



Review

Biodiversity and health: Lessons and recommendations from an interdisciplinary conference to advise Southeast Asian research, society and policy



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ABSTRACT

Southeast Asia is an economic, biodiverse, cultural and disease hotspot. Due to rapid socio-economic and environmental changes, the role of biodiversity and ecosystems for human health ought to be examined and communicated to decision-makers and the public. We therefore summarized the lessons and recommendations from an interdisciplinary conference convened in Cambodia in 2014 to advise Southeast Asian societies on current research efforts, future research needs, and to provide suggestions for improved education, training and science-policy interactions. First, we reviewed several examples of the important role of ecosystems as 'sentinels' in the sense that potentially harmful developments for human health become first apparent in ecosystem components. Other ecosystem services which also benefit human well-being are briefly summarized. Second, we summarized the recommendations of the conference's roundtable discussions and added recent developments in the science-policy interface. The recommendations were organized along five themes: Ethical and legal considerations; implementation of the One Health approach; education, training, and capacity building; future research priorities; and potential science-policy interactions. While the role of biodiversity for human health needs further research, especially for zoonoses and emerging diseases, many direct and indirect benefits to human health are already apparent, but have yet to filter down to the science-policy interface in order to influence legislation and enforcement. Therefore, efforts to strengthen the interface in Southeast Asia should become a high priority in order to strengthen the health and resilience of Southeast Asian societies.

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1. Introduction

The ecosystem functions and services resulting from the presence of biodiversity have complex and sometimes contradictory relationships to human health and well-being (Chivian and Bernstein, 2008; Corvalan et al., 2005; Hough, 2014); e.g., the transmission of vector-borne and zoonotic diseases to humans is based on complex and often very different mechanisms for each disease. Therefore, loss of biodiversity may increase or decrease disease transmission, depending on the ecology of humans, pathogens and vectors (Myers et al., 2013).

Simply put, biodiversity can be both good and bad for people's health: draining a wetland may decrease the likelihood of disease transmission, but many other ecosystem benefits would also be lost. Since any human-caused change to biodiversity has both benefits and costs to human health, the role of research is to elucidate these benefits and costs and to advise stakeholders and decision-makers on solutions which maximize benefits and minimize costs.

The trade-off between development and conservation also needs to be ameliorated. Since higher-income countries generally have better human health outcomes, economic development, even on the back of ecosystem destruction, will often enhance health outcomes in the short-term (Hough, 2014). However, it is becoming increasingly clear that much economic development is not sustainable in the long-term, and that better compromises between the need for economic development, ecosystem management and human health outcomes must be found. Therefore, governance, policies and practices must take into account ecosystem approaches to health.

The implementation of these ideas and principles into the international agenda began with the Stockholm Conference (for all definitions and abbreviations, see Table S1). The resulting Stockholm Declaration stated people's fundamental right to live "in an environment of a quality that permits a life of dignity and well-being," which is thus the first international recognition of the health dimension of environmental issues. Since then, the necessity of an integrated approach to development compatible with the need to protect the environment for the benefit of human health has been repeatedly reaffirmed (Lajaunie et al., 2015).

In 2004, the World Conservation Society proposed the One World – One Health approach which originally was a list of 12 recommendations to establish a more holistic approach to prevent epidemic or epizootic diseases while maintaining ecosystem integrity for the benefit of humans and their domesticated animals (WCS, 2016) (Table S1).

Over the last few decades, Southeast Asia (SEA) has been a hotspot of economic growth. It experienced tremendous population growth (33% increase to 600 million from 1980 to 2012), doubled its gross domestic product (GDP) from 4580 to 9776 million USD between 1990 and 2013, increased livestock populations manifold, and increased the value of its agricultural exports about 10 times (FAO, 2015). The urban population doubled between 1970 and 2010 to reach 42% (Jones, 2013), and regional roads and airlines greatly increased regional connectivity (Coker et al., 2011).

SEA is also a biodiversity hotspot (Orme et al., 2005). However, the usual suspects of habitat loss, overexploitation of species, pollution (including climate change) and invasive species are taking their toll on SEA's biodiversity and ecosystems which are shrinking dramatically (Koh and Sodhi, 2010; Wilcove et al., 2013).

SEA is also a cultural and linguistic hotspot (Harmon and Loh, 2010; Moseley, 2010), and biodiversity loss often combines with cultural and linguistic diversity loss (Gorenflo et al., 2012) because these three diversities are under threat by some of the same forces (Maffi, 2005).

Finally, SEA is a hotspot for established and emerging human diseases (Coker et al., 2011; Jones et al., 2008; Morand et al., 2014; Box 1). Some of the most important emerging infectious diseases (EIDs) of the past two decades have emerged in SEA, e.g., avian influenza, Nipah virus, and SARS.

Despite these worrying trends, there is a growing research effort and an increasing realization by some of SEA's stakeholders and decision-makers that research can guide better policies which benefit both biodiversity and people; e.g., the practice of the Health Impact Assessment (HIA) was introduced by the Thailand Constitution of 2007, and universities are now offering HIA courses. The Thai National Health Act considers health issues within their complex social, cultural, and environmental frameworks in accordance with the holistic definition of health defined as a state of well-being. The Community HIA is of particular interest as it is considered a "joint learning process in the society" where active citizen involvement is considered helpful to identify the various dimensions of health. The communities may invite researchers who can provide evidence of the links between policies and health impacts; e.g., a quarry mining HIA in Mae Song Province led by a graduate student pushed the public decision-making process in favor of local people's health.

As a consequence of Thailand's constitutional HIA, the ASEAN member states commended Thailand's leadership at the regional

Box 1

Habitat loss, land-use change and infectious disease emergence in SEA.

Habitat loss due to land-use changes has dramatic effects on biodiversity and ecosystem services, but also on disease transmission, spatio-temporal trends of epidemics and emerging diseases. In SEA, forest cover has decreased by about 20% from 1990 to 2012 (FAO, 2015; Stibig et al., 2014), and the conversion of forest for agricultural and other uses has considerably impacted the biodiversity (Sodhi et al., 2004; Wilcove et al., 2013; Fig. 1). Therefore, SEA is a hotspot of threatened biodiversity (Schipper et al., 2008), but also of emerging infectious diseases (Coker et al., 2011). Therefore, biodiversity loss and habitat changes may be the very drivers of disease emergence (for possible mechanisms, see main text). Consequently, Morand et al. (2014) investigated correlations between biodiversity at risk and infectious disease emergence among countries in the Asia-Pacific region. First, they showed that the number of reported infectious disease outbreaks has increased exponentially over the last decades (Fig. 2). Second, after taking into account each country's climate, geography, and socio-economics, there remained a positive correlation between the number of infectious diseases and the total number of mammals and bird species. Third, the number of outbreaks of zoonotic diseases was positively correlated with the number of threatened mammal and bird species, while the number of outbreaks of vector-borne diseases and forest cover were negatively correlated. Hence, elements of biodiversity were good predictors of the burden of parasites and pathogens in each country (see also Dunn et al., 2010), while biodiversity at risk was a good predictor of outbreaks (including emerging infectious diseases).

level and a promoter of the One Health approach. Furthermore, the need for evidence-based policies was affirmed in the Asia Pacific strategy to combat emerging diseases (WHO, 2005), and such evidence is generally provided by local communities and researchers (Lajaunie and Morand, 2015). Regarding biodiversity, the ASEAN Center for Biodiversity is an intergovernmental organization which aims to promote biodiversity conservation and management at the regional level (ACB, 2013b).

To further support these positive developments, a conference entitled "Biodiversity and Health in Southeast Asia" was held on 17–18 November 2014 to discuss the importance of biodiversity for human health and well-being in SEA's rapidly changing environment, to provide a platform for the sharing of scientific and technical expertise, and to prioritize future research. The conference was held at the University of Health Sciences, Phnom Penh, and brought together scientists, government officials and non-governmental organizations (NGOs). Below,

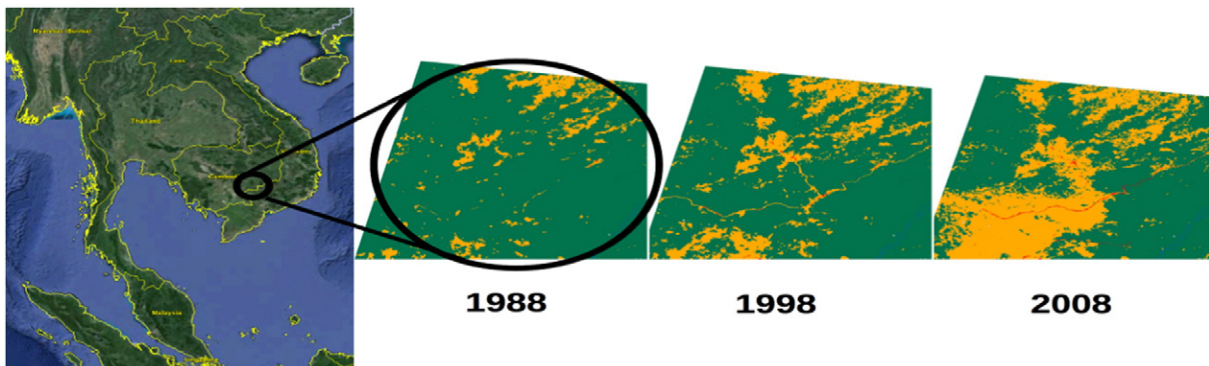


Fig. 1. Land use change in Mondolkiri province, Cambodia, as an example of the rapid deforestation rates within most of SEA. Sources and methods are given in Bordes et al. (2015) and Morand et al. (2015a). Colors refer to: forested areas (green), agricultural areas (orange), built-up areas (red).

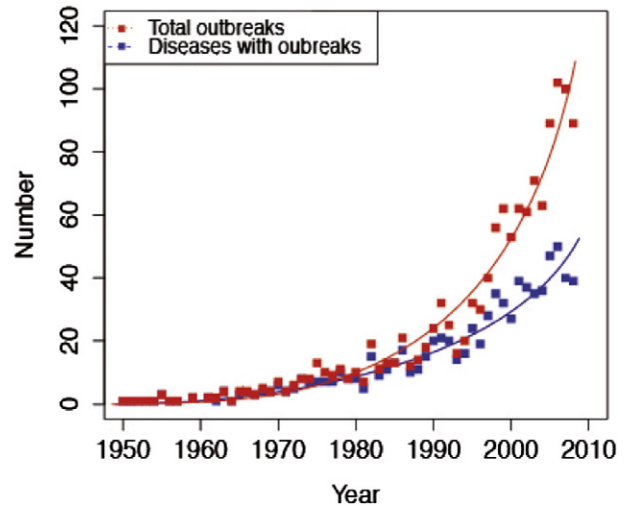


Fig. 2. Increase in total outbreaks and total number of infectious diseases causing outbreaks since 1950 in Asia-Pacific countries. Sources and methods are given in Morand et al. (2014).

we present (1) a review of the main issues presented during the conference, but also (2) the recommendations of the ensuing roundtable discussions. While we do not intend to publish a systematic review here, we review many current issues related to biodiversity and health to set the scene for the science–policy recommendations which came out of this conference. This paper should therefore be seen as a snapshot of the most important health- and biodiversity-related issues affecting SEA today as they were presented and discussed during and after the conference.

2. Materials and methods

This review is based solely on the work of the authors presented at the conference and the discussions between them which took place during and after the conference. The first author also searched Google, Google Scholar and the Web of Science for additional relevant publications.

3. Results and discussion

3.1. Review of main issues

The ecosystem approach is a framework to understand the various interactions between different ecosystems services and their role in the environment, of which humans are a part of (CBD, 2004). Therefore,

ecosystem functions should be taken into account for a sustainable use of natural resources. To conceptualize the use of ecosystem functions by humans in the form of 'services rendered,' the *Millennium Ecosystem Assessment* (2005) divided ecosystem services into provisioning, cultural, regulating, and supporting services. We present the first part of our review along these four categories (we emphasize that this is not a comprehensive review of ecosystem services in SEA, but a review of the conference's main themes). However, the conference emphasized another ecosystem service, namely that ecosystems often serve as 'sentinels' in the sense that potentially harmful developments, e.g., the accumulation of persistent pollutants, become first apparent in ecosystem components (Doherty, 2013). After all, one of the books which kick-started the global environmental movement, Rachel Carson's *Silent Spring*, was triggered by the realization that the accumulation of pesticides in wildlife highlighted potentially harmful effects for human health.

3.2. Ecosystems as sentinels for human health consequences

The sentinel function was apparent in four of the conference's predominant themes.

3.2.1. Contamination with persistent pollutants

The contamination of biotic or abiotic ecosystem components with persistent pollutants can be a warning sign of harmful current and future impacts on human health. With SEA's economic development, environmental pollution has become a growing problem, particularly for the receiving water bodies. While not all countries are facing water shortages, all have serious problems with degraded water quality. Most of the small and medium industries discharge untreated wastewaters into nearby water bodies, while landfill leachates from poorly designed landfill sites contaminate ground water.

The concentration of heavy metals, pesticides and persistent organic pollutants in water causes the bioaccumulation and biomagnification of these compounds in aquatic food chains, with eventual contamination of humans via drinking water or eating aquatic animals. In SEA, most agricultural pesticides are excessively used because of lack of information and regulation. Consequently, high levels of polybrominated diphenyl ethers and DDT were detected in mussel samples from several SEA countries (Ramu et al., 2007). High concentrations of persistent organochlorines were found in 27 species of freshwater and marine fish collected in Cambodia, with DDT being the most predominant one (Monirith et al., 1999; Minh et al., 2006). High concentrations of arsenic in drinking water have also emerged as a major public health problem in several SEA countries (Mukherjee et al., 2006). In Cambodia, measurements of mercury concentrations in the muscle tissues of marine and freshwater fish were so high that fish are probably the main mercury source for people (Agusa et al., 2005).

Cambodia's Tonle Sap is SEA's largest freshwater body, with fishing the most important commercial activity. Few studies have been conducted to detect the organochloride pesticide (OCP) contamination of Tonle Sap's fish. Hence, the University of Health Sciences partnered by the Tonle Sap Authority and the National University of Singapore examined fish and found OCP concentration varied between 0 and 0.949 ng/g. DDE is the most commonly used pesticide in Cambodia, and represented the OCP with the highest concentration, followed by methoxychlor at 0.178 ng/g, tetrachlorobenzene at 0.033 ng/g, and hexachlorobenzene at 0.030 ng/g, which represents some of the first evidence that the Tonle Sap ecosystem is affected by poor OCP use.

3.2.2. Evolution of antimicrobial resistance

The evolution of antimicrobial resistance (AMR) is fast becoming a global health emergency, with alarm bells ringing within the scientific (O'Neill, 2014) and global health community (WHO, 2011, 2014). In SEA, the combination of excessive and often unregulated use of

antimicrobials in animal production and the specific environmental conditions within and around production systems may very well lead to the creation of genuine 'hotspots' of AMR gene transfer between different bacterial species, which may then lead to increased AMR in human pathogens, even nosocomial ones (Box 2). If more research is not funded, and research findings do not translate into effective legislation and enforcement, there certainly will almost certainly be major human health consequences in the future.

3.2.3. Evolution of pesticide resistance

Even if new tools and approaches are currently developed against vector-borne diseases (VBDs) (McGraw and O'Neill, 2013), chemicals are still the key weapons against mosquitoes (Maharaj, 2011). Despite decades-old recommendations for careful use, the scaling up of vector control interventions is clearly associated with the spread of insecticide-resistant alleles (Nkya et al., 2013) as is the use of the same or reformulated insecticides in intensive agriculture (Overgaard, 2006).

In several species of *Anopheles* (including the three major vectors in the region, *An. dirus s.l.*, *An. maculatus s.l.*, and *An. minimus s.l.*), DDT resistance has been detected in the last 30 years (Van Bortel et al., 2008), and resistance against permethrin was suggested in a population of *An. minimus s.l.* from Northern Thailand (Chareonviriyahpap et al., 1999). To detect and manage emerging resistance, regional cooperation within the Mekong region is crucial because malaria transmission is mostly concentrated in forested areas along the countries' borders (Van Bortel et al., 2008).

3.2.4. Established and potentially emerging zoonotic diseases

Despite increasing control measures, numerous parasitic and infectious diseases are emerging, re-emerging or causing recurrent outbreaks in SEA (Coker et al., 2011; Conlan et al., 2011). The overall richness of infectious diseases is positively correlated with the richness of birds and mammals, while the number of zoonotic disease outbreaks is positively correlated with the number of threatened mammal and bird species; furthermore, the number of VBD outbreaks is negatively correlated with forest cover (Morand et al., 2014). Biodiversity is thus a source of pathogens, but the loss of biodiversity or its regulation seems to be associated with an increase in zoonotic and VBD outbreaks. For the emergence of zoonotic diseases in SEA, the importance of bat-borne diseases (Gay et al., 2014) and particularly rodent-borne diseases (Morand et al., 2015b) is very high.

SEA has experienced rapid changes in animal production, processing and distribution networks for animal products, and SEA's consumers have changed their food consumption. The net impact of these changes on the emergence and maintenance of known zoonotic diseases is mixed. On the one hand, intensive production systems are likely to facilitate the emergence and dissemination of pathogens with a direct life cycle; e.g., the odds of H5N1 outbreaks in Thailand were higher in large-scale commercial poultry operations than in backyard flocks (Graham et al., 2008). On the other hand, confinement of animals in environmentally-controlled environments restricts contacts with intermediate hosts and has led to the almost complete eradication of parasites common in animals reared in free-range conditions (Davies, 2011). However, it has also been suggested that intensive farming systems may select for early-transmitted, and hence more virulent, parasites (Mennerat et al., 2010).

Likewise, changes involving rapid urbanization are likely to entail increased susceptibility to classical bacterial zoonotic pathogens (nontyphoidal *Salmonella*, *Campylobacter*, etc.) (Carrique-Mas and Bryant, 2013), but other diseases may decrease in urban settings. After reviewing the available evidence on foodborne zoonoses in Vietnam, Carrique-Mas and Bryant (2013) recommended that (1) several risks for disease transmission need to be addressed, and (2) much more monitoring and research is required.

Box 2

The development and spread of AMR among humans, domestic animals and wildlife in SEA.

Over recent decades, there has been a consistent and global trend towards intensification of animal production systems which utilize animals of genetically improved breeds in narrowly confined spaces, new formulations of animal feed and an increasing reliance on antimicrobials (Silbergeld et al., 2008). Recently, this trend towards intensification has been occurring mainly in developing countries as a response to economic development and increased demand for animal protein. In the Mekong region (Cambodia, Laos, Thailand, Vietnam), the per capita consumption of animal protein has increased by 45% from 36 to 52 kg between 1990 and 2000. Projections for Thailand and Vietnam indicate a further 62–73% increase between 2000 and 2015 (Knips, 2004). Furthermore, countries such as Thailand and Vietnam have become major global exporters of poultry and fish, respectively.

Although the use of antimicrobials in animal production has brought undisputed benefits (e.g., control of diseases, increases in productivity) (Hao et al., 2014), there is mounting evidence of the negative impact of farm-associated AMR on human health through animal contact or consumption of animal food (Marshall and Levy, 2011). Data on antimicrobial use in animal production in SEA are lacking, but estimates from other countries indicate that they are likely to far exceed the quantities used in human medicine (Maron et al., 2013). Van Boeckel et al. (2015) forecasted global consumption of antimicrobials in animal production and predicted an increase ranging from 157% to 205% for Indonesia, Myanmar, and Vietnam. In Vietnam's Mekong Delta, chicken farmers used 5–7 times more antimicrobials than their counterparts in Europe, with 85% for prophylactic use only, and most commercial feed rations were medicated (Carrique-Mas et al., 2014). Furthermore, high levels of antimicrobial use were reported in aquaculture production in Thailand and Vietnam (Pham et al., 2015a; Rico et al., 2013).

In this region, high levels of AMR among foodborne zoonotic bacteria including non-typhoidal *Salmonella* and *Campylobacter* spp. were documented (FAO, 2014; Richter et al., 2015). However, the impacts of AMR on animal and human health go well beyond the risks of infection with specific resistant zoonotic bacteria. Recently, scientists have begun to elucidate the interactions between antimicrobial use, AMR, the environment, and the resulting impacts on health. The study of AMR is complicated by the potentially high number of transmission routes of AMR bacteria and antimicrobial resistant genes (ARG). These relationships are likely to be dynamic and highly dependent on the specific circumstances (level of antimicrobial usage, reservoirs, farming practices, environmental legislation, etc.) of each location (Fig. 3).

For example, farm waste typically contains a mixture of antimicrobials, AMR resistant bacteria and genes and thus farming areas become genuine 'hotspots' of AMR gene transfer between different bacterial species (da Costa et al., 2013; Wellington et al., 2013). In addition, there are serious concerns about the impact that AMR genes and bacteria generated on farms may have on environmental bacteria since the latter represent an immense reservoir pool of resistance genes (Martinez, 2009). One worrying development is the increased incidence and resistance among nosocomial infections caused by environmental organisms (such as *Acinetobacter* spp. and *Pseudomonas aeruginosa*) in SEA (Punpanich et al., 2012; Tada et al., 2013). Although most of multi-drug or pan-resistant infections are known to have originated in hospitals, there is also increasing evidence of genetic links to non-hospital sources (Eveillard et al., 2013).

In SEA, newly built large and intensive animal production systems coexist with a higher number of smaller mixed systems, including integrated aquaculture-livestock systems (Prein, 2002). These production units are generally characterized by poor biocontainment and deficient waste treatment systems and are subject to only lax environmental enforcement. These conditions result in high vulnerability of environmental biomes to the development of AMR. Because of their use in aquaculture, high levels of antimicrobial drug residue were found in water systems in SEA (Rico et al., 2013; Suzuki and Hoa, 2012). Similarly, the incidence of AMR on farms was linked to increasing levels of AMR in commensal bacteria taken from wild animals living in or near these farms (Nhung et al., 2015a). Finally, pollution with heavy metals and other environmental stressors such as biocides can all contribute to AMR via mechanisms of cross-resistance (Davin-Regli and Pagès, 2012; Nhung et al., 2015b; Seiler and Berendonk, 2012). All these conditions are met in SEA and may therefore further exacerbate the situation, but specific studies investigating these problems are generally lacking in SEA.

To conclude: although our understanding on the interactions between the environment and farming systems at the microbiological level is insufficient, we already know that current farming practices are having a negative impact on animal and human health, particularly by exacerbating AMR. More research efforts are needed to document these risks by carrying out biological risk assessments for antimicrobial resistant bacteria in the environment as well as implementing standardized surveillance systems for AMR in the environment, as was recently proposed by Berendonk et al. (2015). In addition, producers in SEA need to be provided with the tools and knowledge to carry out more environmentally-friendly and health-supporting farming practices. Using the precautionary principle, research findings must be translated into more stringent legislation and effective enforcement.

3.3. Provisioning ecosystem services

The contributions of provisioning ecosystem services to SEA's countries are manifold (Box 3) but the conference focused especially on food and medicinal resources because many rural and indigenous communities remain directly dependent on these locally obtained resources.

The Tonle Sap Lake ecosystem is an outstanding example of the conflicts between economic development and maintaining ecosystem functions. The Tonle Sap Lake is one of the largest indiscriminate fisheries in the world, generating about 2.5 million tons of fish annually and accounting for nearly two-thirds of the protein consumed by the region's 14 million people (Baran et al., 2007). The amount of caught fish has actually increased in recent decades because of an increasing number of fishermen as well as modern and sometimes illegal catch methods. However, the higher catches have come at a price in that there has been a shift from larger-sized fish of high market value towards more smaller-sized fish which do not have a high market value (Baran and

Myschowoda, 2008; Valbo-Jørgensen et al., 2009). This overfishing has a direct impact on biodiversity and livelihoods: changes in fish communities led to drastic disturbances in the food chain and declines in migratory birds, including endangered ones (Baran and Myschowoda, 2008) but also to the threat of aggravated poverty among the local fishermen because alternative incomes are rare. Furthermore, water pollution threatens local drinking water and has caused the explosive increase of the harmful invasive water hyacinth.

Traditional medicine is a source of new drug discovery (Fabricant and Farnsworth, 2001) but also continues to play an important role in some health care systems, especially in developing countries, as it is attractive to poor people because of its greater accessibility, lower costs and perceived safety (WHO, 2012). SEA is a hotspot of both biological and cultural diversity, and these two types of diversity are related to each other (Box 4). Therefore, SEA is also a hotspot of medical genetic resources and indigenous medical knowledge, and all of these are threatened; e.g., Tualoang honey is collected for its medicinal properties

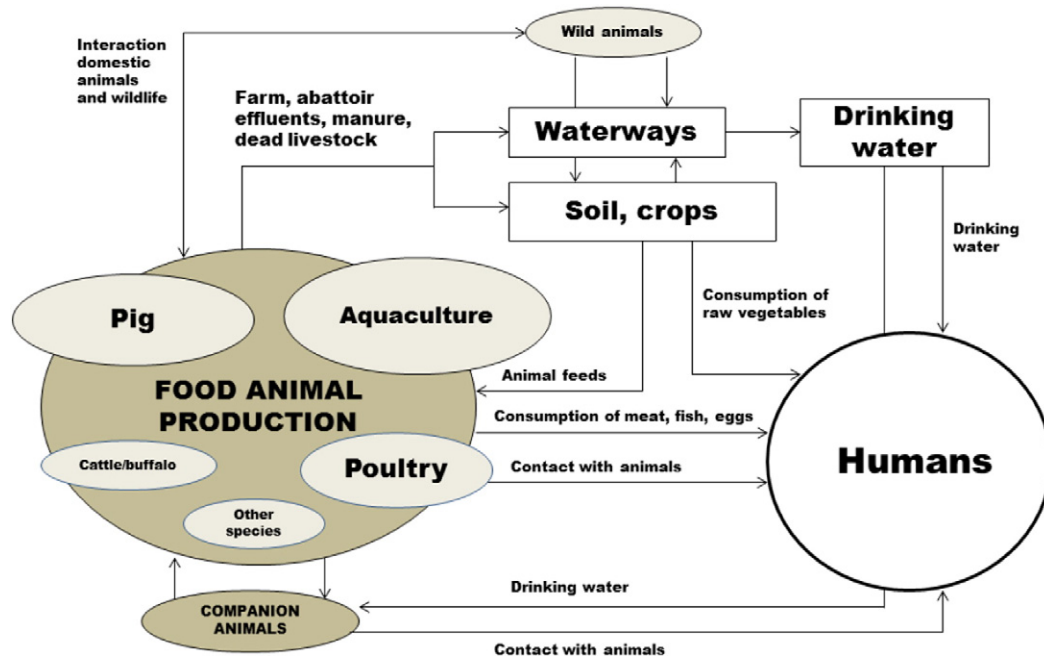


Fig. 3. Non-human sources of antimicrobial resistant genes (ARG) and antimicrobial resistant (AMR) bacteria entering humans and the potential flow of ARG and AMR bacteria between non-human reservoirs and humans (modified from Prescott and Baggot, 1988). Square boxes indicate non-animated reservoirs, and oval boxes indicate animated (animal) reservoirs, with their size being proportional to the strength of their overall contribution as a source to human infection in SEA (as judged by the authors).

in Malaysia (Stolton and Dudley, 2010b); indigenous people living in northern Thailand, use many types of plants for medicinal benefits (Bélair et al., 2010); and indigenous people living in eastern Cambodia use *Solanum sakhani* and *Stephania rotunda* to treat malaria and fevers

(Chassagne and Hul, 2014) and other medicinal plants to help with and reduce medical costs of treating colds, diarrhea, dysentery, and stomach aches (Kham, 2004; Laval et al., 2011). Some of these plants are already being tested for active compounds (see references in Box

Box 3

Ecosystem services related to health documented in the SEA scientific literature.

The Millennium Ecosystem Assessment (2005) divided ecosystem services into provisioning, cultural, regulating, and supporting services. Besides the direct or indirect economic benefits, biodiversity also has an intrinsic value because it enriches life by providing educational, intellectual and recreational opportunities, esthetic and spiritual enjoyment, and a sense of identity (Walther et al., 2011). The presence of healthy and diverse ecosystems may also be considered an essential, fundamental and non-negotiable right to a good life equivalent to human rights which cannot be traded for a monetary value. Conservation and sustainable use of biodiversity thus become ethical issues of good moral conduct towards other life forms as well as towards fellow human beings and cultures. A moral extension of this framework is that biodiversity also has an option value by safeguarding ecosystem services, especially as a legacy to future generations and as an insurance against future challenges and risks (Walther et al., 2011). Such future ecosystem benefits, even the economic ones, are often not apparent to us and thus cannot be quantified economically.

In Table 1, we reviewed all peer-reviewed publications about ecosystem services in SEA published in the last 17 years which we found by searching Google Scholar and Web of Science for related keywords, such as “ecosystem service” and “Southeast Asia.” Naturally, this is not a comprehensive list of all ecosystem services relevant within SEA, as we have only listed those ecosystem services mentioned in the cited references.

All the ecosystem services listed in Table 1 are somehow related to human health and well-being, as the MA (2005) clearly outlined (see also Hough, 2014; Myers et al., 2013; Sandifer et al., 2015). However, some of these are more directly relevant to human health, such as sentinel services, medicinal and genetic resources, disease regulation, and protection against disasters, such as floods, landslides, and storm surges, e.g., tsunamis. Some are of very local relevance, e.g., specific cultural and spiritual practices, while others are of regional or even global relevance, e.g., carbon storage. Our summary also suggests where more research is needed: disease regulation is an obvious one, but genetic resources, social cohesion, or protection against landslides should also receive more attention.

A few studies asked people directly about health benefits of ecosystem services: Abram et al. (2014) found that the direct health benefits which people received from intact forests, such as medicinal plants, were actually considered the most important benefits, with 67% of respondents declaring that forests are ‘very important’ to their health. Likewise, Meijaard et al. (2013) found that 68% and 25% of respondents stated that forests were ‘very important’ and ‘quite important’ for health, respectively, with 65% of respondents naming one or more health benefits. Interestingly, direct health benefits (e.g., medicines) were perceived strongly in forested areas while environmental (and thus more indirect) health benefits (e.g., clean air and water) were perceived strongly in deforested areas where these benefits were disappearing.

As a consequence of the growing realization of the value of ecosystem services, there are growing efforts in SEA to map ecosystem services (e.g., Sumarga et al., 2015) and to pay for them (e.g., Berry et al., 2010; Jourdain et al., 2014; Kolinjivadi and Sunderland, 2012; Leimona et al., 2015; McElwee, 2012; Milne and Adams, 2012; Pham et al., 2015b; Suhardiman et al., 2013; Thompson et al., 2014; van Noordwijk and Leimona, 2010; Wilcove et al., 2013). Such incentives to maintain ecosystem services must be quickly implemented and effectively supervised across SEA to slow the current unsustainable destruction of biodiversity and ecosystems (main text).

Table 1

Summary of ecosystem services document in the scientific literature for SEA. Numbers in the citations column refer to references listed below the table.

Type of ecosystem service	Citations
Sentinels for pollution or evolution of antimicrobial and pesticide resistance	Main text, Box 2
Provisioning services	
Food, both cultivated and wild	Main text, 1, 3, 4, 11, 15, 16, 22, 25, 27, 28, 32, 33, 34, 36, 39, 40, 43
Timber, fuelwood, fibers	1, 3, 15, 22, 25, 27, 28, 33, 34, 39, 40, 43, 44, 46
Wildlife for trade	16, 28, 30, 35
Natural, traditional and new medicines	Main text, Box 4 , 1, 5, 16, 22, 25, 27, 33, 34, 49
Genetic resources	27, 37, 43
Cultural services	
Education and research	Main text, Boxes 5 and 7 , 16, 23, 43
Esthetic, cultural identity, religious and spiritual practices	1, 3, 16, 23, 25, 27, 28, 33, 34, 40, 43
Social cohesion	1, 25, 27
Tourism, ecotourism, recreation	1, 3, 10, 18, 23, 27, 40, 42, 43
Regulating and supporting ecosystem services	
Disease regulation	Main text, Box 1 , 6
Protection against landslides	9, 38, 40
Pollination, seed dispersal	7, 17, 19, 27, 28, 40
Mangroves: Flood regulation, storm protection, erosion control, water purification, carbon storage, nutrient cycling, primary production, etc.	3, 8, 43, 45
Watersheds: Flood regulation, erosion control, drought mitigation, soil formation	23, 24, 31, 47
Forests and peatlands: Flood regulation, erosion control, air and water purification, carbon storage, climate stability, fire mitigation, soil formation, primary production, etc.	1, 2, 12, 13, 15, 20, 23, 26, 28, 29, 39, 41, 42, 40, 48
Agroforestry and home gardens: Pest control, erosion control, water purification, carbon storage, climate regulation, soil formation, nutrient cycling, etc.	21, 27, 28, 33, 38, 39
Rice-bird and rice-fish farms: Pest control, soil formation, nutrient cycling	14, 32, 39

Citation identifiers: [1] Abram et al., 2014; [2] Berry et al., 2010; [3] Brander et al., 2012; [4] Brooks et al., 2010; [5] Chan et al., 2008; [6] Chua, 2003; [7] Clough et al., 2009; [8] Dahdouh-Guebas et al., 2005; [9] De Graff et al., 2012; [10] Dressler et al., 2013; [11] Dugan et al., 2010; [12] Estoque and Murayama, 2013; [13] Glover and Jessup, 2006; [14] Guttman, 1999; [15] Hansen and Top, 2006; [16] Hocking and Babbitt, 2014; [17] Hoehn et al., 2008; [18] Hummel et al., 2013; [19] Klein et al., 2003; [20] Labrière et al., 2015; [21] Maas et al., 2013; [22] McElwee, 2009; [23] McKay, 2013; [24] McKay et al., 2014; [25] Meijaard et al., 2013; [26] Miettinen and Liew, 2010; [27] Mohri et al., 2013; [28] Muhamad et al., 2014; [29] Naidoo et al., 2009; [30] Nijman, 2010; [31] Pattanayak, 2004; [32] Permollet et al., 2015; [33] Pfund et al., 2011; [34] Putri et al., 2014; [35] Rao et al., 2010; [36] Rowley et al., 2008; [37] Schmidt et al., 2008; [38] Sidle et al., 2006; [39] Simelton and Dam, 2014; [40] Sodhi et al., 2010a; [41] Sodhi et al., 2010b; [42] Sumarga et al., 2015; [43] Tengberg et al., 2012; [44] Thephavanh et al., 2011; [45] Thompson et al., 2014; [46] Tola and McKenney, 2003; [47] Valentin et al., 2008; [48] Wösten et al., 2008; [49] Yeo and Tham, 2012.

3). To preserve this knowledge, the Cambodian Traditional Healers Association in collaboration with the National Center of Traditional Medicine at the Ministry of Health has established botanical gardens with medicinal plants at public schools which teach students and adults how to cultivate and sell herbal products.

3.4. Cultural ecosystem services

One important cultural ecosystem service is research ([Box 3](#)). Since SEA is a biodiversity hotspot, research about how this biodiversity was generated and spread in space and time is of both fundamental interest and also benefits, in particular cases, our understanding of diseases.

One such case is the ecology and evolution of *Anopheles* mosquitoes because information on mosquito diversity helps to understand and control the transmission of mosquito-borne diseases ([Sinka et al., 2012; Box 5](#)). A large amount of SEA's biodiversity remains to be discovered ([Giam et al., 2010](#)) which includes actual and potential reservoirs and vectors of human and zoonotic pathogens. It is therefore important to determine the evolutionary processes that have generated and shaped the distribution of biodiversity in taxa of conservation concern which would aid long-term conservation strategies ([Woodruff, 2010](#)). In turn, improved knowledge of biodiversity in SEA can inform our understanding of the risks of zoonotic disease emergence ([Weaver and Reisen, 2010](#)).

Besides long-term evolution, evolution can also happen in relatively short, ecological time scales, often in response to drastic man-made changes ([Carroll et al., 2007; Hendry et al., 2010](#)). On the one hand, taxa of conservation concern may not be able to adapt quickly enough to such rapid changes. On the other hand, disease agents typically have a great capacity to evolve, often with detrimental effects to human health; e.g., *Aedes aegypti* has evolved insecticide resistance throughout SEA ([Vontas et al., 2012](#)). Evolutionary studies, while often considered to be primarily of cultural value, are in fact intrinsic to the effective conservation of biodiversity and to the control of vector-borne disease.

3.5. Regulating and supporting ecosystem services

Although the regulating and supporting ecosystem services are the most fundamental and arguably the most important services, they are also the least appreciated and therefore the least documented ones. Hence, laws, policies, and the resulting economic development pay little attention to them, with often detrimental and sometimes catastrophic consequences (see references in [Box 3](#)).

For example, much of SEA is quite mountainous, and watershed protection should thus be of paramount importance. However, the various ecosystem benefits of intact forests, especially erosion and flood control ([Box 3](#)), are not accounted against the economic gain of forest conversion. Forests are consequently being degraded or lost, with catastrophic consequences for downstream communities which likely had no benefit from the forests' use ([Dasgupta, 2010](#)). Forests are also essential for climate change mitigation and adaptation at local, regional and global scales. However, such ecosystem services are simply not adequately accounted for in purely economic cost-benefit analyses which then lead to the almost inevitable destruction of the ecosystem for immediate economic gain (e.g., [Fisher et al., 2011; Limberg et al., 2009; Ruslandi et al., 2011](#)) unless payments for ecosystems services are becoming more widespread ([Box 3](#)).

Another regulating service is disease regulation, but it is also one of the most difficult to assess because loss of biodiversity may increase or decrease disease transmission to humans, but also animals and plants ([Grace et al., 2011; Nguyen-Viet et al., 2015](#)). Factors which contribute to an increase in the rate of emergence or re-emergence of infectious diseases are: intensified human encroachment on natural ecosystems, especially along new roads and logging activities; reductions or changes in biodiversity (e.g., increase of breeding sites or decrease of natural predators of disease vectors); increased long-distance trade in wild animal species; and human-induced genetic changes of disease vectors or pathogens (e.g., antibiotic or pesticide resistance) ([Corvalan et al., 2005](#)). All of these factors are currently increasing in SEA, but with almost no studies investigating them.

Box 4

Biodiversity, cultural diversity and health in SEA.

Morand et al. (2014) showed that there were correlations between elements of biodiversity and measures of pathogen burden among SEA countries (Box 2). We took these data and correlated them with a measure for cultural diversity, namely the number of recognized languages (Ethnologue, 2016). As shown in Morand et al. (2014), bird and mammal richness of each country correlated positively with pathogen richness in a linear regression ($n = 10$, std. coeff. = 0.71, $r^2 = 0.51$, $p = 0.02$). Moreover, the number of languages in each country also correlated positively with bird and mammal richness (std. coeff. = 0.89, $r^2 = 0.80$, $p = 0.0005$) and pathogen richness (std. coeff. = 0.59, $r^2 = 0.34$, $p = 0.08$; Fig. 4). However, the former correlation disappeared if an obvious outlier (Indonesia) was removed (std. coeff. = 0.49, $r^2 = 0.24$, $p = 0.19$). Nevertheless, these two positive albeit weak relationships demonstrate that there are possible linkages between elements of biodiversity and cultural diversity in SEA (Gorenflo et al., 2012).

3.6. Recommendations of the roundtable discussions

We organized the conference's recommendations along five themes.

3.6.1. Ethical and legal considerations

The existence of healthy and diverse ecosystems is considered a prerequisite for a healthy life, and has been confirmed as a fundamental human right since the Stockholm Conference in 1972. Conservation and sustainable use of biodiversity thus become ethical issues which call for a good conduct towards other life forms and fellow human beings and cultures, far beyond any monetary considerations. Biodiversity also has an option value by safeguarding future ecosystem benefits.

Therefore, more discussion between researchers and stakeholders is needed about what ecosystem services should be enumerated in quantitative benefit–cost assessments, and what aspects of ecosystem and human health should be placed beyond such assessments because they should be considered non-negotiable human rights. For example, rich countries are already paying poor countries to take on some of the unhealthy consequences of their high-consumption lifestyles, e.g., by exporting contaminated waste or polluting industries. While such actions may be justified within an economic benefit–cost framework, they may not be justified in a human rights framework. Another example concerns watersheds: downstream communities or national governments could financially compensate upstream communities for watershed protection, and such funds could also be used to enhance sustainable development of upstream communities; or, governments could simply regulate watershed protection without financial compensation in order to protect human lives.

Currently, few constitutions, legal frameworks, or development plans in SEA take such concerns and conflicts into consideration, but we suggest a stronger commitment towards those issues in the future. Legal documents and guidelines are more advanced when it comes to the ethical implications of human health research and practice; e.g., National Ethics Committees for health research have been set up in almost every SEA country (Lajaunie et al., 2014). These ethical guidelines should serve as blueprints for advancing the protection of biodiversity for human health and well-being and should integrate animal and environmental health.

Currently, the legal protection of the environment, biodiversity and ecosystems is still applied in a multi-scale way (i.e., at the global, regional and national levels). For example, seven biodiversity-related international conventions constitute an international framework to protect biodiversity (Table S1), but the nation states maintain sole rights over their own biological resources; it is thus the states' responsibility to implement these international conventions into their own judicial systems. While many constitutions in SEA acknowledge the necessity to integrate environmental concerns to achieve sustainable development, crucial elements are still lacking, such as the political will to implement the conventions, and effective law enforcement which depends on a

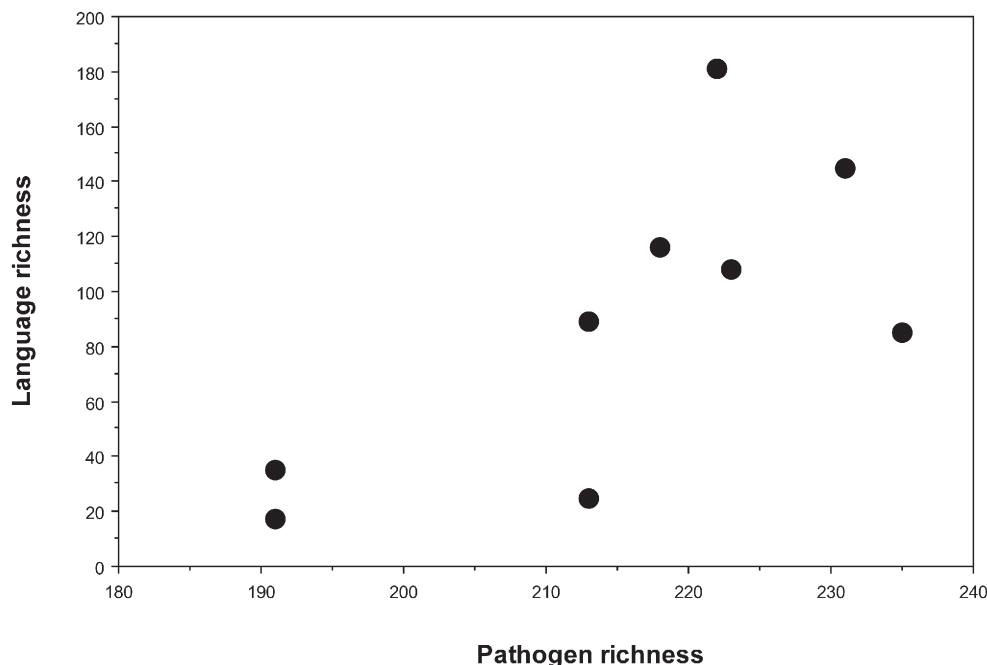


Fig. 4. Correlation between pathogen richness and language richness of 10 SEA countries (see text for details).

Box 5

The role of diversity and evolution in the transmission of mosquito-borne diseases.

Mosquito-borne diseases, such as chikungunya, dengue, malaria, and Japanese encephalitis virus, are widespread in SEA and, despite some success, their effective control remains elusive (Hotez et al., 2015; WHO, 2015). One factor in the difficulty to control malaria is the exceptional diversity of *Anopheles* vector species that occur in SEA (Sinka et al., 2012) which result in complex malaria epidemiology and, consequently, a need for diverse control methods. The diversity of malaria vectors is due to the region's dynamic geological and environmental history and its wide range of ecological conditions (Lohman et al., 2011) which facilitate speciation due to dispersal and allopatric divergence (Morgan et al., 2010) and adaptation to diverse and novel environments (Morgan et al., 2009; Morgan et al., 2013; O'Loughlin et al., 2007). One consequence of historical environmental change is that many morphologically described species are in fact genetically distinct to the east and west of the Thai-Myanmar border due to divergence in allopatric forest refugia over the last few million years. The extent to which these genetic differences result in differences in vector biology and malaria epidemiology remains unknown. Further, although *Anopheles* species have been relatively well studied, there is little such information on other vector (or potential vector) mosquito taxa, such as *Aedes* and *Culex*.

Further vector adaptation and diversification is expected even on relatively short time scales in response to extensive anthropogenic environmental changes across SEA, typified by forest loss due to increased agriculture and urbanization. One such example may be the use of village wells instead of forests pools by *Anopheles baimaii* in Myanmar that has resulted in perennial malaria transmission (Htay-Aung et al., 1999). Environmental change is also changing the relative abundance of mosquito species in different habitats which can change vector-pathogen-vertebrate host interactions (Thongsripong et al., 2013), and these changing interactions can affect disease risk. For example, the emergence of monkey malaria in humans is due at least partly to human incursions into forests where they encounter infected mosquitoes (Ramasamy, 2014). In addition, changing vector-pathogen-vertebrate host interactions can increase future disease prevalence by providing opportunities for adaptation, e.g., the vector adapting to novel habitats and/or new vertebrate hosts, or the pathogen adapting to transmission into novel vectors and/or novel vertebrate hosts. Adaptation by mosquito vectors is facilitated by their large population sizes and potentially also chromosomal inversions (Ayala et al., 2014). The devastating effects of vector adaptation can be seen in the mosquito *Aedes aegypti* which transmits dengue throughout SEA. Originally breeding in tree holes in African forests and feeding on forest wildlife, this mosquito has become domesticated, breeding in artificial containers in and around houses and feeding on humans (McBride et al., 2014; Powell and Tabachnick, 2013).

Of the pathogens, those most capable of rapid adaptation are arthropod-borne viruses (arboviruses) due to the high mutation rate of their RNA genomes. Arboviruses are of growing concern worldwide as exemplified by the recent rapid pandemics of chikungunya and Zika (Musso et al., 2015; Weaver and Lecuit, 2015). It is likely that the recent Zika epidemic results from adaptation of the virus in the form of increased viral replication in humans (de Melo Freire et al., 2015). Similarly, the spread of chikungunya has also been facilitated by adaptation to a new mosquito vector, *Ae. albopictus*, which is widespread in SEA (Weaver and Forrester, 2015).

Studies to characterize the biodiversity of mosquito vectors and the pathogens they transmit, particularly arboviruses, are therefore more important than ever before. In particular, studies on genetic adaptation in disease agents and mosquito vectors, such as the capability of mosquitoes to adapt to new human-made environments, are essential if we want to be able to predict and combat disease risks (Sternberg and Thomas, 2014; Weetman and Clarkson, 2015). Scenarios of the emergence and outbreaks of diseases also need to consider the effects of climate change and LULCC. The use of ecosystem services for disease regulation (Box 3) also needs to be urgently investigated. In conclusion, evolutionary and ecological studies focusing on disease vectors and the pathogens they transmit are fundamental to the successful implementation of the One Health approach in SEA.

strong legal framework and trained and reliable officers. The conference recommended the strengthening of these crucial elements in order to achieve sustainable development.

3.6.2. Implementation of the One Health approach

Over the last decade, a global consensus among international governmental organizations has emerged that human and veterinary public health and environment sectors must work together to better manage health threats due to EIDs and VBDs. This new approach has been called 'One Health' (Binot and Morand, 2015; Calistri et al., 2013), and a closely related approach is called 'Ecohealth' (Grace et al., 2011; Nguyen-Viet et al., 2015). Its objective is to improve health through the prevention of risks which originate at the interface between humans, animals and their environments. One Health promotes multi-sectoral and interdisciplinary implementations of health and environmental issues (Box 6) and thus enhances collaborative risk management and improves the coordination between the policies of different sectors (Vandesmissen, 2014).

Since the environmental and social changes in SEA impact on disease emergence and burden, the conference heavily emphasized the early successes of the 'One Health' approach in tackling these problems and made recommendations to strengthen this approach across SEA. Institutional SEA actors must improve their capacity at bridging the health, environment and rural development sectors, given the increase in the movements and contact frequencies of animals, humans, and pathogens across the region.

About 60% of EIDs are zoonoses (Jones et al., 2008) which pose a serious threat, especially among the poorest communities (Janes et al., 2012). Beyond the need to improve collaboration between human and veterinary medicine stakeholders at different levels, it is also crucial to better understand environmental (host-pathogen-vector-environment interactions) and social processes (e.g., local practices, risk perception) which affect the burden of zoonotic diseases (Wilcox and Colwell, 2005).

Future research should focus on how public health is also impacted by risk exposure (e.g., contact with stagnant water, pesticide use) and livelihood strategies (e.g., agricultural intensification, urban migration). Since the agricultural and educational sectors remain key players to improve awareness among rural communities, the framework of health policies must urgently consider external drivers such as agricultural practices, environmental policies, market evolutions, and social relationships that influence health risks at the scale of a village. The implementation of the One Health approach should be facilitated through participatory approaches and mediating tools which enhance the collective decision making process among different stakeholders (Ruankaew et al., 2010).

Good management decisions rely on good data. Thus, the integration of multi-disciplinary data into analytical frameworks and models implies that stakeholders need to work together from the very beginning to co-design tools for the management of heterogeneous knowledge (e.g., "health GIS", interdisciplinary databases). The abilities of civil servants, researchers and field operators to conduct field work and to

Box 6

The international and ASEAN regional governance for health and biodiversity, with a focus on the “One Health” approach.

In 2006, the “One Health” approach was integrated into GLEWS. An international conference co-organized in Hanoi in 2010 by the European Union and the United States of America (IMCAPI, 2010) and in partnership with the ADB, FAO, OIE, UNICEF, WB, and WHO gathered ministers and seniors officials of more than 70 countries in order to respond practically to the need of a coordinated action to prepare for pandemics; this conference constituted another decisive step for the integration of the “One Health” approach. The participating states declared that the “country strategies should be aligned nationally and regionally to address the global ‘One Health’ challenges” (IMCAPI, 2010).

The implementation of the One Health approach implies to deeply understand the interconnections between ecological, social, veterinary and public health dynamics, and to call for capacity building in order to properly address health issues at the animal-human-environment interface. However, even though formally the IMCAPI Declaration insisted on the necessity to address issues at the animal-human-environment interface, its content focused on the human and animal health interactions. Thus, it did not practically consider how to take environmental issues into account into national strategies. Moreover, the IMCAPI conference did not convey any organization specialized in biodiversity or environmental issues to take part in the definition of regional and national strategies to combat infectious diseases.

In 2008, ASEAN created an ASEAN Secretariat Working Group for One Health to manage zoonotic crises but it only insisted on working on medical issues. Along the same line, in 2010, the ASEAN Ministers of Agriculture and Forestry committed to progress on the One Health approach and to “support existing collaborative frameworks on animal and public health governance at global, regional and national levels to address vulnerabilities associated with zoonotic diseases” (ASEAN MAF, 2010). In fact, even though the ASEAN acknowledges the necessity of the multi-scale aspect of the One Health approach, in reality, it focuses only on animal and human health and public health issues but does not even refer to the environment which is an essential component of the One Health framework.

Therefore, it has become an urgent necessity to improve the collaboration and communication between human and veterinary medicine stakeholders at different levels (civil servants, researchers, health workers, and members of international organizations) for a proper implementation of the One Health approach, and it is crucial to understand and take into account environmental processes. This approach should include the interactions between pathogens (hosts, environment and possibly vectors) and related social processes (risk perception, local practices, surveillance and control measures acceptable to the beneficiaries) in order to address the burden of zoonotic diseases (King, 2010; Wilcox and Colwell, 2005).

Furthermore, acknowledging the importance of the interactions between health, agriculture and environmental sectors raises many research questions linked to the implementation of these integrated approaches. Public health is also impacted by socioeconomic factors linked to livelihood strategies (urban migration, use of chemical inputs, agricultural intensification, exposure to mosquito bites, contact with stagnant water, etc.). Such drivers of human behavior are not sufficiently taken into consideration in the framework of the ‘One Health’ approach, and must be in order to understand risk exposure factors at the community level and to characterize social actors’ vulnerabilities.

Moreover, because of economic imperatives, health risks are often not considered as a priority by the rural communities. Therefore, agriculture and education sectors must become key players when addressing public health issues of rural communities (Benson, 2011). Another aim of the “One Health” approach in practice is to allow an intersectoral collaboration which associates the environmental, agricultural and health sectors and which goes beyond the traditional administrative division of sectors of political interventions. The One Health approach’s implementation at the local level could be facilitated through existing participatory approaches which is sometimes already integrated into the national legal framework, such as the Health Impact Assessment detailed in the Thai Constitution of 2007 and to be developed at the regional level (among ASEAN members) under the leadership of Thailand.

Local systems of collective natural resources management could be combined with the local public health systems of information to alert the public to improvements of the management of risks related to zoonotic diseases. This combination could help to provide the information needed to design appropriate policies able to respond clearly to the local health and environmental issues (Lajaunie and Morand, 2015). Along these lines, the ComAcross project (2014–2018) implemented by the CIRAD/GREASE network and funded by the European Union is developing an integrated One Health approach at the Human/Animal/Environment interfaces in Cambodia, Laos and Thailand. The project relies on participatory modeling applied to specific case studies in order to improve inter-sectoral coordination and combine the inputs of the diverse participants (Binot et al., 2015).

The strength of the One Health approach is to underline the intertwined links between animal health, human health and the environment and to call for a concerted action of various stakeholders. However, the One Health approach has unfortunately been mainly driven by the actors in human and animal health, or by the tenants of conservation, with little concrete consideration for the environmental context and environmental factors associated with zoonotic diseases (Della Rossa et al., 2015). Therefore, this environmental context should be examined at various scales, whether they are local, national or regional, to identify common or specific patterns of diseases. As Webster et al. (2016) emphasized, the One Health approach should clearly integrate the ecological and evolutionary interactions of zoonotic diseases. The understanding of disease ecology and its evolution is thus a pre-condition for the determination of appropriate policy responses to tackle the risks related to zoonotic diseases. Environmental, ecological and evolutionary research thus remains fundamental to resolve these human health risks.

motivate the communities at risk to participate in the monitoring work should be improved which could lead to a better understanding of zoonoses’ burdens, ecological patterns and cultural, political and socio-economic stakes.

However, it remains a considerable challenge to implement such multi-sectoral collaborations among agricultural, environmental and health sectors in the current national contexts because they usually remain characterized by sectorial political management: groups which should communicate remain in separate silos (Capps et al., 2015). The conference therefore recommended that FAO, UNEP and WHO facilitate the One Health approach in SEA by financially and logistically

supporting regular exchanges between scientists, government officials, and other stakeholders.

3.6.3. Education, training, and capacity building

Taxonomy is fundamental to the understanding and sound management of biodiversity. Although the dwindling number of taxonomists and trained curators worldwide is recognized by Convention on Biological Diversity’s ‘Global Taxonomy Initiative’ which encourages ASEAN members to incorporate this concern into key policy-setting instruments such as National Biodiversity Strategy and Action Plans, many have yet to do so (ACB, 2013a). This deficiency is compounded by the

fact that most extensive collections of SEA's biota still reside in institutions outside the region, and most publications are still published by researchers based outside of the SEA (Giam and Wilcove, 2012). Furthermore, the conservation sector has generally tended to focus on the so-called 'charismatic mega-fauna' leading to a marked underrepresentation of lesser-bodied and taxonomically complex groups (small mammals, herpetofauna, invertebrates) which actually form the bulk of zoological life and disease carriers. These shortcomings greatly impede the development of national capacities critical to achieving the sustainable development of biodiversity. The conference therefore advocated for sustained investments into creating a representative network of adequately resourced museum collections and taxonomists, such as has been initiated in Cambodia (Box 7).

Although SEA is a biodiversity hotspot, few scientific papers authored by SEA nationals have historically appeared in major international journals dedicated to applied ecology or conservation biology (Sodhi and Liow, 2000). Conservation science also has a poor record of translating science into action; one explanation for this 'research-implementation gap' is that conservation findings do not reach the conservation practitioners in developing countries (Gossa et al., 2015). National initiatives are attempting to bridge these shortcomings; e.g., one of the aims of the *Cambodian Journal of Natural History* (see references in Box 7) was to coach Cambodian conservationists to publish peer-reviewed papers that address the critical need for information on the status and management needs of biodiversity. Consequently, the conference advocated for more investments into open-access scientific publishing to promote both scientific capacity and evidence-based approaches to biodiversity conservation and sustainable development.

Another major impediment to achieving sustainable trade-offs between conservation and development in SEA is the lack of human expertise and capacity. Tertiary education plays a major role in increasing capacity, yet this sector is often weak, particularly in post-graduate curricula that deal with the multi-sectorial and interdisciplinary nature of the present challenges. Since only a few initiatives are addressing this issue, e.g., a Masters in Biodiversity Conservation in Cambodia at the Centre for Biodiversity Conservation and the newly developed international master called InterRisk "Assessment and management of health risks at the human, animal and ecosystems interfaces" in Thailand, the conference called for much greater capacity building.

For the very same reasons, the implementation of the One Health approach will require an improvement in education, training, and capacity building in the animal health sciences, public health, social sciences,

engineering, and ecological and environmental sciences. The strengthening of One Health academic training programs in SEA requires (1) thinking about "the next generation" of researchers and practitioners implementing this approach and (2) a range of academic and short course training programs for biologists, human and animal health care providers and staff from related health disciplines. Such interdisciplinary training could take place in and around protected areas because such areas are very amenable to train people within a holistic, integrative and comprehensive research framework (Box 8).

The conference recommended that human resource developments along with research platform installations in SEA countries are necessary to allow the building of networks which connect the local biodiversity hotspots to the regional and global levels. Such platforms could be clinical laboratories in the communities where the samples are collected, or a highly equipped research laboratory at the national level. Indeed, NGOs whose mission is to improve population health should consider how to improve biodiversity, and they should support laboratory infrastructure and equipment as one of their priority missions before organizing a network.

3.6.4. Future research priorities

Besides the examples mentioned above, the conference emphasized the following research priorities for SEA because they represent current knowledge gaps.

3.6.4.1. Evolution of AMR. Immediate policy action is required to alleviate the current overuse of antimicrobials in animal production systems and the resulting rapid evolution of AMR. The conference recommended that an integrated regional research program supports policy actions. Rather than viewing AMR as 'mainly a hospital issue,' AMR must be seen as a complex development and ecological issue that should be studied at the interface of farms, hospitals, humans and the environment. Furthermore, much of the AMR problem is caused by mobile genetic elements (plasmids, transposons, etc.); research should therefore focus more on these and less on specific organisms. Alternatives to the current overuse of antimicrobials need to be explored, e.g., vaccines to control bacterial diseases, better hygienic efforts, and quarantine and even slaughter of diseased animals. Research should also prioritize practical measures to reduce the spillover of antimicrobials and AMR genes into the environment, e.g., improvements in farm biocontainment and manure management systems.

Box 7

The recent development of capacities for biodiversity collections in Cambodia.

Until recently, almost all biological material originating from Cambodia was deposited in overseas collections, effectively depriving Cambodian researchers of access (Daltry, 2009). This situation began to change in 2006–2007 with the establishment of the country's first herbaria at the University of Health Sciences and Royal University of Phnom Penh, and a zoological reference collection at the latter. The zoological collection is dedicated to poorly documented groups (e.g., bats, snakes, lizards, frogs, small birds, butterflies and zooplankton) and has facilitated significant developments in domestic taxonomic expertise, with the discovery of six new vertebrates to science (Csorba et al., 2011; Geissler et al., 2012; Geissler et al., 2014; Neang et al., 2012; Neang et al., 2014; Neang et al., 2011b), long lost species (Neang et al., 2013), and hundreds of new country records to date (Chheang et al., 2013; Chhin et al., 2012; Furey et al., 2012; Ith et al., 2011; Meas and Sanoamuang, 2010; Min et al., 2011; Monastyrskii et al., 2011; Neang et al., 2011a; Neang et al., 2015; Sor et al., 2015). The herbaria have simultaneously become important repositories for vascular plants; in the case of the Royal University of Phnom Penh collection, this process was aided significantly by overseas repatriation of material dating back to 1865, i.e., the earliest days of the French colonial era (Souter, 2014). Related research efforts have included taxonomy (Dary et al., 2015; Mey et al., 2010), pharmacology (Chassagne and Hul, 2014; Khay et al., 2012; Kim et al., 2015a; Kim et al., 2015b; Kim et al., 2010; Uy et al., 2015) and phytochemistry (Galle et al., 2013; Kouloura et al., 2014). These new collections are critical to the abovementioned research efforts and the development of much-needed species identification guides for diverse and traditionally-neglected groups (e.g., Neang and Holden (2008) and Leti et al. (2013) for Cambodian amphibians and plants, respectively), but their future and that of their curator-taxonomists presently remain dependent on overseas support. While recently created natural history collections have also sprung up in countries such as Laos and Thailand (Tsang et al., 2016), their taxonomic coverage and resources for future development remain limited, and there remains a broader need to improve accessibility to these and other collections in SEA through the digitization of material and creation of virtual collections online, particularly for type specimens.

Box 8

Health benefits of protected areas and 'ecosystem health'.

Currently, the best protection for biodiversity and ecosystems is the establishment of sufficiently sizeable protected areas which, in the best of worlds, are surrounded by buffer zones and connected by corridors (Chape et al., 2008). However, forest cover both within and around protected areas has been rapidly decreasing in SEA (DeFries et al., 2005), and significant gaps remain in protected areas coverage (ACB, 2010). Given the various ecosystem services beneficial to human health and well-being (Box 3), we here briefly review a few studies which focus on the ecosystem services beneficial to human health which people derive specifically from protected areas.

Protected areas play a critical role in maintaining human health and well-being, although these benefits are just beginning to be understood and applied by the health sector. Environmental degradation is causing serious detrimental health impacts for humans, but protecting natural habitats can reverse this trend and instead supply positive health benefits, including current and future medicinal resources, cleaner air and water, the mitigation of detrimental health effects from climate, floods, and landslides, and the provision of recreational spaces that support physical, mental and spiritual well-being (Stolton and Dudley, 2010b). Even just viewing nature-like settings increases self-reported positive feelings, mental alertness, and cognitive performance (Frumkin, 2001).

The 'Healthy Parks, Healthy People' movement links protected area and health agencies which use protected areas to provide relaxing places for people with mental health issues and/or substance addiction (Stolton et al., 2015) because a pleasant, natural environment has been shown to be good psychological and physical therapy (Stolton and Dudley, 2010a). Parks Victoria, which manages 4 million hectares of protected areas, has progressively adopted this approach to all aspects of its business (Stolton and Dudley, 2010b). Likewise, United Kingdom health authorities are therefore encouraging the use of local nature reserves as safe and appealing places for exercise (often referred to as 'green' or 'outdoor gyms') in order to combat a national obesity problem (Stolton et al., 2015).

A study in Indonesia that communities living near a protected area had fewer cases of malaria and dysentery, children missed school less because of ill health, and there was less hunger associated with crop failure, than in communities without intact forests nearby (Stolton and Dudley, 2010b). Jakarta, Manila and Singapore are just one of several SEA cities which draw clean water from protected areas (Stolton and Dudley, 2010b), and protected areas contribute to the maintenance of the Tonle Sap fisheries (Claridge, 2003; see also main text). However, protected areas are still often seen as impediments to a better life by local and especially socio-economically disadvantaged people for a variety of reasons (e.g., Bennett and Dearden, 2014; McElwee, 2009). Therefore, payment schemes for ecosystem services should ensure that all parts of a community benefit (see references in Box 3).

A final thought: we suggest that the combination of the ecosystem approach (CBD, 2004) with the One Health and the Ecohealth approaches (main text, Box 6) into an holistic 'ecosystem health' approach (Zinsstag et al., 2011) is worthy of further research in SEA because it considers the inextricable linkages between ecosystems and human health. The study of health outcomes in and around protected areas should be a worthwhile point of departure for such an integrative and comprehensive research approach.

3.6.4.2. The study and maintenance of in situ biodiversity and traditional medical knowledge. To safeguard genetic resources, in situ protected areas, especially around communities practicing traditional medicine (Box 8), but also ex situ botanical gardens and herbaria and a database of the traditional medical use of biodiversity (Box 7) should be implemented. Policies to ensure the proper maintenance of specimens and genetic samples are needed. The standardization of traditional medicines should be developed to ensure their quality, safety, and effectiveness (Kunle et al., 2012).

3.6.4.3. Linking biodiversity, ecosystems, and human health. While provisioning ecosystem services, e.g., the maintenance of genetic and medical resources, have undeniable benefits to human health, the empirical evidence to support the claim that human health benefits from other ecosystem services is still relatively thin (Myers et al., 2013). For example, the regulation of infectious diseases is one of the recognized regulating ecosystem services, but whether such regulation is beneficial to human and animal health or not is still hotly debated, perhaps unsurprising given the complexity of host-pathogen-environment interactions (see Introduction). Binot and Morand (2015) concluded that the implementation of ecosystem services for the regulation of diseases is still in its infancy because of the lack of (1) knowledge on how ecosystem functioning might alter the epidemiological environment and (2) interdisciplinary studies joining ecologists, epidemiologists and social scientists. The conference therefore recommended (1) further basic research into host-pathogen-environment interactions, but within interdisciplinary teams, and (2) more research which specifically aims at determining interventions which benefit both ecosystem functions and disease regulation.

3.6.4.4. Urban biodiversity and ecosystem services. Most cities in SEA are both unhealthy for their citizens and are exerting a heavy

environmental footprint on the ecosystems which support them (Estoque and Murayama, 2014). Much more research and action is needed to transform cities into healthy places to live while also minimizing their environmental footprint. The ecosystem functions of cities must be enhanced to include the retaining and cleaning of water, the production of food, the reuse of biological wastes, the protection of biodiversity, and educational and recreational opportunities which increase the citizens' well-being. Studies which enhance biodiversity and ecosystem services within the city and in its immediate surroundings (e.g., connected watersheds, wetlands, forests) should be a most productive exercise which should benefit from closer cooperation between researchers and urban planners (Tan and bin Abdul Hamid, 2014; Wolf and Robbins, 2015).

3.6.4.5. Understanding inter-dependencies of regional and global climate, ecosystem services and human health. Given that the protection of forests and wetlands is essential to protect the ecosystem services which regulate climate, flooding, and soil erosion (Arias et al., 2014; Kuenzer et al., 2013; Taylor, 2010), more research should focus on elucidating these services to provide better arguments to decision-makers to protect the ecosystems, and, even more importantly, should outline sustainable multi-use solutions which add to the economic benefits (e.g., bio-prospecting, eco-tourism, education, sustainable harvesting, biofuels, carbon sequestration).

3.6.4.6. Short- versus long-term benefits. More research is needed which compares the economic benefits of ecosystem destruction (which through short-term increases in GDP often leads to better health outcomes) from the often longer-term negative effect on health of such destruction (e.g., long-term increases in flooding risks). Research should also focus on the less tangible and understudied long-term benefits of ecosystems, such as physical activity, stress reduction, social cohesion,

intellectual development, and artistic inspiration and ways to enhance them, especially in cities (Clark et al., 2014; Hartig et al., 2014; Pretty et al., 2015) (see also point 4 above).

3.6.5. Potential science–policy interactions

Efforts to strengthen the science–policy interface in SEA should become a high priority in order to strengthen the health and resilience of SEA societies. In various science–policy interactions, it has become clear that the government must be involved not just at the level of environmental officials or ministries, but at all levels, including the most powerful ministries of agriculture, economics, finance, security and human health (Watson, 2005). Such efforts cannot succeed through efforts of scientists alone, as they are overworked with research and education demands. Rather, governments should finance research programs staffed with permanent personnel and dedicated to organizing science–policy interactions and driving these processes forward. Successful examples at the global level, such as DIVERSITAS, GEO BON, IPBES and TEEB (Table S1), should be used as blue-prints for such efforts in SEA (Scholes et al., 2008; Walther et al., 2011). Regional institutions such as ASEAN should facilitate such interactions through dedicated task forces.

The intention of the recently established GEO BON and IPBES is to strengthen the science–policy interface for the conservation of biodiversity, ecosystem services, long-term human well-being, and sustainable development (Diaz et al., 2015; Mace et al., 2010). Its conceptual framework envisions cross-disciplinary and even cross-cultural studies which bring on board stakeholders across disciplines, cultures, and knowledge systems to foster the sustainable use of biodiversity. With its diverse ethnic groups and manifold stakeholders, SEA would certainly benefit from such community-type research and action to monitor the state of its biodiversity and the benefits it provides. An Asia-Pacific workshop on the regional interpretation of the IPBES Conceptual Framework convened in 2013 and proposed to create an IPBES Regional Hub to (1) promote regional collaboration, policy coherence and the use of universal methods, (2) coordinate regional assessments and interventions, and (3) address assessment shortfalls (UNU-ISP, 2013). To implement these recommendations, the conference suggested that policies and regulations which protect and enhance ecosystem services in European agricultural and forestry systems should be adopted in an appropriate manner in SEA.

To be successful, both legislative action but also effective and well-financed administrative enforcement are vital. For example, to stem the overuse of antibiotics in animal production, policymakers should focus on the current default medication of animal feeds, and move to progressive restrictions of antimicrobial access to discourage the blanket treatment of whole herds and flocks, and to improve hygiene and bio-containment in animal production units. Research on cost-effective management options that help reduce the release of antimicrobials, AMR genes and zoonotic pathogens to the environment should be supported. Whenever new technologies, drugs or vaccines are available, they need to be quickly and thoroughly tested, and the respective policies and guidelines need to be revisited. The conference emphasized that the role of policymakers should be to counterbalance the use of antimicrobials by introducing legislation which promotes the use of farming practices which do not endanger human health either directly through providing contaminated food or creating harmful pathogens or indirectly by contaminating air, water and soil or destroying vital ecosystems. Any movement towards such environmentally-friendly practices should be supported by education and concrete solutions, including financial incentives, otherwise farmers will reject them and powerful agro-businesses and pharmaceutical companies will oppose them. In addition, the imbalance of power and influence between very resourceful drug companies and under-resourced researchers and NGOs must be addressed.

Besides the topics mentioned above, the conference identified the greatest needs for science–policy interactions in the following fields:

land planning, law, ecological engineering, evolutionary medicine, and sustainable development. These activities should involve social scientists and legal experts as well because they can bring into the discussion important considerations, such as acceptability, decision-making processes, economic valuation, conflicts of interest, social perceptions of health risks, etc.

In some SEA countries, researchers are not even paid for their research because no ministry for research or higher education exists. Governments should urgently establish such ministries, including viable budgets, as a first essential step towards science–policy interaction.

Finally, environmental education, including ecology, environmental science, evolution, geology, and sustainable development, must become part of education at all levels. There simply cannot be any progress in achieving the conference's recommendations and related scientific efforts if stakeholders and decision-makers do not even understand what researchers are talking about. Such education should begin at primary school, and continue all the way to the graduate level, and should be mandatory for government employees. Special efforts should also be made to educate the media and business leaders. To succeed, teaching materials must be translated into any of the important languages of SEA and must be freely available. Special training centers and teachers should be financed, such as educational centers attached to nature reserves, botanical and zoological gardens, and herbaria, which can be visited by school children, students and other interested parties.

4. Conclusions

It cannot be stressed enough that there cannot be sustainable development and the pursuit of human health and well-being without the realization that (1) exponential and infinite economic growth is impossible (Meadows et al., 2004), (2) the current policies to pursue such growth are exponentially increasing the pressures on biodiversity and ecosystems and ultimately human well-being (Millennium Ecosystem Assessment, 2005; Pereira et al., 2010), and, therefore, time to address these issues is running out quickly (Ceballos et al., 2015). SEA's decision-makers must realize that human progress does not equate with economic progress alone, especially economic progress measured only in the ridiculously inadequate measure of GDP (Dasgupta, 2010; Delang and Yu, 2015; Lawn and Clarke, 2010; Pretty et al., 2015). Rather, we need to re-evaluate our cultural choices and moral values in connection with our environment, and then remake our legislative frameworks and reset our socio-economic-ecological priorities (Czech, 2013; Ehrlich and Ehrlich, 2013; Nair, 2011a, 2011b; Pretty, 2013), e.g., by paying for ecosystem services (Box 3). At the moment, the priorities of most of SEA's decision-makers run contrary to the ideas put forth by the conference (e.g., De Lopez, 2002; Koh and Sodhi, 2010; Sodhi, 2008), as do most consumers' priorities (e.g., Koh and Lee, 2012). However, we hope that by putting forth the best scientific evidence and advice, we can change the future course of SEA's policymaking to improve the well-being of humans and all the other creatures with which they are intricately connected, mostly for mutual benefit, but sometimes locked in mortal battle.

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