Key Findings and Recommendations from the Infectious Disease Emergence and the Economics of Altered Landscapes and Emerging Pandemic Threat PREDICT Projects.

Summary

Background:

Infectious diseases caused by wildlife viruses and bacteria have an important impact on the economy. Recent viruses (SARS Coronavirus, Nipah virus, Zika and Ebola virus) originated from wildlife and cost the **global economy more than USD$60 billion** (1). Nipah virus alone cost the **Malaysian economy USD$550 million** (2). The current COVID-19 pandemic and measures to slow its spread have cost the **global economy USD$16 trillion** (3) **and 255 million full time equivalent working hours losses in 2020** (4). **The crisis has resulted in an estimated loss of 81 million jobs in the Asia-Pacific region in 2020 over pre-crisis trends and pushed an additional 22 to 25 million employed persons into extreme poverty** (5). Deforestation, intensive agriculture practices, and the wildlife trade all increase contact between people and wild animals heightening the odds of virus and bacteria spillover and its corresponding negative impacts to local and global economies.

Aims:

The Infectious Disease Emergence and Economics of Altered Landscapes (IDEEAL) project investigated how human activities (e.g., deforestation and land-use change) contribute to disease outbreaks and aimed to: 1) Estimate the economic benefits of conserving forest to regulate disease; 2) Estimate the total economic costs (private and public) of converting land; and 3) Provide a tool to inform land-use planning.

The Emerging Pandemic Threats PREDICT project focused on pathogen surveillance, viral discovery, and strengthening global health capacity to shift the prevention and surveillance paradigm towards identification and mitigation of viral spillover and amplification risk by: 1) Identifying and better characterizing viruses of pandemic potential; 2) Recognizing animal reservoirs and amplification hosts of human-infectious viruses; 3) Efficiently targeting intervention action at human behaviours which amplify disease transmission at critical animal-animal and animal-human interfaces in hotspots of viral evolution, spillover, amplification, and spread.

Results:

Malaria has already cost Sabah more than USD$8.9 million per year. Reducing malaria transmission by just 10% comes to approximately USD$14 million in future savings (6). That is, for each dollar invested in reducing malaria by utilising land-use planning tools, Sabah's government secures a return of USD$4 dollars on future savings it can pass to its citizens (7). More broadly, an investment of USD$500,000 on IDEEAL implementation could save the Sabah economy at least USD$2 million (8). The IDEEAL economic model indicates that Sabah has exceeded the optimal amount for forest to agricultural land conversion. The economic loss from the overdeveloped amount of forest cover from the social optimal today exceeds US$25M annually (9). The PREDICT project in Malaysia has found 76 novel viruses, the risk of another disease emergence event like Nipah is ever- present. **Improving land-use management is a vital step in reducing the risk of disease emergence and minimizing the potential economic and public health impact of land-use change.**

Recommendation:

The impact on human, animal, and environmental health – as well as the potential burden on the local and global economy – calculated with tools based on sustainability and scientific evidence (like those IDEEAL has developed) should be paramount in any decision about land management. This approach could improve industry practices and regulations, reducing environmental and health-associated costs to the Malaysian government and its citizens and reduce the risk of disease emergence.

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Key Findings and Recommendations from the Infectious Disease Emergence and the Economics of Altered Landscapes (IDEEAL) and Emerging Pandemic Threat PREDICT Projects.

Executive Summary: Disease outbreaks that come from wildlife are increasing in frequency and economic impact. The most recent outbreaks including SARS Coronavirus, Nipah virus, Zika, and Ebola virus outbreak all had a wildlife origin and has cost the global economy billions (1). Although the chances of a big pandemic are low (2-3 pandemics every 100 years) the social and economic impacts of outbreaks can be quite devastating. For example, the 1999 outbreak of Nipah virus cost the Malaysian economy US$550 million, while Ebola, Avian Influenza, and SARS outbreaks have cost the global economy more than US$60 billion (1). SARS-CoV-2 emerged in China in late 2019 and has precipitated a global pandemic that has infected over 181,856,808 people from 215 countries and caused more than 3,939,034 deaths (10) as of the 30th of June 2021. The COVID-19 pandemic and measures to slow its spread have cost the global economy US$16 trillion (3) and 255 million full time equivalent working hours losses in 2020 (4). The crisis has resulted in an estimated loss of 81 million jobs in 2020 in the Asia-Pacific region (5).

Human activities such as deforestation, agricultural and urban expansion, and the legal and illegal wildlife trade displaces wild animals and forces heightened interaction between wildlife and people, increasing the chances for the transmission of new diseases with potential high economic impact. The **Infectious Disease Emergence and Economics of Altered Landscapes project (IDEEAL)** was a USAID-supported initiative that investigated how human practices contribute to disease emergence. This project aimed to: 1) Develop knowledge about the benefits of conserving forest to regulate disease; 2) Estimate both the far-reaching pros and cons of converting land; and 3) Provide governments, industries, and communities with tools and data to make informed land-use decisions. **IDEEAL's maxim is that any land-use decision should maximize both private and public wellbeing.** A trade-off occurs each time a hectare of natural land is developed for human use. Decisions by private entities to develop natural forests for human use create job opportunities and economic growth; but this can also reduce ecosystem services that benefit the public (disease regulation) and have potential negative effects like water pollution, flooding, wildfires, and biodiversity loss. By calculating the economic impact of public health risks introduced via land-use change, IDEEAL advocates sustainable land management policies. Malaria has already cost Sabah more than USD$8.9 million per year (11). Reducing malaria transmission by just 10% comes to approximately USD$14 million in future savings (6). That is, **for each dollar invested in reducing malaria by utilising land-use planning tools, Sabah's government secures a return of USD$4 dollars on future savings** that it could pass to its citizens (7). The return on this investment would be even higher when considering the potential for sustainable land management policies to reducethe risk of a spillover event like Nipah virus in 1999.

This report provides the Government of Malaysia with data to support making the following policy recommendations. **Land-use planning** should: **1)** Consider the **negative impact on the health of humans, wildlife, and the environment**; **2)** Promote the use of **science-based land-use planning tools** for more sustainable land management. Our framework develops a blueprint for policymakers to identify the **optimal rate of forest conversion** each year, as well as **what land should be protected**; **3)** Improve **industry practices and regulations to reduce health-associated costs to society**. For example, determining the optimal fine for violations of disease control regulations by companies whose economic activity may increase the risk of infectious diseases; and **4)** All proposed development projects should be assessed, utilising science-based land-use planning tools, to consider the negative impact on the health of humans, wildlife, and the environment; to ensure the development and its planned location is sustainable and to provide recommendations on industry practices related to that development, to reduce the risk of disease emergence.

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PREDICT Background: EcoHealth Alliance/Conservation Medicine and our government partners in Malaysia began work in 2009 identifying new infectious diseases that could become a threat to human health and to uncover the factors that drive their spread into people, this work was supported by the U.S.Agency for International Development (USAID) Emerging Pandemic Threats (EPT) PREDICT project. PREDICT Malaysia is a collaboration between EcoHealth Alliance (EHA)/Conservation Medicine (CM), the Ministry of Health (MOH), the Department of Wildlife and National Parks, Peninsular Malaysia (PERHILITAN), the Department of Veterinary Services (DVS), Sabah Wildlife Department (SWD) and Sabah State Health Department (SSHD). **Over ten years we sampled 5972 animals (including 2540 bats, 220 birds, 528 carnivores, 1288 NHP, 343 pangolins, 949 rodents/shrews, 66 ungulates and 38 other taxa) and 1400 people with most of the samples collected from concurrent (human, wildlife, and livestock) sites in Peninsular Malaysia and PREDICT Deep Forest sites in Sabah.** There are 3 concurrent sites in Peninsular Malaysia which are Gua Musang in Kelantan, Kuala Kangsar in Perak, and Kuala Lipis in Pahang, and 9 Deep Forest sites in Kinabatangan and 9 Deep Forest sites in Telupid. In addition to discovering new viruses the Deep Forest Project has allowed us to better understand the impact of land-use change on species diversity and population dynamics. (12)

Wildlife samples were screened at the Wildlife Health, Genetic and Forensic Laboratory in Sabah, built with funding provided by EHA, USAID and SWD, and the Molecular Zoonosis Laboratory in Peninsular built with funding provided by EHA, USAID and PERHILITAN at the National Wildlife Forensic Laboratory. These state-of-the-art facilities are Bio-Security Level 2 laboratories, certified to international standards as detailed by the National Institutes of Health and the Centers for Disease Control and Prevention (CDC). They allow PERHILITAN and SWD to engage in comprehensive disease screening efforts and are vital to addressing the threat posed by emerging infectious diseases of animal origin. Human samples were screened at the National Public Health Laboratory and the Kota Kinabalu Public Health Laboratory. Domestic animal and livestock samples were screened at the Molecular Zoonosis Laboratory and the Faculty of Veterinary Medicine at UPM.

Key findings from PREDICT Viral Surveillance and Risk Modelling: Through the PREDICT project (2009-2019), **we detected 29 known viruses and 76 novel viruses in animals and humans using the PREDICT testing strategy of consensus PCR assays that detect a broad range of known and novel viruses**. 15 new paramyxoviruses found in bats (Figure 1) and 12 new coronaviruses were found in bats and rodents with 3 from Sabah that are genetically related to SARS-CoV-1 and SARS-CoV-2 (Figure 2). In addition, findings of note include 1 novel flavivirus detected in a bat, 2 novel enteroviruses and 1 novel rhabdovirus detected in Bornean orangutans. Enteroviruses can cause mild respiratory illness and central nervous system disease in humans while rhabdoviruses are associated with fatal encephalitis in people and animals. **Based on current understanding, 12 viruses were identified that belong to viral families that include known human pathogens and are potentially of public health concern. However further characterization of many of the novel viruses including the novel coronaviruses and paramyxoviruses is needed to determine their disease-causing potential, this effort is ongoing.**

In Sabah, Deep Forest Sites had the highest viral detection – 15 viral detections with 7 unique viruses at Intermediate Disturbance site 1 in the Kinabatangan, followed by 9 viral detections with 8 unique viruses at Low Disturbance site 3 in the Kinabatangan, 9 viral detections with 2 unique viruses at Intermediate Disturbance site 1 in Telupid, and 6 viral detections with 4 unique viruses at Intermediate Disturbance site 2 at Kinabatangan. In Peninsular Malaysia, both Concurrent Sites and Independent Sites mostly had 1 viral detection with 1 unique virus detected except at Kuala Kangsar in Perak which had 4 viral detections with 2 unique viruses (13).

Figure 1: PREDICT- Paramyxoviruses Detections.

15 novel and 2 known paramyxovirus were detected in people and wildlife at these sites. The purple dot indicates the 1 person detected with a known Human parainfluenza virus through the Syndromic Surveillance Project at Queens Elizabeth Hospital in Kota Kinabalu. The orange dots indicate sites where animals were detected with the 15 novel and 1 known (measles) paramyxoviruses. The green dots show the sampling sites where paramyxoviruses were not detected (13).

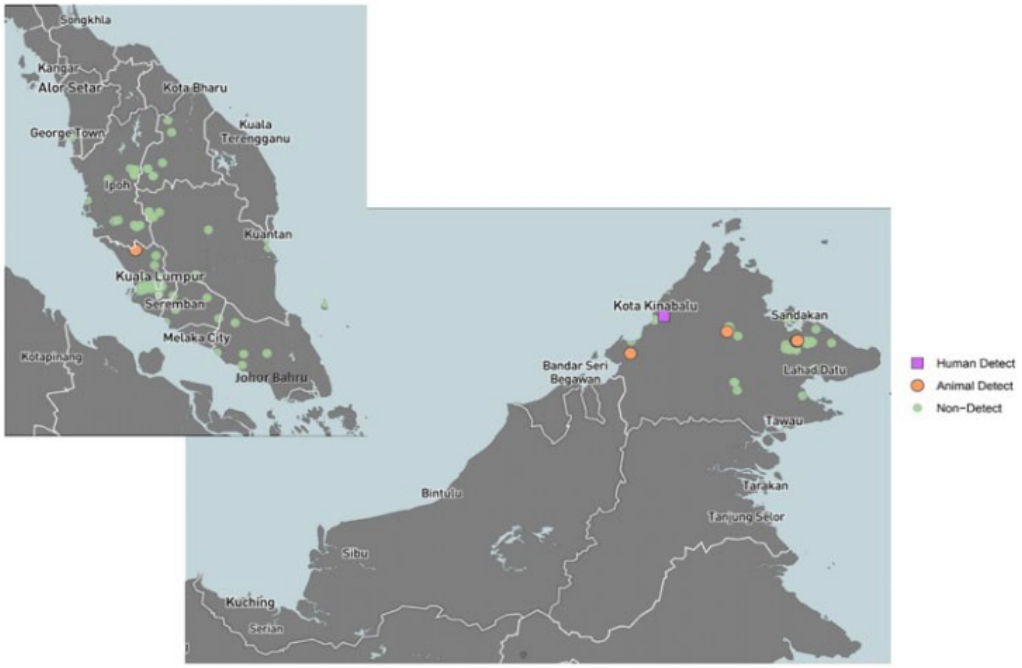
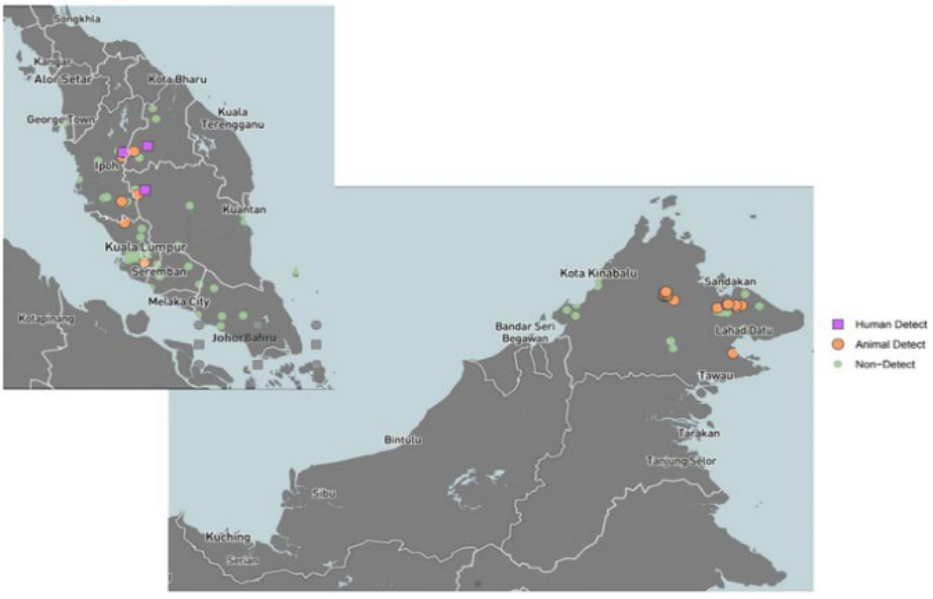


Figure 2: PREDICT- Coronaviruses Detections.

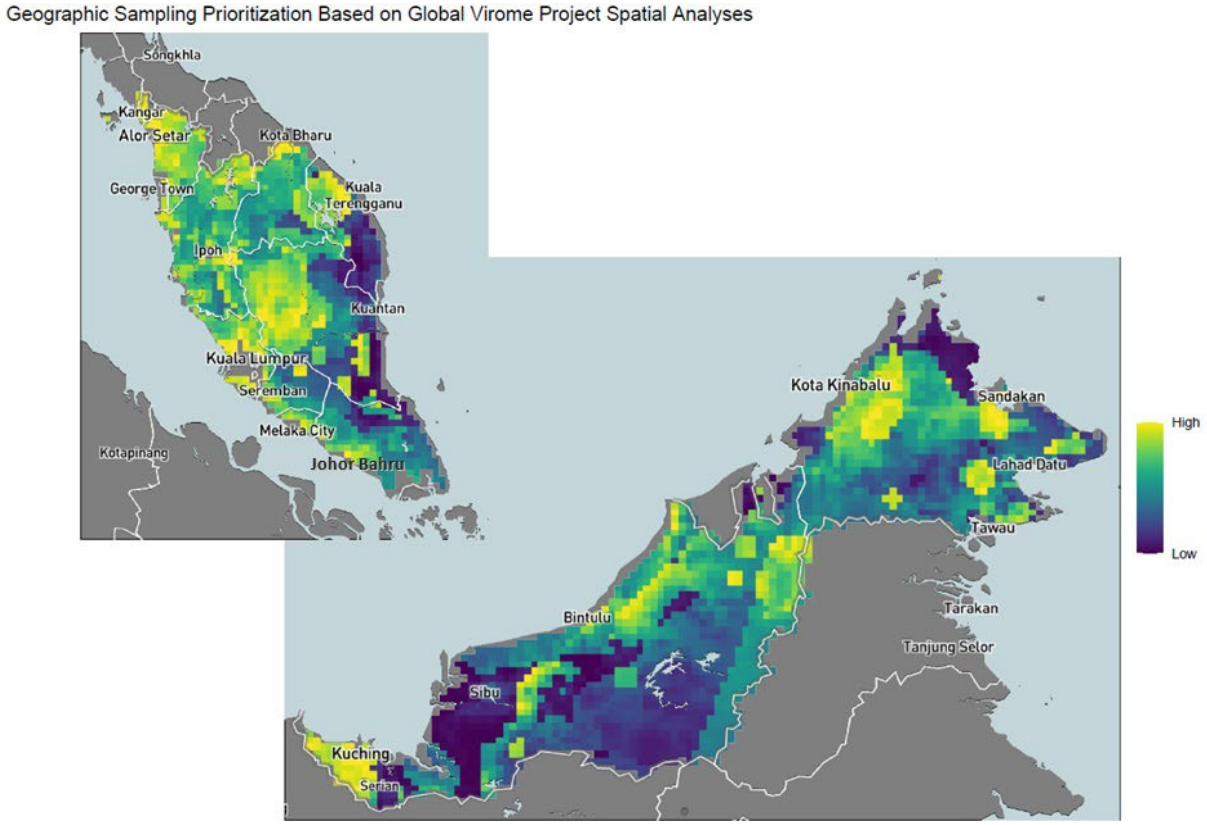
12 novel coronaviruses were detected in wildlife and livestock at these sites. The purple dots indicate the concurrent sites where 4 people had known coronaviruses (Alpha coronavirus NL63, Human coronavirus HKU1, Beta coronavirus 1 OC43, Human coronavirus 229E). The orange dots indicate sites where animals were detected with 12 novel and 3 known (Infectious bronchitis virus, Murine coronavirus and Philippines/Diliman1525G2/2008) coronaviruses. The green dots show the sampling sites where coronaviruses were not detected (13).



Using data obtained from the PREDICT project, various Malaysia specific risk maps were created that show the risk of zoonotic spillover in Malaysia. These maps are generated based on predictive modelling used in two recently published global PREDICT reports: Hotspots 2.0 (14) and Host Pathogen Phylogeny Project (15). These country-level maps provide spatial information that show the zoonotic disease spillover risk in both Peninsular Malaysia, Sabah and Sarawak, population density and land-use change over time (Appendix Figure 10, 11, 12, 13, 14, 15, 16). The aim of these maps is to complement and contextualize risk characterization and support the planning of future surveillance efforts and land-use planning.

Figure 3: Geographic Sampling Prioritization Based on Global Virome Project Spatial Analyses.

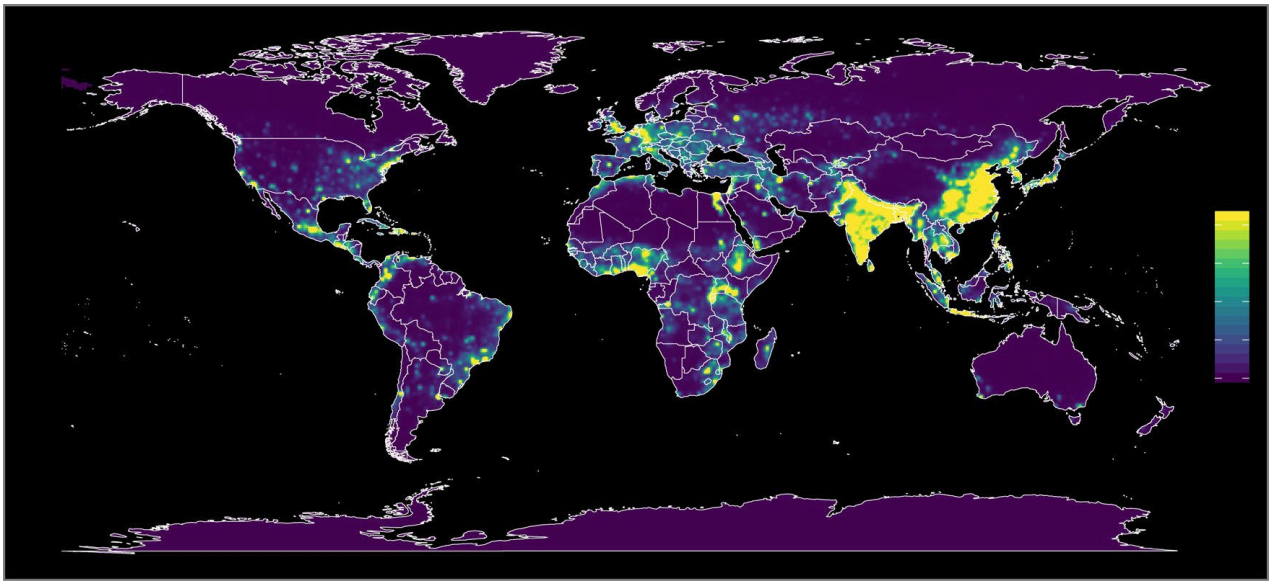
Geographic Sampling Prioritization is an inventory of prioritized geographic sampling spots. The Global Virome Project (GVP) identifies and develops a global atlas for pathogens and provides geographical data maps that can help us understand the risk of unknown virus spillover and determine where to prioritize sampling efforts (16). The GVP aims to build a comprehensive viral database and identify zoonotic viruses with the greatest potential to infect humans in hopes of ultimately reducing the likelihood of viral spillover events. This map shows viral sampling priority areas in Malaysia, ranked from most optimal (yellow) to least optimal (dark blue). We used the Zonation Conservation Planning Software to select and rank sites of highest sampling value based on the number of unique zoonotic viruses predicted to occupy each grid cell (15) and the relative cost of accessing each site from nearby cities of greater than 50,000 people (17). We identified optimal areas for viral sampling using a decision support system for spatial planning that allocates resources (e.g., sampling costs) and prioritizes areas. The result is a ranking of all potential sampling sites based on the highest return on investment for sampling in a particular area (13). This map shows locations closer to state capitals have high geographic sampling prioritization.



Over the past three centuries, land-use change has grown exponentially to keep pace with human population growth and the subsequent demand for natural resources. Intact forests provide invaluable benefits to people and our planet, including water filtration, carbon storage and sequestration, flood prevention, biodiversity conservation, and the maintenance of human health and welfare. Although changes in land-use practices have benefited people through economic and social development, they have also led to long-term negative impacts on human health and the provision of ecosystem services. The risk of a new zoonotic disease emergence event (Disease X) changes depending on where you are in the world (Figure 4). Critically, there is increasing evidence that land-use change is a major driver of emerging infectious diseases (EIDs). Previous analyses demonstrate that over 30% of the EIDs affecting people are causally linked to land-use change (Figure 5). This includes deadly diseases such as HIV/AIDS, Ebola, and Zika Virus; all of which originated in altered forest landscapes (9). The main cause of EBOV outbreaks has been shown to be eating and hunting habits (18), which increase in areas of deforestation, land-use change and agricultural expansion (19, 20, 21, 22, 23). The Nipah virus outbreaks in Malaysia and Bangladesh have also been linked to deforestation, and land-use change including agricultural intensification (24, 25, 26). The impact of EIDs on human and livestock health is significant, with single outbreaks (e.g., HIV/AIDS, West African Ebola) leading to substantial mortality and morbidity, and some causing significant economic impact (8).

The updated EID Hotspots 2.0 analysis published in Nature Communications in 2017 shows that zoonotic disease spillover risk is greatest in tropical regions with high levels of biodiversity, expanding human populations, and rapid ecological change, which unfortunately includes Malaysia (27). **The fact that Malaysia is a hotspot means it is even more critical that the impact of any future development on human, animal, and environmental health, as well as the potential burden on the local economy is calculated with tools based on sustainability and scientific evidence and should be paramount in any decision about land management. Proper land-use planning tools, and environmental impact assessments can help the Malaysian government plan for future development maximizing profits, while minimizing the risk of disease spillover and the negative impacts of land-use change.**

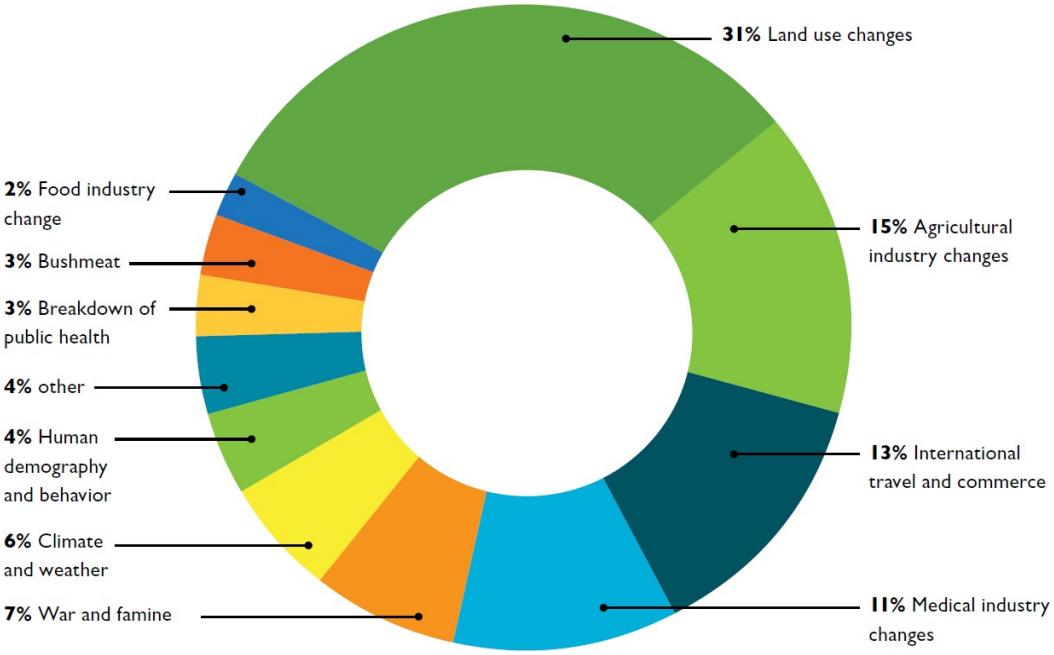
Figure 4: Hotspot map showing the relative risk of a new emerging zoonotic disease.
Yellow shows the regions with the highest and purple shows the regions with the lowest risk. This map is corrected for global variations in reporting effort to give a true measure of geographic spillover risk (14).



While at the global scale Figure 4 shows that Sabah and Sarawak have a lower risk of disease emergence than Peninsular Malaysia, Figure 3 shows that the risk around the populated areas of Sabah and Sarawak are just as high as Peninsular Malaysia (Figures 11 and 12 in the appendix also show that the risk for Sabah and Sarawak is similar to Peninsular Malaysia). It is also important to note that of the 76 novel viruses found through the PREDICT project, 65 were found in Sabah (no sampling was carried out in Sarawak),this included most of the novel coronaviruses and paramyxoviruses. The discovery of SARS-like coronaviruses in Sabah is of obvious concern, given the economic and public health impact of the 2002-2003 SARS-CoV pandemic and the current COVID-19 pandemic. **While the Malaysian government continues taking important steps to build capacity for zoonotic disease surveillance and outbreak response, improving land-use management is also a vital step in reducing the risk of disease emergence and minimizing the potential economic and public health impact of land-use change.**

Figure 5: Primary Drivers of Past Disease Emergence.

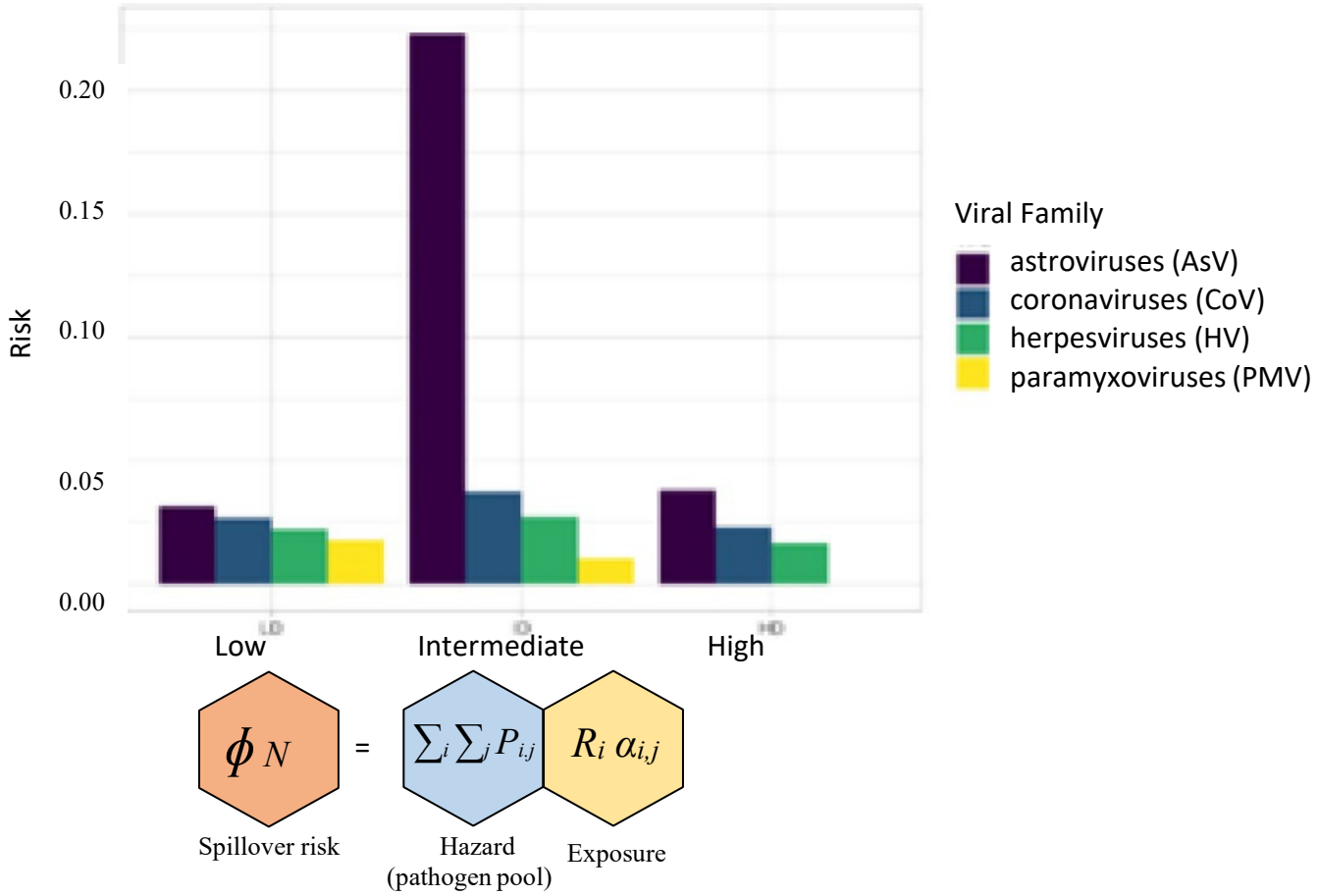
Approximately 31% of the infectious diseases that have originated in wildlife since 1940 have been related to some form of land-use change, followed by 15% due to agricultural industry changes and 13% due to international travel and commerce (9).



The global annual economic loss from EIDs due to excessive forest land conversion was estimated at between US$18 and US$52 billion annually (US$4.2-US$11.1 ag ha/year). That is equivalent to a present value of US$602 [US$536- US$1,553] billion in additional costs for the global economy over the next 30 years. The average loss per hectare of agricultural land is estimated at US$646.

To further dissect the roles of land-use, human behaviour, and wildlife diversity in driving disease emergence, EHA and CM coordinated with our government partners SWD and SSHD on data collection across a land-use gradient and with the help of the PREDICT modelling team analysed virus diversity in a transformative collaborative effort, under the Deep Forest project, which was conducted at Kinabatangan and Telupid in Sabah. PREDICT calculated the spillover risk across the landscape based on the diversity of wildlife in driving disease emergence, the viruses they harbour (the pathogen pool) and the contact behaviour of people (their exposure) (Figure 6).

Figure 6: Deep Forest analysis of spillover risk across different land-use gradients for four viral families. Results showed that the risk of spillover was highest at the intermediate level of disturbance, at sites where deforestation has already begun to transform the landscape, but there is still a relatively high diversity of wildlife. Here, increasing numbers of people have contact with wildlife with a higher number of pathogens and drive a higher risk of pathogen spillover (27).



IDEEAL Background: The Infectious Disease Emergence and the Economics of Altered Landscapes (IDEEAL) project was a USAID-supported initiative investigating how ecosystem degradation and landscape manipulation by humans contribute to disease emergence. Illustrating the economic impact of land-use change induced public health risks encourages sustainable land management policies to mitigate these threats. This program built upon USAID's investments in pathogen discovery and characterization of disease emergence risk. Leveraging existing and new data sets from ongoing pathogen surveillance in animals and people in Malaysia, the program's economic model projects expected costs attributable to disease emergence specific to the location and magnitude of land alterations. These costs—from patient care and treatment, emergency response and containment, to travel and trade restrictions, work stoppages due to disease, and reduction in ecosystem services—provide valuable information for discussion among governments, the private sector, and civil society to define optimal land-use policies.

This collaboration between EHA, CM, Universiti Malaysia Sabah, SWD, SSHD, MoH, SFD, local NGOs, and USAID (Appendix Table 4. for the complete list of IDEEAL partners and stakeholders), dealt with underlying socioeconomic and ecological factors that drive pandemics. Environmental degradation (deforestation) drives emerging disease spillover by increasing interaction between people and wildlife. These spillover events can cost hundreds of millions of dollars to the global economy and are a hidden cost of development

that is not historically considered in land development planning. IDEEAL measured the economic impact of emerging diseases and quantifies the value of services provided freely by nature like food production, air purification, water retention, biodiversity, and disease regulation to encourage reduced impact land-use and development policies. Our revolutionary approach treats disease regulation as an additional ecosystem service from nature. This allowed a better quantification of the economic cost of developing land.

IDEEAL's premise was that any land-use decision should **maximize private and public wellbeing**. There is a trade-off every time a hectare of land is developed. Private decisions on land development create job opportunities and economic growth by increasing quality of life, infrastructure, creation of wealth, and tax revenues for public spending, among others. However, land development can also reduce ecosystem services provided for free by nature that benefit the public and increase negative externalities (e.g., soil erosion and water pollution). The way to maintain a balance is by choosing the **optimal amount** of land to develop each year in a particular area, considering all benefits and costs. This benefit-cost balance is achieved by choosing to develop areas where those ecosystem services are already lowest (degraded land) and industry's net benefits are highest and, logically, conserving areas where ecosystem services are the highest and industry's net benefit yield is lowest. We provided a blueprint for land development benefitting both the private and public sector, prioritizing areas for conservation while reducing the risk of infectious disease emergence linked to land-use change.

IDEEAL used data from Malaysia with a focus on Sabah where the project began, to estimate the value of nature's role in mitigating infectious disease threats. This work will continue to help produce economically sound strategies to achieve optimal land-use policy. Our framework was built using a revolutionary application of economic theory that can be used to generate a schedule for land conversion over time that maximizes social welfare and accounts for both the economic potential of land conversion and public benefits and costs from land conversion, loss of ecosystem services, and health costs (Figure 7).

Figure 7: The IDEEAL Economic Model.
The model is unique because for the first time, health costs are considered along with the loss of other ecosystem services.

$$\overbrace{V(u)}^{\text{land value}} = \int_{t=0}^{\infty} \left(\overbrace{\underbrace{R(x)}_{\text{gained with conversion}}}^{\text{rent}} + \underbrace{\overbrace{S(1-x)}^{\text{e. services}} - \overbrace{C(u)}^{\text{conv. cost}} - \overbrace{H(x)}^{\text{health cost}}}_{\text{lost with conversion}} \right) \overbrace{e^{-\rho t}}^{\text{discount}}$$

Gains from conversion: Palm oil rent, jobs, and economic growth
Loss from conversion: Ecosystem services (Costanza et al. 2014)
Health costs: Sabah annual cost of malaria mitigation: US$8.9 million (Sabah Department of Health)

Our results can be used to inform **future land-use planning, prioritizing areas for conservation, and reducing the likelihood of infectious disease emergence linked to deforestation**. The simulations using data from Sabah suggest that there has been excessive deforestation in the past decade in Sabah. **The cost burden of disease outbreaks ultimately falls to the Malaysian government and its citizens**. Both private and public welfare benefit from a strategy to manage land conversion, which then prevents disease emergence and slows deforestation and forest degradation. Our tool also generates maps to help with decision-making by identifying optimal land areas for development, considering the value of ecosystem services on land left undeveloped (Appendix Figure 17 for examples).

Key findings from IDEEAL Modelling: We used malaria for the study case in Malaysia. At a national level, the Malaysian government allocates funds for the prevention and control of Malaria. In 2017, the Malaysian government invested US$48.36 million for malaria control and prevention activities (28) (Appendix Table 1). In 2014, there were more than 3,000 cases of malaria in Malaysia, mostly in Sabah (29). People at most risk are workers in rural development projects such as plantations, mining, road, and dam construction. Almost 80% of Sabah and Sarawak's land surface has been impacted by commercial logging or increase in oil palm plantation from the year 1990-2009 (28). The most important factors that drive malaria incidence in Sabah, are related to land conversion and degradation. Specifically, reduction of the tree cover (broadleaved evergreen forest) and the increased density of patches of a mosaic of cropland and natural vegetation were consistently identified as the most important variables that could explain malaria incidence. Additional drivers, in decreasing importance, were precipitation and both the patch density and proportion of tree or shrub cover. Studies show rates of malaria transmission correlate directly with increased deforestation (Appendix Figures 18 and 19 for relationship between malaria and deforestation in Sabah). High deforestation rates since 1993 results in high costs for the public and reduced profits for the plantations involved in land conversion.

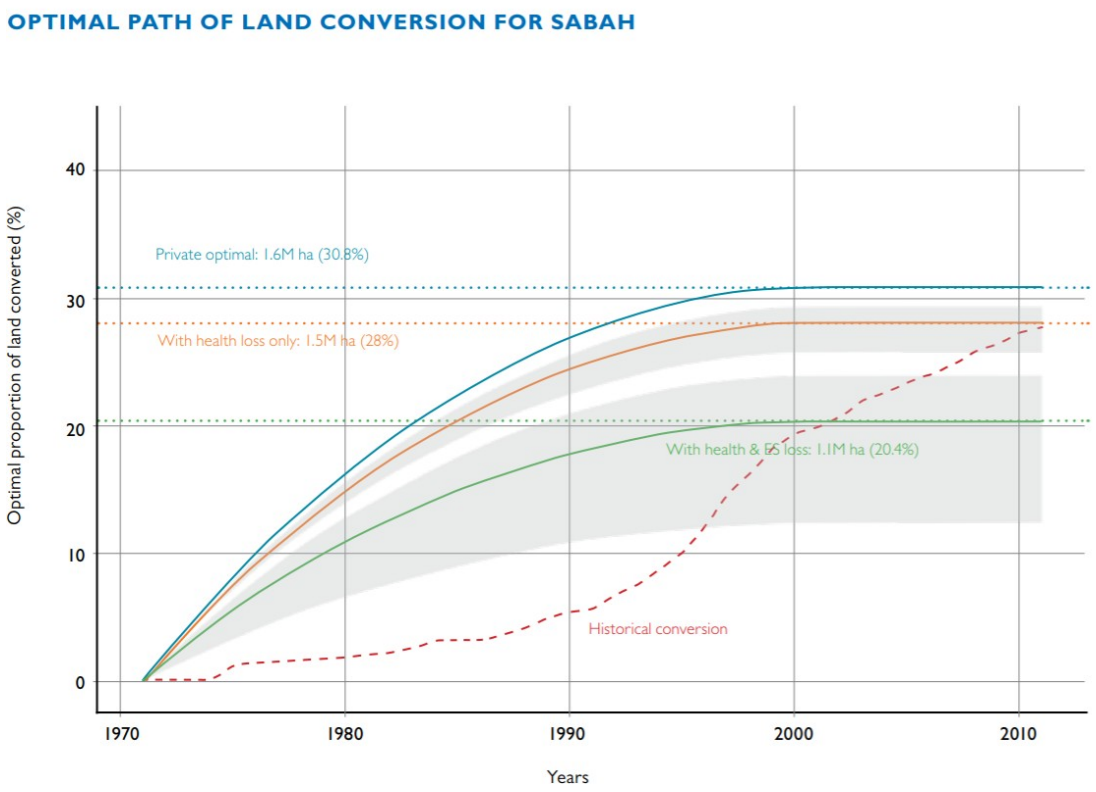
Drivers of malaria incidence in Sarawak were related to climate and water availability, specifically to precipitation, saltwater flood regions, water bodies and irrigated cropland (30). Risk of malaria across Sarawak varies every year, likely because of prevention methods employed. (Appendix Figure 20 for relationship between malaria and deforestation in Sarawak). In Peninsular Malaysia, the risk of malaria appears to be greatest in the states of Perlis and Selangor, fluctuating each year between 2006-2014. Land-use types most associated with these risks include freshwater flood areas, urban regions, water bodies, tree shrubs, and irrigated cropland (Appendix Figure 21).

Taking into consideration ecosystem service values and malaria costs in Sabah, actual rates of development have already outpaced the economically optimal rate of forest conversion to palm oil plantation, leading to an economic loss. Even when considering only private costs (excluding ecosystem services), development has occurred rapidly. When ecosystem services and the costs of infectious disease are included, this effect is even stronger and indicates that the current level of land conversion (> 25%) is approaching double the social optimum (~15%) (8) (Figure 8).

Figure 8: The Optimal Path of Land Conversion for Sabah.

The model considers that there are **unavoidable environmental and health costs (everything under the green dotted line)**. In principle, this is the "**social optimum**". Anything above that line is considered a loss due to **excessive land conversion**. We then compared this number against two scenarios the economic loss due to: 1) **Just malaria costs** (orange dotted line) and 2) **Malaria plus ecosystem services** (green dotted line) (9).

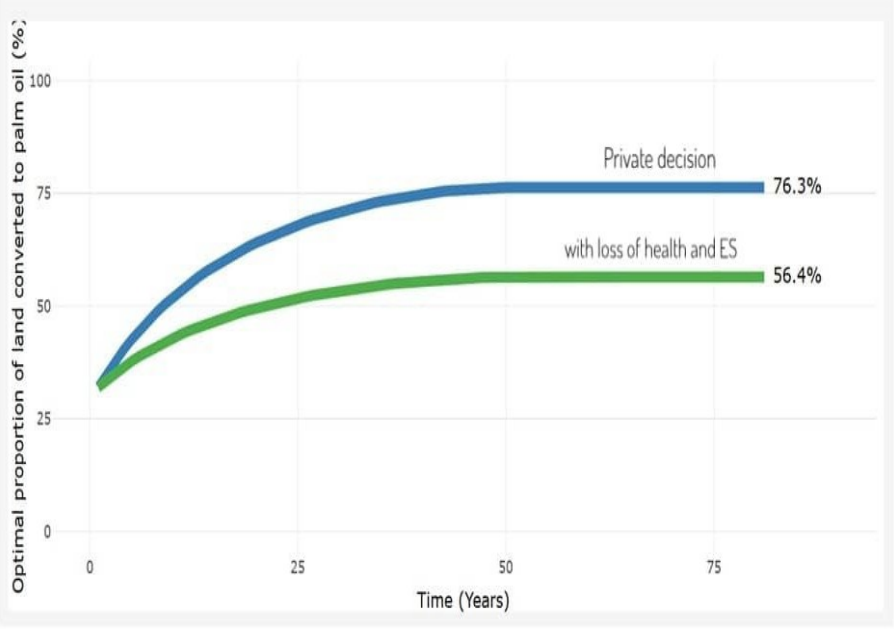
The figure below shows that there has been an economic loss to the citizens of Sabah, through a loss of ecosystem services and increased malaria health costs and shows that the oil palm industry is not maximizing its net benefits. The blue lines represent the current value of converting land into palm oil considering only the private profits which is estimated at US$ 1.1 billion, and the green line represents the present value of converting land into palm oil also considering the social costs of malaria and the loss of ecosystem services is US$352 million. The difference between these two present values is considered the economic loss due to **increased malaria incidence and loss of ecosystem services through excessive land conversion in the past 30 years, and it is estimated at US$748 million or an average of US$25 million annually** ($1100 million - $352 million = $748 million over 30 years. The annualized estimate is 748/30 = 24.9 or approx. $25 million per year) (9).



In Peninsular Malaysia, consideration of infectious diseases costs and the value of ecosystem services reduces the optimal level of land conversion by 20% (9) (Figure 9).

Figure 9: Optimal Path of Land Conversion for Peninsular Malaysia.

The blue line shows the land conversion schedule when just considering benefits and costs of oil palm operations (this is the "private optimum" because all that is included is what matters to industry). The green line shows the land conversion schedule considering multitude of factors such as benefits and costs of oil palm operations, crude oil palm yield/hectare, percentage of forested land, ecosystem services and disease burden (the "social optimum") (9).



IDEEAL examined how different ecological, and land-use change variables impacted the number of malaria cases in each location. The results showed that these variables differed across regions and timescales, ranging from precipitation to amount of flood, forest, or cropland. When considering the link between deforestation and malaria, the IDEEAL economic model indicates that Sabah, Malaysia has exceeded the optimal amount for forest to agricultural land conversion.

Currently IDEEAL incorporates only the cost of malaria into its model. However, our framework is flexible and can be adapted to include other diseases whose transmission is also linked to land-use change like deforestation. Were IDEEAL able to reduce malaria cases by just 10% in Sabah, it could reduce Sabah's annual mitigation expenditure of US$8.9 million (6). Simply put, for each dollar invested in utilising science-based land-use planning tools to reduce malaria, Sabah's government stands to save US$4 that it can pass to its citizens (7). The cost in figure 8 (average of US$25 million annually) consider **both the costs of malaria and lost ecosystem services** (e.g., carbon sequestration) and the $8.9 million **is just Malaria** costs. The return on this investment has the potential to be even higher when considering the potential for sustainable land management policies to reduce the risk of a spillover event like Nipah virus in 1999.

Improving land-use management is a vital step in reducing the risk of disease emergence and minimizing the potential economic and public health impacts of land-use change. This is something governments across the world need to consider, but for a country like Malaysia that is at increased risk due to its geographic location and natural environment, this effort is even more important to protect the economy, public health, and the environment. Utilising the risk maps and modelling from PREDICT and IDEEAL, proper land-use planning tools, and environmental impact assessments can help the Malaysian government plan for future development maximizing profits, while minimizing the risk of disease spillover and the negative impacts of land-use change.

To improve land-use management this report suggests the following steps that could be taken to help achieve this in Malaysia.

1) Consider land-use planning's negative impacts on human, animal, and environmental wellbeing for future proposed land development.

2) Promote the adoption of science-based land-use planning tools for more sustainable land management. The IDEEAL framework developed a blueprint for policymakers to identify the optimal annual rate of conversion, as well as areas of land that should be protected. The project quite literally pointed out areas which were and were not suitable for development. The PREDICT maps provided further country-level spatial information on disease spillover risk and expected number of zoonoses in mammals. Utilising the IDEEAL framework and the PREDICT maps or similar tools and maps will allow policy makers to make more informed decisions about where and where not to develop land, maximizing profits and minimizing negative economic and health impacts.

3) Improve industry practices and regulations to reduce health-associated costs to communities. For example, recommending the optimal fine, under Section 13(1) of the Destruction of Disease – Bearing Insects Act 1975, for violations of disease control regulations by companies whose economic activity may increase the risk of infectious diseases; require companies whose economic activity may increase the risk of infectious diseases to provide health facilities in areas where they plan to operate to help deal with this increase risk to their workers and the local population; or ensure that these companies take preventive measures such as providing treated bed nets and screens on windows of staff housing. This recommendation could be achieved by extending and enforcing Act 446 Workers Minimum Standards of Housing and Amenities Act 1990 throughout Malaysia not just for Peninsular.

4) All proposed development projects regardless of size should be assessed with an environmental impact assessment, utilising science-based land-use planning tools including cost-benefit analysis, to consider the negative impact on the health of humans, wildlife, and the environment; to ensure the development and its planned location is sustainable and to provide recommendations on industry practices related to that development.

Using Sabah as an example, the implementation of sustainable land management will cost the Sabah government approximately RM859,390.00 (US$217,000.00). This would allow for the creation of a unit to carry out a proper review, utilising science-based land-use planning tools, of all proposed development projects to consider the negative impact on the health of humans, wildlife, and the environment; to ensure the development and its planned location is sustainable and to provide recommendations on industry practices related to that development (Appendix Table 3).

This paper contains information relevant to the following agencies: Sabah Forestry Department, Sabah Lands & Surveys Department, the State Economic Planning Unit, Sabah Land Development Board, Sabah Forest Development Authority, Sabah Wildlife Department, Sabah Agriculture Department, Sabah Department of Irrigation & Drainage, Sabah Rubber Industry Board, Sabah Biodiversity Centre, Ministry of Rural Development, Ministry of Water, Land & Natural Resources, Ministry of Tourism, Culture and Environment, Sabah Environment Protection Department, Sabah State Health Department, Ministry Of Health, Sabah Economic Development Corporation, Universiti Malaysia Sabah, Department of Wildlife and National Parks (Peninsular Malaysia), Department of Veterinary Services, Universiti Putra Malaysia, National Wildlife Forensic Lab, National Public Health Lab, Veterinary Research Institute, Universiti Malaysia Sarawak, Sarawak Forestry Corporation, the Construction Industry Development Board and any other stakeholder involved in land-use change. **Collaboration between these agencies following the recommendations of this paper will help ensure sustainable economic development for Malaysia, while protecting the health of Malaysians, and the unique environmentthat is so important for tourism and the health of its animals and people.**

<u>Report Prepared by –</u>

Tom Hughes, Malaysia Project Coordinator EcoHealth Alliance / Director Conservation Medicine

Mei Ho Lee, Laboratory Coordinator EcoHealth Alliance / Conservation Medicine

Velsri Sharminie, Programme Assistant EcoHealth Alliance / Conservation Medicine

Jimmy Lee, Field Coordinator EcoHealth Alliance / Conservation Medicine

Carlos Zambrana-Torrelio, Associate Vice President EcoHealth Alliance

Yasha Feferholtz, Senior Economist EcoHealth Alliance

Noam Ross, Principal Scientist, Computational Research EcoHealth Alliance

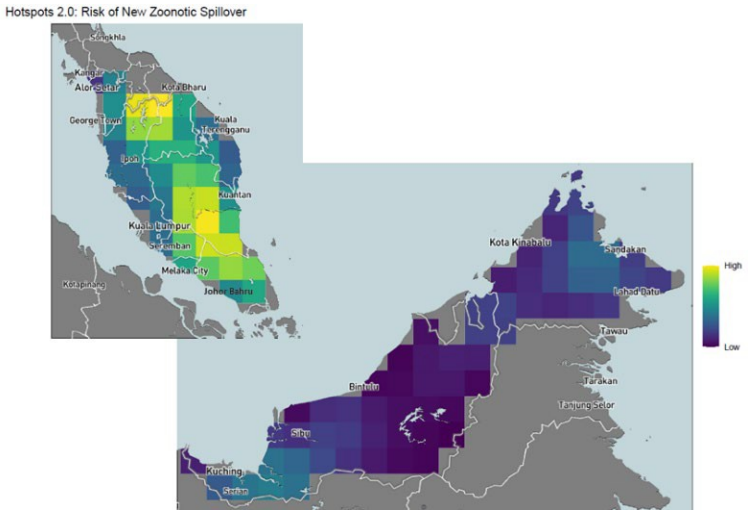
Emma Mendelsohn, Research Scientist EcoHealth Alliance

Peter Daszak, President EcoHealth Alliance

Appendix.

Figure 10: Hotspots 2.0: Risk of New Zoonotic Spillover.

This map of the relative spatial risk of new zoonotic spillover is based on the PREDICT Hotspots 2.0 model, a global model fit to 224 new disease emergence events found in the scientific literature (3 of which occurred in Malaysia) (14). Risk of a new spillover event into humans is modelled and predicted based on a variety of demographic, environmental and biological variables. The model corrects for differences in reporting and surveillance effort within and between countries.

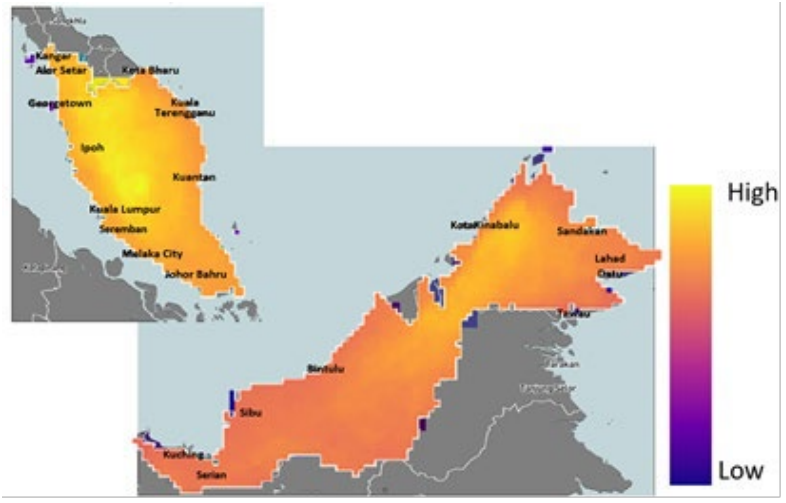


Host Pathogen Phylogeny Project: Predicted Zoonotic Viruses.

This map shows the relative expected predictions of zoonotic viruses to be found in mammal species according to the PREDICT Host Pathogen Phylogeny Project (HP3) model.

Figure 11: Predicted Zoonotic Viruses in All Mammals.

This model predicts the number of zoonotic viruses to be found in a mammal species based on ecological and taxonomic traits. Here we convert this to a spatial measure by mapping these predictions over mammal host ranges (15).



In Sabah, we found that of all the species sampled, *Hipposideros cervinus* and *Rhinolophus creaghi* bat species had the highest viral detection, with 17 viral detections and 9 unique viruses, and 18 viral detections with 8 unique viruses, respectively. For rodents and shrews in Sabah, *Sundamys muelleri* and *Maxomys whiteheadi* had the highest viral detection with 6 viral detections and 2 unique viruses, and 4 viral detections with 2 unique viruses, respectively.

For Peninsular, we found that of all the species sampled *Eonycteris spelaea, Nycteris tragata, Tylonycteris pachypus* and *Pipistrellus coromandra* bat species all had viral detection of 1 with 1 unique virus, respectively. For rodents and shrews *Maxomys whiteheadi* was the only species that had viral detection with 1 viral detection with 1 unique virus (13).

Key Geospatial Variables.

Below we provide maps of several variables important for predicting the risk of new zoonotic disease emergence and the presence of zoonotic viruses based on density.

Figure 12: Human Population Density.

Human population density is a major predictor of locations of new zoonotic disease outbreaks. Also, mammal species with habitat in urban areas host more zoonotic viruses. We present human population density on a log-scale for easier visualization (31).

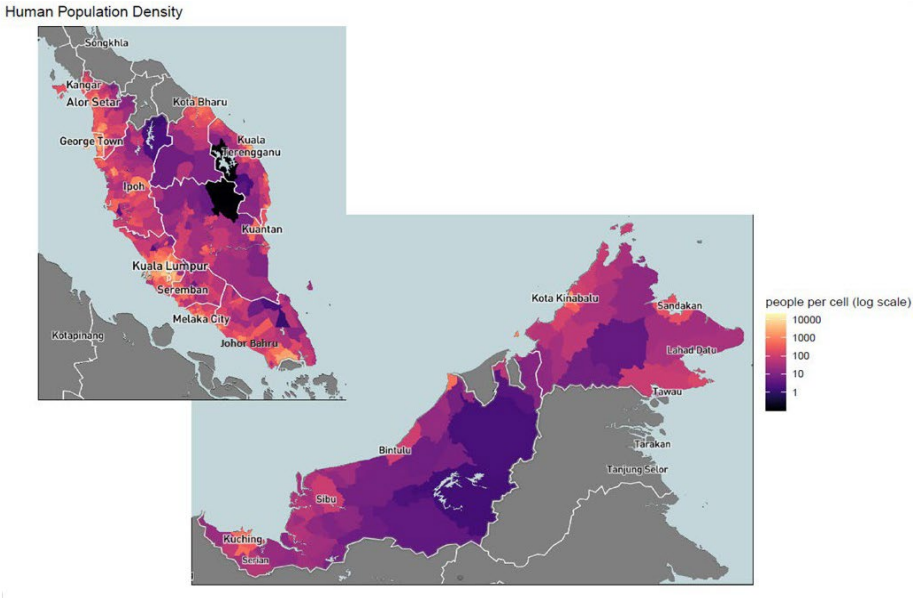


Figure 13: Mammalian Livestock Density.

Mammalian livestock density is an important predictor of zoonotic disease risk as livestock often act as "bridge hosts" in spillover of disease from wildlife. Here we show the total combined livestock population density of buffaloes, cattle, goats, pigs, and sheep. These densities are calculated from an FAO model that combines animal census data with predictors including several vegetation, climate, topography, and demography variables. We present mammalian livestock density on a log-scale for easier visualization (31).

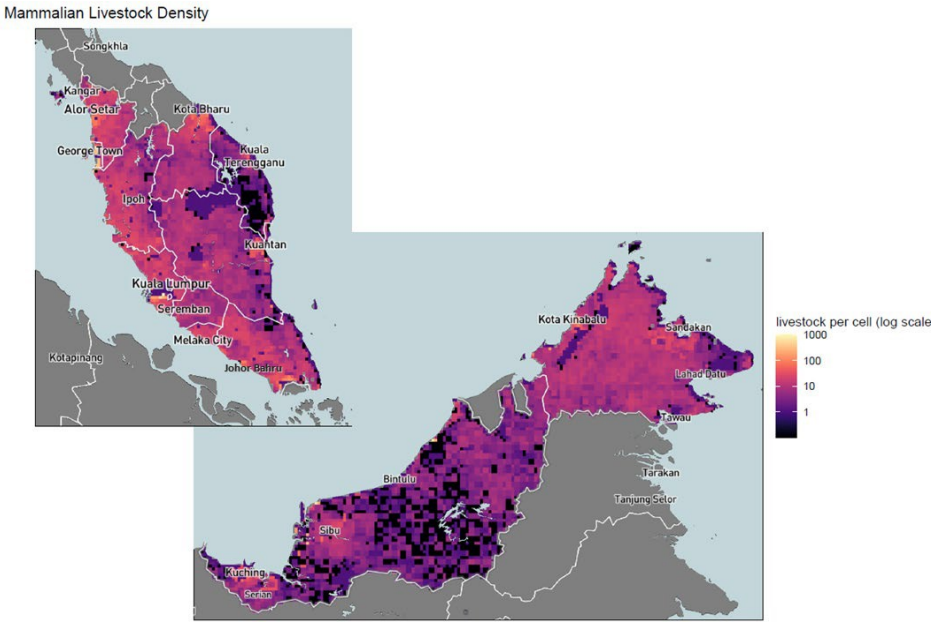
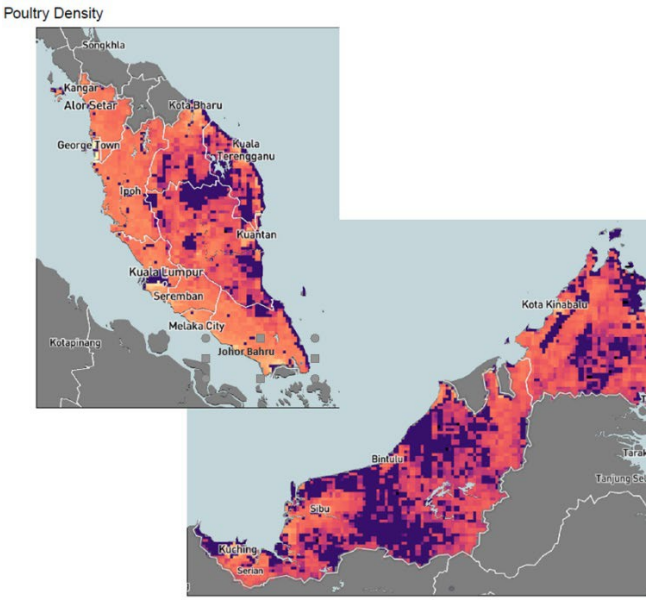


Figure 14: Poultry Density.

Poultry densities are also a predictor of zoonotic disease spillover, and poultry are a major source of influenza viruses. These densities are calculated from an FAO model that combines animal census data with predictors including several vegetation, climate, topography, and demography variables. We present poultry density on a log-scale for easier visualization (31).



Recent Land-Use (2005) and Land-Use Change (1970 - 2005): Land-cover and land-use are important determinants of zoonotic disease risk. Areas with high forest cover as well as areas undergoing pasture-land expansion or contraction are more likely to have zoonotic spillover events. Here we combine several datasets to provide a summary of recent (2005) human land-use and land-use change from the year 1970 - 2005.

Figure 15: Recent Land-Use (2005).

We classify areas into Urban or Crop. Urban cells are defined as those containing greater than 25% urban land. Cells with at least 50% human land-use are assigned Crop, depending on the most dominant of those two categories. Areas with less than 50% human land-use and less than 25% urban land are not assigned a land-use type (37, 38).

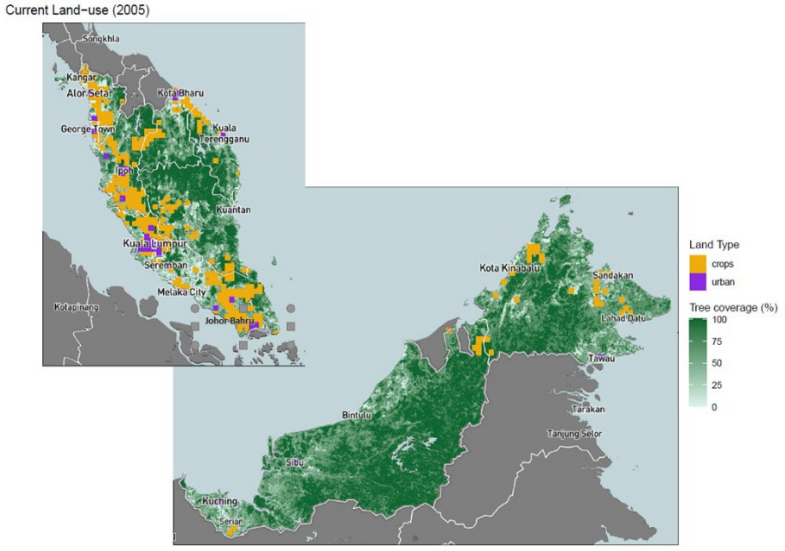


Figure 16: Land-use change (1970 - 2005).

Shows the changes in land-use and urban area from 1970 - 2005. Changes in land-use are important in predicting zoonotic risk as interfaces with wildlife can occur along the "frontier" of development into wild areas. Here, we assign human land-use categories as in figure 15 for both 1970 and 2005, and show urban, and cropland areas that expanded during that period (37, 38).

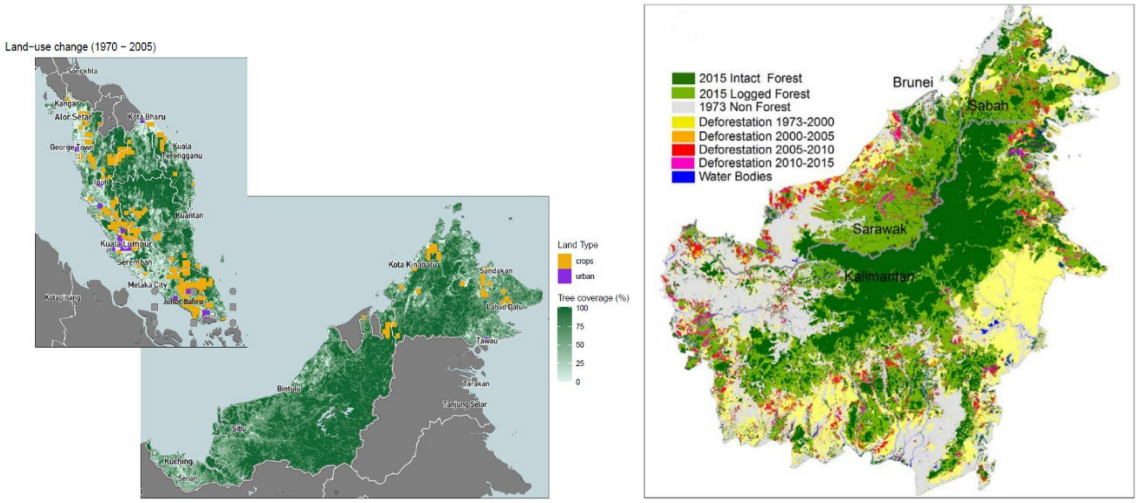


Figure 17: Land-Use Maps for Sabah.

These maps illustrate what would have been the best potential places to convert land to oil palm to maximize profit and minimize loss. There are two scenarios for land development, either by maintaining high or low forest connectivity. Maps could be generated to help guide future development projects by identifying optimal land areas for development (9).

Red areas best for conversion as they are more connected, yellow and green areas are buffer zones and blue areas should be conserved.

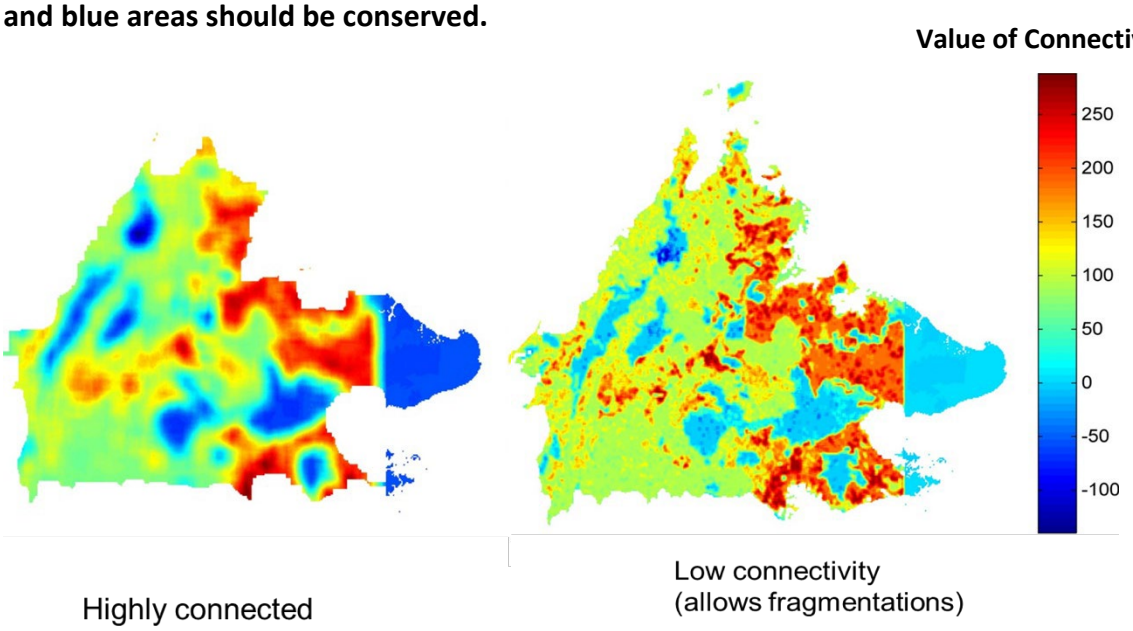
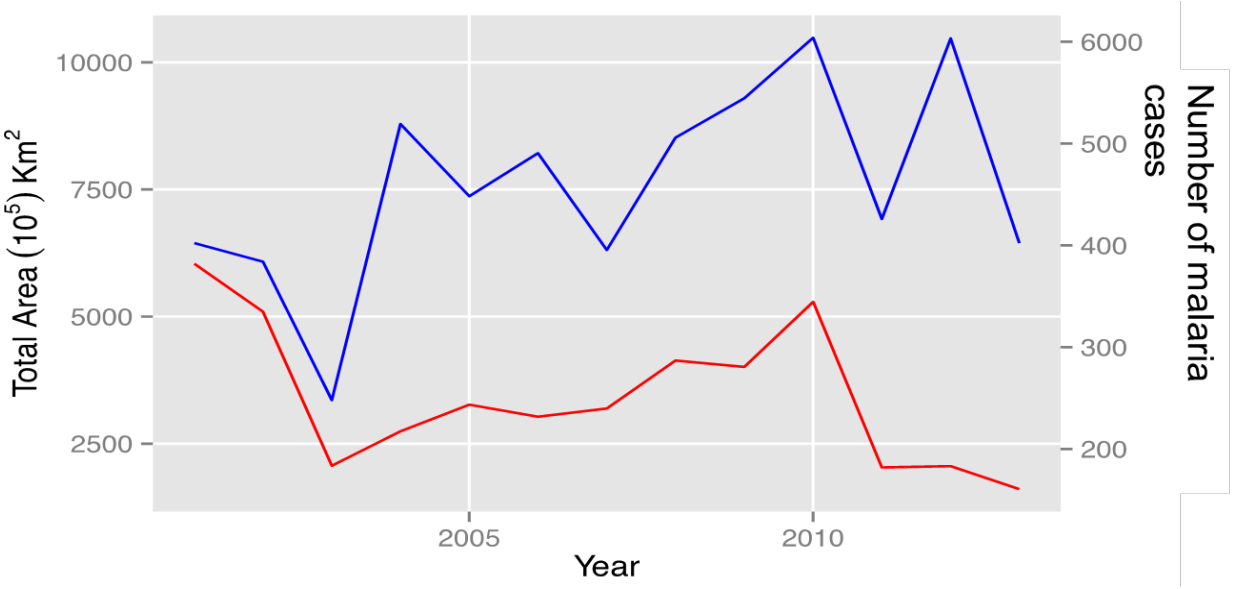


Figure 18: Deforestation and Malaria in Sabah.

This graph shows trends in deforestation and Malaria cases in Sabah.



Red Line - Deforested area in Sabah – Malaysia
Blue Line - the number of cases of Malaria (2001 – 2013)
(Zambrana-Torrelio unpublished data)

Figure 19: Deforestation and Malaria in Sabah.

This Spatial Autoregressive Model estimates the likelihood of malaria cases in a particular district relative to the likelihood of malaria cases in other districts. Standardized mortality/morbidity rate (SMR). An estimated SMR of 3 means that district is 3 times more likely to have malaria cases than its neighbours. Analysis found that SMR is positively related to the number of forest patches (increased fragmentation) and negatively related to total forest area. More forest fragmentation results in more malaria (9).

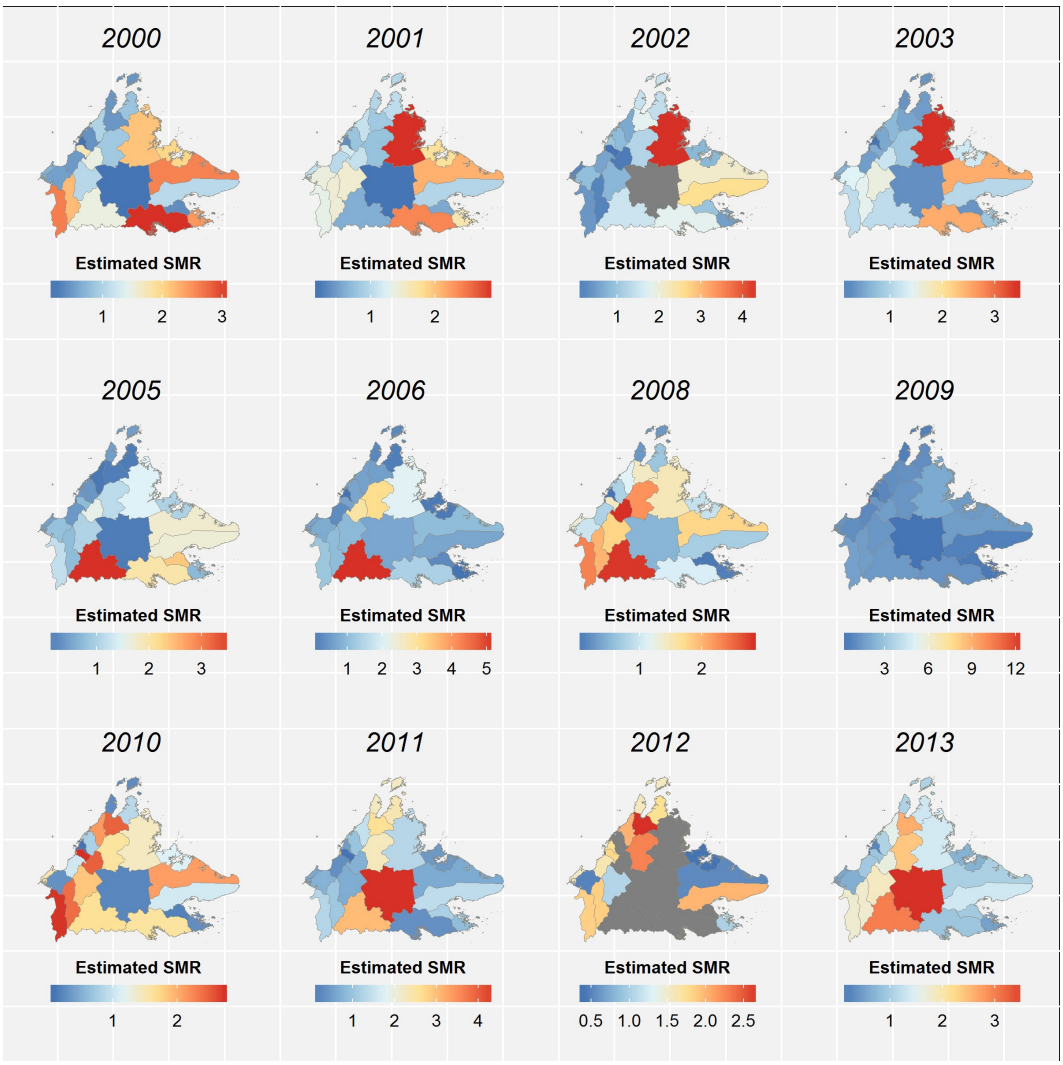


Figure 20: Deforestation and Malaria in Sarawak.

The rate of deforestation in the state of Sarawak, Malaysia is lower than in Sabah. By 2011, around 11% of Sarawak had been converted to palm oil plantations, compared to the 27% of land in Sabah. Risk of malaria across Sarawak varies every year, likely because of prevention methods employed. Drivers of malaria incidence were related to climate and water availability, specifically to precipitation, saltwater flood regions, water bodies and irrigated cropland (9).

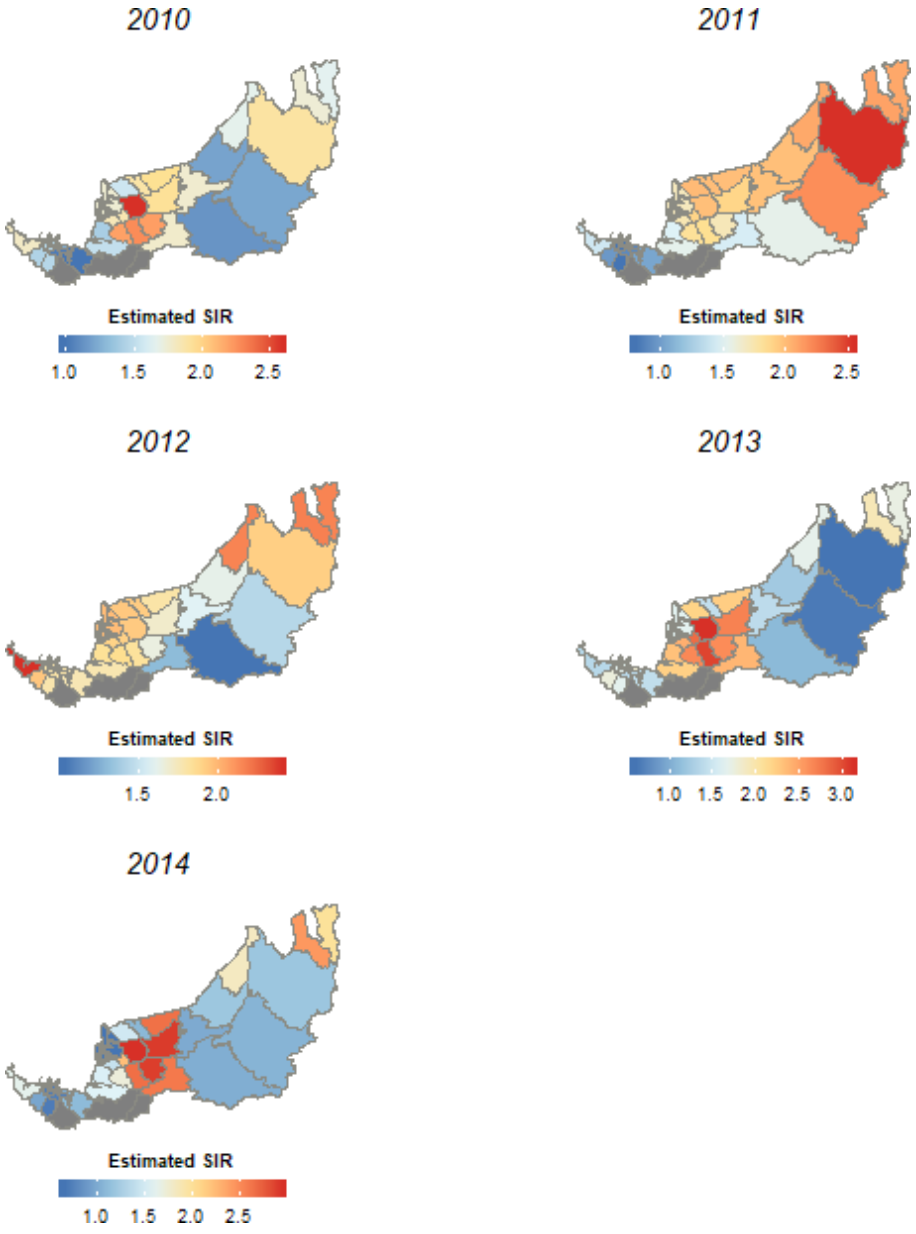


Figure 21: Deforestation and Malaria in Peninsular Malaysia.

This Spatial Autoregressive Model estimates the likelihood of malaria cases in a particular state relative to the likelihood of malaria cases in other states. Standardized mortality/morbidity rate (SMR). An estimated SMR of 100 means that a particular state is 100 times more likely to have malaria cases than its neighbours. Analysis found that SMR is negatively related to total forest area. More forest fragmentation results in more malaria.

The standardized morbidity ratio for malaria varies over space and time and is related to the amount of deforestation. Main drivers of malaria incidence in Peninsular Malaysia are variables related to agricultural activities such as irrigated croplands area, urban areas, patch density of shrubs, and patch density of irrigated croplands (9).

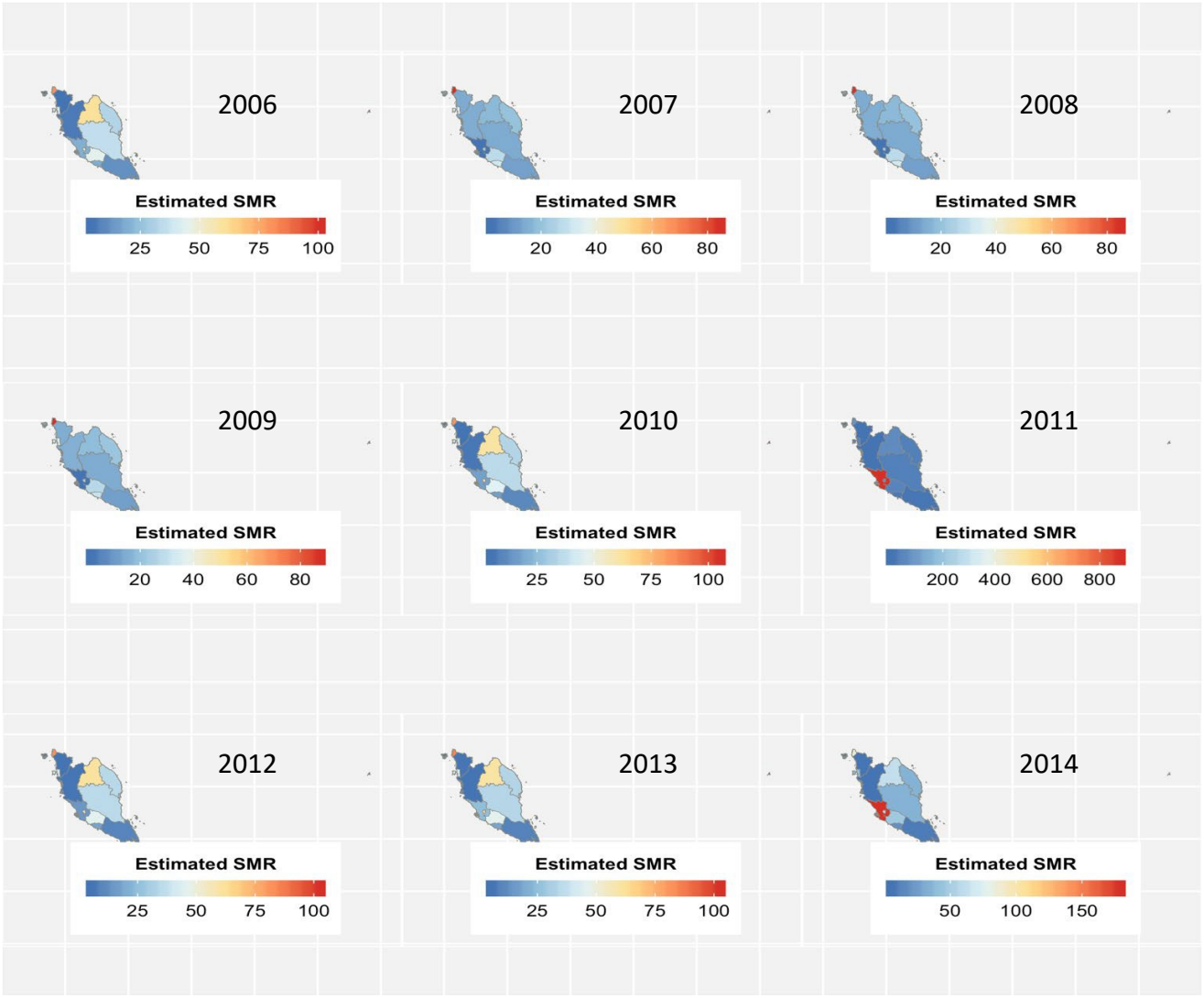


Table 1: National Funding for Malaria in Malaysia (28).

Year	Malaysian Government (NMCP) (USD)
2015	68.88 Million
2016	39.70 Million
2017	48.36 Million

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IDEEAL Baseline Surveys.

The IDEEAL project collected baseline and updated information from stakeholders (including local communities) on infectious disease and land-use topics to assess how visibility and understanding of these topics differed by demographic characteristics and over the period of the project. Brief questionnaires were designed as an informal modelling tool and distributed to key stakeholders during stakeholder and other outreach meetings. Between 2014 and 2017, 1,047 individuals completed the 46-item baseline questionnaire with at least 50 participants completing the questionnaire twice. Participants were asked to report perceived risk of several scenarios regarding interactions with animals and wildlife. For all questions, most respondents reported at least some perceived risk ("somewhat risky") associated with each action. Participants were also asked if they were aware of diseases linked to agriculture, logging, and hunting. Of those participants who listed a disease, malaria was the most common response across all three interfaces (9) (Table 2).

Table 2: Most common diseases across environments identified by stakeholders.

RESPONSE	TOTAL	AGRICULTURE	HUNTING	LOGGING
Malaria	541	123	185	233
Dengue	250	54	84	112
Fever	192	73	45	74
Itchy Skin	139	60	33	46
Skin Diseases	101	36	18	47
Coughing	99	34	7	58
Flu	79	28	18	33
Headache	64	37	4	23
Diarrhea	61	18	7	36
Vomiting	45	20	14	11

Table 3: Summary Annual Budget to establish a unit to review all proposed development projects.

To execute cohesive and successful projects within a development unit like the one proposed here, it is necessary to have a team of professional experts who can conduct research and implement the results. Below is the description for each position:

- The Project Manager oversees the team. It is the person with the highest responsibility in the team. This position gives directions and manages the execution and analysis of each project.
- The Communication Officer oversees public relations and make the analysis available to the public.
- The Economist conduct economic analysis and mathematical modelling for the projects.
- The Data Analyst manages the data collected and conducts data analysis for the team. Ample experience in Geographic Information Systems (GIS) and statistical software.
- The Forest Conservation Officer, Land Planning Officer, and Estate/Plantation/Park Manager oversee all issues related with land-use change and forest/plantation planning. They assist the rest of the team on forest and plantation related issues. They make sure that the analyses conducted by the team are relevant to the specified region.
- The Researcher supports all the research activities of the team.
- The Program Assistants support all the administrative work of the team.

Summary Annual Budget	
Category	**Cost per year**
Personnel	RM712,344
Travel	RM21,218
Materials & Supplies	RM47,702
Total	RM781,264
Administration (10%)	RM78,126
Total (Indirect + Direct)	**RM859,390**

Personnel	Annual Average Salary Malaysia
Data Analyst/ IT	RM71,598.00
Economist	RM69,792.00
Project Manager/ Admin Officer	RM69,756.00
Researcher	RM71,598.00
Program Assistant / Assistant Investigation Officer	RM73,830.00
Program Assistant / Assistant Environmental Health Officer	RM72,510.00
Communication Officer / Strategic Communication Officer	RM73,830.00
Land Planning Officer	RM69,810.00
Forest Conservation Officer	RM69,810.00
Estate/ Plantation/ Park Manager	RM69,810.00
Total Personnel	**RM712,344.00**

Table 4: IDEEAL partners and stakeholders.

The following have attended IDEEAL meetings at the Development and Health Research Unit set up at Universiti Malaysia Sabah, and/or have helped provide or compile data, and/or helped review the data sets and model and/or helped put together the IDEEAL toolkit for stakeholder engagement.

- BC Initiative
- Bornean Rhino Alliance
- Biotechnology Research Institute, Universiti Malaysia Sabah
- Danau Girang Field Centre
- Department of State Health Sabah
- Department of Veterinary Services
- Department of Wildlife and National Parks (Peninsular Malaysia)
- EcoHealth Alliance
- Faculty of Business and Economics and Accounting, Universiti Malaysia Sabah
- Faculty of Humanities, Art and Heritage, Universiti Malaysia Sabah
- Faculty of Medical and Health Sciences, Universiti Malaysia Sabah
- Forest Research Institute Malaysia
- Human Resource Ministry
- HUTAN
- Faculty of Science and Natural Resources, Universiti Malaysia Sabah
- Institute for Tropical Biology and Conservation, Universiti Malaysia Sabah
- Johnson and Johnson Company
- Kota Kinabalu City Hall
- LEAP - Land Empowerment Animals People
- Living Landscape Alliance
- Ministry of Health
- Ministry of Housing and Local Government
- Ministry of Water, Land and Natural Resources
- Malaysian Palm Oil Council
- National Public Health Laboratory
- National Wildlife Forensic Laboratory
- Proctor and Gamble
- PACOS Trust - Partners of Community Organisations Sabah Trust
- Roundtable on Sustainable Palm Oil Sabah Economic Development Corporation
- Sabah Department of Fisheries
- Sabah Department of Veterinary Services
- Sabah Economic and Development and Investment Authority (SEDIA)
- Sabah Forestry Department
- Sabah Labour Department
- Sabah Land and Surveys Department
- Sabah Public Works Department
- Sabah State Health Department
- Sabah State Water Department
- Sabah Town & Regional Planning Department Sabah Wildlife Department
- Sarawak Forestry Corporation
- Sime Darby
- Universiti Malaysia Sabah
- Universiti Malaysia Sarawak
- Universiti Putra Malaysia
- United States Agency for International Development
- Veterinary Research Institute
- Wilmar International
- World Wildlife Fund (WWF)

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Zika: World Bank report. The short-term economic costs of Zika in Latin America and the Caribbean 2016 (http://pubdocs.worldbank.org/en/410321455758564708/The-short-term-economic-costs-of-Zika-in-LCR-final-doc-autores-feb-18.pdf)

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(6) The present value at a 5% discount rate of costs to perpetuity is US$178 million. Assuming the cost of implementation is approximately US$3.8 million. The 10% reduction in costs is equal to US$14 million (US$178*10% – US$3.5).

(7) Return on investment (ROI) = US$14 million/ US$3.5 million = 4 times higher. This implies that for each dollar invested in the project, the social return is 4 dollars.

(8) Given a ROI of 4, an investment of US$500,000 could return US$2 million (US$500,000*4).

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