” therefore enthusiastically accepted the invitation, and many other prominent researchers in the field applied to come as participants.

The program was divided into 7 different **oral communication sessions** (see below). Oral communications consisted of combinations of invited speaker talks (30 min) and contributed participant (15 min) talks chosen from the contributed abstracts. As in previous years, the quality of the non-invited participant abstracts was extremely high (many coming from established scientists), making the choice of short talks an extremely difficult one.

The conference demographics were as follows

### 25 invited speakers

France:

Stéphane BLANC (Montpellier, France), Thierry BOULINIER (Montpellier, France), Richard CORDAUX (Poitiers, France), Oliver KALTZ (Montpellier, France), Natacha KREMER (Lyon, France), Louis LAMBRECHTS (Paris, France), Franck PRUGNOLLE (Montpellier, France), Thierry RIGAUD (Dijon, France), Ana RIVERO (Montpellier, France), Gabriele SORCI (Dijon, France), Fabrice VAVRE (Lyon, France)

Europe:

Angus BUCKLING (Exeter, UK), Dieter EBERT (Basel, Switzerland), Manfred MILINSKI (Plön, Germany), Jane PARKER (Köln, Germany), Amy PEDERSEN (Edinburgh, UK), Sarah REECE (Edinburgh, UK), Roland REGOES (Zurich, Switzerland), Lena WILFERT (Exeter, UK)

[Last minute cancellations due to political and family duties: Arcadi NAVARRO (Barcelona, Spain), Heather FERGUSON (Edinburgh, UK), Rob DE BOER (Utrecht, The Netherlands)]

Rest of the world:

Elisabeth BORER (Minnesota, US), Troy DAY (Kingston, Canada), Vanessa EZENWA (Georgia, US), Andrea GRAHAM (Princeton, US), Curt LIVELY (Indiana, US), ZUK Marlene (Minnesota, US)

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<sup>1</sup> The one that comes closest is the American Ecology and Evolution of Infectious Diseases (EEID) conference, but EEID often has a strong focus on theoretical epidemiology and public health, with few experimental or co-evolutionary studies represented.

[Last minute cancellations due to health and family matters: Janis ANTONOVICS (Virginia, US) and Jaap DE ROODE (Atlanta, US)]

**75 non-invited participants** (for a total of 89 participation requests, 14 participants had to cancel their attendance for a variety of reasons) **from 11 different countries** (France, UK, Germany, US, Switzerland, Canada, Norway, Finland, India, The Netherlands and Spain). One-third (n=25) of the participants were PhD students.

The **14 participants** who were invited to present a **short talk** were:

Crystal FROST (Liverpool, UK), Katrina LYTHGOE (Oxford, UK), Benjamin SADD (Illinois, US), Camille JACQUELINE (Montpellier, France), Meggan GREISCHAR (Toronto, Canada), Ann TATE (Vanderbilt, US), Meggan CRAFT (Minnesota, US), Sylvain GANDON (Montpellier, France), Boris SCHMID (Oslo, Norway), Alex HALL (Zurich, Switzerland), Amy KENDIG (Minnesota US), Christian VAN DORP (Utrecht, The Netherlands), Silvie HUIJBEN (Barcelona, Spain) and Nathanael HOZE (Zurich, Switzerland).

[Lotta-Riina SUNDBERG (Helsinki, Finland) was also selected but had to cancel her participation a few days before the conference]

In addition, there were **two poster sessions**, each lasting 2h, on the Tuesday and the Thursday, which proved very popular and convivial, and generated lively discussions between the attendees and the poster-contributors. The quality of the poster presentations was extremely high.

The conference was particularly remarkable for its **balanced sex ratio**: 52% of the attendees and 44% of the speakers (10 invited speakers, including the Chairman and Vice-Chairman, and 7 short talk contributions) were women. Attendees were unanimous in celebrating this very positive and promising trend that increases the visibility of women scientists in the field. There was also a remarkable (and remarked) participation of women, including junior scientists, in the question and answer rounds, a point that has been recently highlighted as being issue in international conferences<sup>2</sup>. During the final discussion, one of the points which was debated was whether our choice of an all-female list of session chairs to run the Q&A may have encouraged women to be more participative.

We took care to organize the program so as to leave as much time as possible for **informal discussions**: long (2h) lunch breaks, an afternoon on Batz Island, and a long post-conference dinner “soiree” which, with the very kind permission of the Gulf Stream owner, allowed the participants to mingle and chat for a few hours before the following morning’s departure.

## Scientific program

Human, animal and plant diseases pose a serious and continuing threat to human health, food security, food safety, national economies, biodiversity and the rural environment. As a result, the study of infectious disease from an ecological and evolutionary perspective is one of the most dynamic and topical areas in biology. This conference aimed to both *decipher the fundamental ecological and evolutionary processes* that drive infectious diseases and to *explore the potential to apply this research to programs that mitigate the effects of infectious diseases* in humans, wildlife, and plants.

The conference program followed closely the structure outlined at the time of the application and was divided into seven different Sessions.

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<sup>2</sup> Kuo M (*Science* 23 Oct, 2017) Women ask fewer questions than men at conference talks, new studies suggest

Session I: Parasite virulence

Session II: Between/within host dynamics

Session III: Symbionts and extended phenotype

Session IV: Multiple hosts, multiple parasites and host shifts

Session V: Vectors (behaviour, manipulation, transmission)

Session VI: Host-parasite coevolution

Session VII: Applying the concepts to human, animal and plant health

### **Session I: Parasite virulence**

Understanding parasite virulence is the crux of disease-ecology research. The conundrum faced by parasites is that they tend to maximize their fitness through host exploitation, but excessive host exploitation may kill the host too quickly, thereby reducing the parasite's transmission opportunities. This session explored several of the ways in which parasites may solve this puzzle. The session started with a captivating talk by Stephane BLANC (Montpellier, France) on the fascinating life style of multipartite viruses in plants. These are viruses that have their genome divided into different segments, which are separately encapsidated in a distinct virus particle. The evolution of this bizarre strategy, which seems to present numerous disadvantages from the viral perspective, is extremely puzzling. Theoretical models have shown that the risks of missing a vital segment during cell-to-cell transmission events is so high that these viruses should not exist. Stephane presented new results showing that the different segments do not need to be together within an infected cell for the system to be functional, and that the unit of virus exploitation is not the cell but the tissue. This stunning observation challenges some basic concepts of virology and evolution. Many in the audience were surprised to hear that these little-known viruses, represent between 30-40% of all plant viruses. The next speaker was Roland REGOES (Zurich, Switzerland), whose very didactic talk dealt with the relative roles of viral load and per-parasite pathogenicity in determining virulence in HIV infections. He presented some recent results showing that per-parasite pathogenicity is highly heritable, and that viral genotypes affect virulence mainly by modulating the per-parasite pathogenicity while the effect of viral load is relatively minor. The next talk by Christiaan VAN DORP (Utrecht, The Netherlands) continued exploring the issue of HIV virulence through a multi-level model of HIV immunology that explores the issue of immunological pre-adaptation: the observation that escape mutations for the hosts T-lymphocyte responses can already be present in the transmitted viruses. Katrina LYTHGOE (Oxford, UK) explored another fascinating aspect of viral evolution which she termed 'short-sighted' evolution, whereby the short generation times and high mutability of viruses allow them to rapidly adapt to their current host, thereby hampering their chances of onward transmission within a diversified host population. A crucial example she offered was that as HIV evolves away from specific adaptive immune responses in a current host, it often becomes acutely sensitive to the type I interferon response that it would encounter if it were transmitted to a different host. The session therefore shed new light on viruses that have attracted attention of evolutionary biologists for some time (e.g., retroviruses such as HIV) and also brought the wonders of multipartite viruses into view.

### **Session II: Between and within host dynamics**

A central theme of this session was the extent to which both between-host and within host parasite dynamics determine the evolution and epidemiology of diseases. Sarah REECE (Edinburgh, UK) dealt with the issue of the circadian rhythms of malaria parasites. Why do malaria parasites coordinate their cycles of replication in the blood with the host's circadian rhythms? She suggested that rhythms in immune defense and parasite development could provide an evolutionary advantage to hosts, parasites or both. The results she presented reveal that when parasite schedules are perturbed to be out of synchrony with the host's circadian rhythms, the replication and transmission of parasites is reduced and hosts suffer less severe infections. However, the extent to which these rhythms may be controlled by the host or the parasite remains mysterious. Meggan GREISCHAR

(Toronto, Canada) looked at malaria within-host dynamics from a different perspective. When should malaria parasites stop proliferating within the blood in order to produce specialized stages for transmission to mosquitoes? Her theoretical models show a link between within and between host dynamics in that the optimal parasite strategy is likely to change as the epidemic spreads. Ann TATE (Vanderbilt, US) argued that the temporal dynamics of host immune expression hosts must be taken in to account when taking measures of immunocompetence, and she presented results showing that in bacteria-infected beetles the expression patterns of immune genes are far from being monotonic with respect to time nor independent of microbe density. Andrea GRAHAM (Princeton, US) showed that disease resistance is strongly shaped by genotype-by-environment interactions and that, as a result, testing for disease resistance under septic laboratory conditions may be full of pitfalls. When placed in an outdoor mesocosm, mice that are highly resistant to nematodes in the lab, become highly susceptible. Her work shows that one potential explanation for these surprising results is that the environment can significantly alter gut microbial communities and mucosal responses of the mice. Oliver KALTZ's presentation dealt with the impact of environmental fluctuations on disease dynamics in a meta-population context. Using a particularly tractable and unusual bacteria-infected *Paramecium* experimental system, he showed how the temporal autocorrelation structure of environmental fluctuations can affect the host's population dynamics and the spread of the infection. The session therefore spanned host taxa from protozoa to insects and mammals, and infectious disease agents from bacteria to protozoa and worms. Covering such breadth of systems helped to emphasize conceptual similarities driving cross-scale disease dynamics.

### **Session III: Symbionts and the extended phenotype**

This session highlighted how, in spite of the tremendous diversity and functional importance of the microbial biome of free-living organisms, we still have little understanding of their role in shaping host evolution and disease dynamics. Richard CORDAUX (Poitiers, France) gave a fascinating talk on how *Wolbachia* bacterial endosymbionts have driven a shift in the sex determination mechanism of its host, the common pillbug (*Armadillium vulgare*). Their results show how a *Wolbachia* insert termed the “f element” has evolved as a new sex chromosome, showing that bacterial symbionts can be powerful sources of evolutionary novelty. Fabrice VAVRE (Lyon, France), showed that while some hosts maintain facultative associations with their symbionts, others become entirely dependent on them for crucial functions such as their egg production. Using different examples from a variety of arthropod systems, he illustrated the diversity of evolutionary paths that can lead to this evolutionarily counter-intuitive dependence. Using a completely different system, the interaction between a squid and its luminescent bacteria, Natacha KREMER (Lyon, France) showed us the molecular dialogue that leads to the establishment of this unique mutualistic association and how symbionts are able to re-program the squid's gene expression. Elisabeth BORER's (Minnesota, US) talk dealt with the role of nutrients in shaping host-microbiome-parasite interactions in plants. Her recent results show that an elevated nutrient supply reduces the overall diversity of microbial fungi in a grassland plant, while also increasing the diversity of pathogenic taxa. Finally, Benjamin SADD (Illinois, US) told us of how phytochemicals can modify host parasite-interactions in bumblebees when hosts co-opt plant chemicals for their own defense, or when parasites evolve resistance to these products. The session therefore provided ample evidence that defensive and reproductive phenotypes of an array of plants and animals depend upon microbial symbionts, suggesting that host-parasite interactions will be best understood in this holistic context.

### **Session IV: Multiple hosts, multiple parasites, host shifts**

In recent years, there has been a shift in the one host-one parasite paradigm with the acknowledgement that, in the field, infections often involve multiple hosts and parasites. These complex communities of hosts and parasites can have profound evolutionary impacts on all component taxa. This session aimed to capture the real-life complexity of multi-host/multi-parasite

interactions through a variety of approaches: from field-based empirical to laboratory-based experimental studies. Vanessa EZENWA (Georgia, US), gave a fascinating talk on the interaction between gastrointestinal helminths and bovine tuberculosis in free-ranging African buffalo. By coupling data from experimental and longitudinal studies, she's been able to show that active infection with helminths dampens the immune responses of the buffalo and that this has profound implications for the outcome of tuberculosis both at the individual level but also at the level of the population (epidemiology). Amy PEDERSEN (Edinburgh, UK) also spoke about immunosuppressive nematodes in wild, albeit much smaller, mammals. Her talk dealt with how both co-infection and malnutrition impact helminth burdens in wild wood mice. The role of nutrients in determining co-infection outcomes was also at the core of Amy KENDIG's (Minnesota, US) talk. She showed results that indicate that nitrogen and phosphorous mediate interactions between two different plant viruses, which means that human interventions through the use of fertilizers may have unintended consequences in disease ecology. Angus BUCKLING (Exeter, UK) presented evidence, from cystic fibrosis patients, that polymicrobial communities within hosts can affect pathogen mutation rates as well as selection on mutants. He suggested that such community dynamics are likely to affect emergent virulence and the evolutionary response to antibiotic treatments. The rest of the talks dealt with the issue of host shifts. Crystal FROST (Liverpool, UK) provided an interesting perspective on the role of host shifts as drivers of rapid parasite gene evolution. Using bacterial parasites of parasitoid wasps, she has been able to show that parasite genes undergo a dramatic burst of evolution following host shift events. Through a series of experimental investigations and field based approaches, Thierry RIGAUD (Dijon, France) investigated the host-shift potential of microsporidian parasites that have been found infecting an invasive amphipod in European rivers. Although this microsporidian has not yet invaded native amphipods, the potential for such host shifts is high and he suggested that the parasite be included in emergent disease surveillance programs across Europe. Lena WILFERT (Exeter, UK) gave a fascinating talk on how a largely benign honeybee virus (Deformed Wing Virus) becomes pathogenic when transmitted by an emerging ectoparasitic mite (*Varroa destructor*) because the vector allows the virus to circumvent the bee's defense barriers. The spread of *Varroa* mites is not only fueling a global epidemic of Deformed Wing Virus in honeybees but is also leading to a spillover of the virus into wild bumblebee populations. The last talk in the host shift series was given by Franck PRUGNOLLE (Montpellier, France), who captivated the audience with a talk about host shifts in malaria parasites between apes and humans, which sheds light on the origin of *Plasmodium falciparum*, the most virulent agent of human malaria. The session therefore addressed important disease ecology themes – both conceptual (e.g., community ecology to superparasitism) and applied (e.g., invasion biology to zoonotic risk) – with a compelling suite of experimental, epidemiological and molecular genetic perspectives.

### **Session V: Vectors (behaviour, manipulation, transmission)**

This session was unexpectedly short during to the last-minute cancellation of one of the main invited speakers due to a knee injury (Janis ANTONOVICS, Virginia, US), who was to talk about vector-borne diseases of plants. Two of the talks dealt with the issue of parasite manipulation of vector behaviour from different perspectives. Sylvain GANDON (Montpellier, France), developed a theoretical model that identifies multiple evolutionary conflicts over the control of vector behaviour: in general, vectors should avoid infected hosts, however, if vectors are being manipulated by pathogens, uninfected vectors should prefer infected hosts, while infected vectors should seek uninfected hosts. The next speaker, Boris SCHMID (Oslo, Norway) provided an experimental illustration of vector manipulation by *Yersinia pestis*, the bacteria responsible for the plague. This bacterium has two different transmission strategies: blockage-dependent transmission (through the formation of biofilms that block the flea vector's midgut and force it to regurgitate infected blood) and early-phase transmission (which does not require a biofilm). Through an extensive sampling of infected fleas collected in China, he has been able to identify a particular gene which is associated



with biofilm formation and is under strong directional selection. Ana RIVERO's (Montpellier, France) talk dealt with the issue of whether drug resistant *Plasmodium* parasites have the same transmission potential as their drug-sensitive counterparts. She showed recent unpublished results that suggest that drug-resistance carries significant costs for transmission: drug resistant parasites seems less successful at infecting mosquitoes than sensitive ones. She discussed the implications of these results for the emergence and spread of drug resistant vector-transmitted mutations. The session therefore shed light on the evolutionary ecology of vector-borne diseases of animals, highlighting the impacts of parasite strain competition vs. cooperation on transmission ecology.

### **Session VI: Host-parasite coevolution**

This session's aim was to explore the context and extent of host-parasite co-evolution and Red Queen dynamics. The session began with talks from two of the leading scientists in the field. Curt LIVELY (Indiana, US) gave an overview and presented new results on his hallmark long-term work on fresh water snails and their highly virulent trematode parasites. His results show that the coexistence of sexual and asexual populations of fresh water snails is mediated by these parasites and that there's periodic selection both for and against sexual reproduction in the host, leading to oscillations in the frequency of asexual females. Interestingly, even within a single lake there's considerable variation in the strength of parasite-mediated selection. Dieter EBERT (Basel, Switzerland) dealt with the issue of the genetic specificity in host-parasite interactions, which is a crucial determinant of the mode and tempo of host-parasite co-evolution. He presented his latest results from his *Daphnia magna* – *Pasteuria ramosa* system showing a strong support for balancing selection at resistance loci which matches predictions of elevated levels of diversity at these loci. Louis LAMBRECHTS (Paris, France) talked about the use of genome-wide genetic mapping and association studies to identify genes involved in the specificity of interactions between dengue viruses their main mosquito vector *Aedes aegypti*. His work provided compelling examples of basic scientific discoveries in a medically relevant empirical system. Next, Manfred MILINSKI (Plön, Germany) discussed Major Histocompatibility Complex (MHC)-mediated mating biology in sticklebacks. He summarized previous work on organismal-scale mate-choice behaviours that optimize MHC allelic diversity of offspring, and then showed new, cellular-scale evidence that, after mating, fish eggs preferentially permit fertilization by MHC-optimized sperm. Jane PARKER (Köln, Germany) gave a fascinating talk on the evolutionary forces underlying plant immune receptor maintenance and diversification. She talked about the multiple mechanisms that plants have in place to limit the inadvertent activation of certain immune pathways that, although essential for plant pathogen resistance, are very costly to the plant (autoimmunity), and on how these immune pathways operate within the natural context of hybridization opportunities and environmental stress variations. Gabriele SORCI (Dijon, France) talked about how immunosuppressant gastrointestinal nematodes adapt to their mice hosts, and in particular about the relative importance of parasite phenotypic plasticity and microevolutionary responses, as well as on the role of the host's microbiota in determining the parasite's immunomodulatory strategies and reproductive success. The session therefore encompassed classic as well as new "model systems" for host-parasite co-evolution. All demonstrated remarkably close ties among the defense, attack and reproductive strategies of host and parasite.

### **Session VII: Applying the concepts to human, animal and plant health**

This session dealt with how ecological and evolutionary approaches to disease dynamics can help us tackle current challenges in human, animal and plant health and conservation issues. Marlene ZUK (Minnesota, US) gave an interesting overview of one of the deadliest and most cinematographic of diseases: plague. Her recent work has been dealing with how plague epidemiology in Russia is determined by the social organization and behaviour of its rodent reservoirs. The talk was accompanied by a fascinating perspective on the plague surveillance and control programs that were

put in place in the Soviet era and the impact they had on the disease dynamics. Continuing with the issue on how host behaviour determines disease spread, Meggan CRAFT's (Minnesota, US) dealt with recent work in which she has been using a network modelling approach to establish how the contact networks of raccoons, a key reservoir for rabies, determine the spread of the disease. Thierry BOULINIER (Montpellier, France) focused on maternal immunity and wild seabird conservation. He presented results showing that seabird offspring show a very slow decay of maternal antibodies and how this could be used to protect endangered species such as albatrosses through maternal vaccination. There followed a number of talks on evolutionary perspectives of disease therapy and drug-resistance management. Troy DAY (Kingston, Canada) provided some interesting theoretical insights on how the different resource requirements of drug resistant and susceptible *Plasmodium* parasites could be used to prevent the evolution of drug resistance in malaria. Continuing on the issue of malaria drug resistance, Silvie HUIJBEN's (Barcelona, Spain) tackled the association between low innate immunity and the emergence of anti-malarial drug resistance. She presented new unpublished data from a large African study where they are quantifying the frequency of drug resistant mutations in a variety of immune contexts, including HIV infections and immunosuppressed pregnant women. Nathanaël HOZÉ (Zurich, Switzerland) dealt with the issue of tolerance-based therapies, which aim to decrease the morbidity and mortality of the host without necessarily clearing the parasite. Because these tolerance-based treatments impose fewer selective pressures on the pathogen they have been hypothesized to be “evolution-proof” (i.e. to prevent or delay the evolution of resistance). However, through a series of mathematical models, he showed how these therapies may increase the prevalence and incidence of diseases, and may even cause more deaths than the absence of treatment! Alex HALL (Zurich Switzerland) also presented results on how to curb antimicrobial resistance evolution, this time through the use of bacteriophages. One critical issue for the successful implementation of phage therapy is whether there may be phenotypic or genetic correlations between resistance to antibiotics and resistance to phages. His results on a large dataset of clinical bacterial isolates shows, however, that although there are positive correlations between different antibiotic-antibiotic and phage-phage combinations, resistance to phages and antibiotics evolves largely independently. Finally, Camille JACQUELINE (Montpellier, France) discussed the interaction between non-oncogenic infections and cancer in a fascinating *Drosophila* experimental system. She showed that flies infected with a bacterium show reduced tumor sizes, and she suggested that this may be due to the infection-driven stimulation of the immune system. The session therefore capitalized on applied themes emerging from some of the previous sessions. It then brought into sharp focus the contributions of evolutionary biology to promoting wildlife conservation, human health, and the design of evolution-proof therapies.

## General discussion and conclusion

In recent years, the emergence or re-emergence of animal and human infectious diseases has been increasingly documented around the world. Threats from old and new parasites and pathogens are fuelled by changes in the environment, in agriculture and food production, and in human demography. Anthropogenic changes, particularly those involving ecosystem alterations, and movements of infected people and animals, provide new opportunities for host-parasite mixing, and can further drive the introduction of both known and novel parasite genotypes to previously unaffected host individuals or species. Understanding the evolution and transmission ecology of infectious diseases is one of the greatest challenges in biology. **Yet biomedicine remains unfortunately disconnected from evolutionary and ecological research.** This JM Conference aimed to bridge that gap, by focusing on two broad issues: 1) deciphering the fundamental ecological and evolutionary processes that drive infectious diseases, and 2) exploring the potential to apply this research to programs that may mitigate the effects of infectious diseases in humans, wildlife, and domestic animals and plants.

The points which were highlighted during the last day's General Discussion were

- As pointed out by one of the invited speakers (Elisabeth BORER) parasites do not respect disciplinary or taxonomic boundaries, yet most individual research programs are narrowly focused on a particular pathogen or favourite host taxon (protozoans, plants, vertebrates, invertebrates). The strength of this conference and what renders it **unique** is that it captures the **diversity of approaches and model systems** thereby promoting exchanges between the different disciplines. Indeed, evolutionary biology and ecology elucidate general rules governing the diversity and dynamics of all organisms, so these fields are uniquely placed to inform our understanding of infectious diseases in general. The conference also allowed younger researchers to obtain an overview over this rapidly growing field and to foster new collaborations and job opportunities.
- There was a unanimous and enthusiastic agreement for this conference to be **renewed in 2020** and for **Andrea GRAHAM** (Princeton, US <http://algraham.princeton.edu/>) and **Oliver KALTZ** (ISEM, Montpellier <http://www.eec.univ-montp2.fr/people/oliver-kaltz/>) to be the next Chair and Vice-Chairs. The complementarity of the research topics (Andrea is an evolutionary immunologist with a strong track record in empirical research on mammals, with immediate applications in medicine; Oliver is an experimental evolutionary ecologist working on the role of environmental heterogeneity in the epidemiology of infections in protozoan meta-populations) will be a great asset for the organisation of the next conference and is likely to have as enthusiastic a reception as that of previous conferences.
- Participants also highlighted that the atmosphere of the conference was extremely **friendly and uncompetitive**, the best evidence of which is that many of the talks presented unpublished results and ideas. Maintaining such a productive and collaborative environment will be a primary aim in any renewed conference.
- An issue that was highlighted was the **balanced sex ratio** (see Outlook, above), and the very visible participation of women both as invited speakers, chairwomen, but also through their very active participation in the question and answer round. This too will remain a key goal.
- Both the Chairman and Vice-Chairman, but also the rest of the attendees highlighted the fantastic organizational work carried out by **Nathalie BABIC**, whose efficiency and friendliness and did much to improve and facilitate everybody's experience.