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Prediction, Assessment of the Rift Valley Fever Activity in East and Southern Africa 2006–2008 and Possible Vector Control Strategies

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Abstract. Historical outbreaks of Rift Valley fever (RVF) since the early 1950s have been associated with cyclical patterns of the El Niño/Southern Oscillation (ENSO) phenomenon, which results in elevated and widespread rainfall over the RVF endemic areas of Africa. Using satellite measurements of global and regional elevated sea surface temperatures, elevated rainfall, and satellite derived-normalized difference vegetation index data, we predicted with lead times of 2–4 months areas where outbreaks of RVF in humans and animals were expected and occurred in the Horn of Africa, Sudan, and Southern Africa at different time periods from September 2006 to March 2008. Predictions were confirmed by entomological field investigations of virus activity and by reported cases of RVF in human and livestock populations. This represents the first series of prospective predictions of RVF outbreaks and provides a baseline for improved early warning, control, response planning, and mitigation into the future.

INTRODUCTION

Rift Valley fever (RVF) is a mosquito-borne viral disease with pronounced health and economic impacts on domestic animals and humans in much of sub-Saharan Africa.[1] The economic loss from RVF in East Africa is estimated to exceed $60 million because of disruption in trade from the recent epizootics between 2006 and 2007.[2] The disease causes high mortality and abortion in domestic animals, and significant morbidity and mortality in humans. The RVF epizootics and epidemics are closely linked to the occurrence of the warm phase of the El Niño/Southern Oscillation (ENSO)[3] phenomenon and elevated Indian Ocean temperatures that lead to heavy rainfall and flooding of habitats suitable for the production of immature *Aedes* and *Culex* mosquitoes that serve as the primary RVF virus (RVFV) vectors in East Africa.[4,5] Previous research has shown that the life cycle of RVFV has distinct endemic and epidemic cycles. During the endemic cycle the virus persists during dry season/inter-epizootic periods through vertical transmission in *Aedes* mosquito eggs (Figure 1).[4] Flooding of mosquito habitats can introduce RVFV into domestic animal populations by the production of vertically infected *Aedes* mosquitoes (Figure 1). Epizootic/epidemic cycles are driven by the subsequent elevation of various *Culex* mosquito populations, which serve as excellent secondary vectors if immature mosquito habitats remain flooded long enough.[5] On the basis of this previous research, we have developed a monitoring and risk mapping system[6,7] that uses a variety of satellite measurements including sea surface temperatures, outgoing longwave radiation, rainfall, and landscape ecology using the normalized difference vegetation index (NDVI). The measurements represent the total variety of climate and ecological drivers that would lead to conditions associated with the emergence of RVFV vectors resulting in episodic patterns of epizootics/epidemics through time. These data are input into an RVF prediction system to map in a dynamic manner areas at potential risk for RVF activity.[6] This system operates in near real-time to monitor RVF risk on a monthly basis and offers the opportunity to identify eco-climatic conditions associated with potential vector-borne disease outbreaks over large areas, and has been in operation for the last 10 years.[7] The system predicted conditions likely to lead to an RVF outbreak in East Africa in September 2006, 3 months before confirmation of disease transmission by the end of November 2006 and human RVF cases mid-December 2006.[8] In this work we focus on the assessment of the predictions with regard to the clusters of outbreaks in East Africa (Kenya, Somalia, and Tanzania): September 2006–May 2007; Sudan: May 2007–December 2007; and Southern Africa and Madagascar: September 2007–May 2008. The dates mentioned previously represent the time periods when elevated rainfall occurred at least 2 to 3 months before reported RVFV activity (Figure 2). In all of the regions examined except for Madagascar, most of the areas where RVF cases were reported received in excess of 200 mm of rainfall during the outbreak period with the highest excess rainfall occurring in East Africa with amounts up to +400 mm. Details of the setup and implementation of the monitoring and prediction system have been presented in previous works.[3,6–8]

RVF risk mapping prediction and assessments. As described by Anyamba and others,[8] RVF risk maps are produced both at continental and regional scale on a monthly basis. This moving window implementation insures that the risk mapping is dynamic

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14. ABSTRACT
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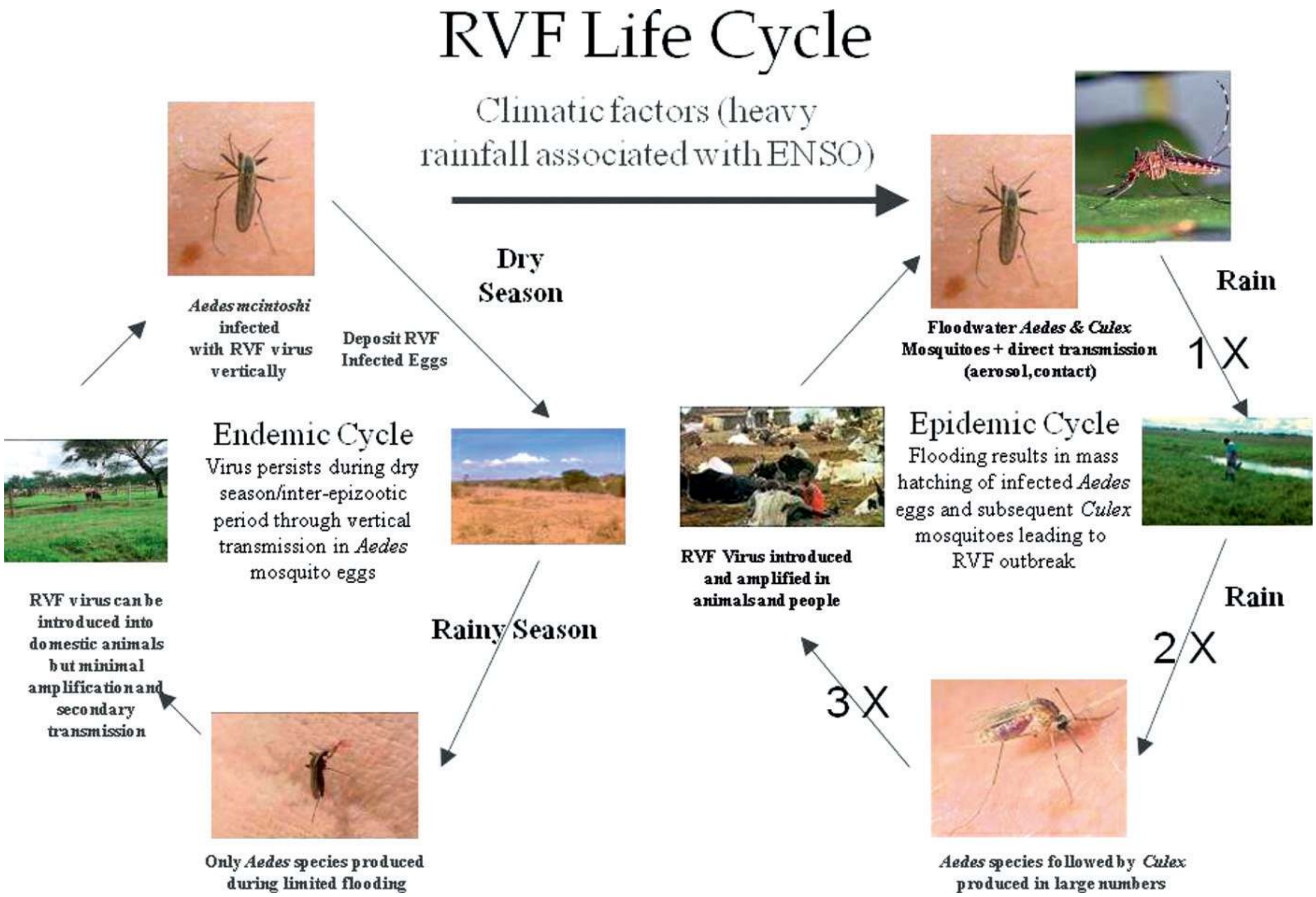

FIGURE 1. Endemic (on left) and epidemic (on right) life cycles of Rift Valley fever involving close association between heavy rainfall conditions, vector *Aedes* and *Culex* mosquitoes, domestic animals, and humans. The epidemic cycle is precipitated by excessive heavy rainfall associated with the El Niño/Southern Oscillation (ENSO) climatic phenomena. The three Xs depicted in epidemic cycle represent critical pathways, which can be interrupted by targeted and specific mosquito control activities.

and captures the changing nature of climatic and ecological conditions that inherently determine areas at risk to RVF. The assessment of the risk predictions are both 1) general, i.e., did the event occur in the region of concern; and 2) specific, i.e., did any RVF human or livestock case occur both in the month mapped to be at risk and at anytime during the entire period for the time periods outlined above for each of the region? For each of the regions under consideration the general risk predictions were confirmed by RVF activity reported in East Africa, Sudan, Southern Africa, and Madagascar. The specific assessment can be considered as "post-outbreak evaluations" because all human cases had illness or mortality confirmed as an RVF infection from a variety of field data sources collected by various agencies, including national governments, Institut Pasteur of Madagascar, World Health Organization (WHO), and the U.S. Centers for Disease Control and Prevention-Kenya (CDC-K).

Human case data were collected and compiled for Kenya by the Ministry of Health Kenya (MoH-K) in collaboration with CDC-K and WHO, for Somalia by WHO, for Tanzania by Ministry of Health and WHO, for Madagascar by Ministry of Health and Institut Pasteur of Madagascar, for Sudan by Sudan Federal Ministry of Health and WHO, and for South Africa by the National Center for Infectious Disease (NCID). In general, all human RVF case data were compiled in spread sheet format and made available in May 2007 for East Africa, January 2008 for Sudan, March 2008 for South Africa, and May 2008 for Madagascar.

The MoH-K/CDC-K data were the most complex including the following data fields: case ID number, location (district, division, location, sub-location, and village), latitude and longitude, sex and age of the individual, (estimated) date of onset of RVF, RVF case outcome, and current status of the individual with date. The individuals listed in the MoH-K/CDC-K data set were assigned to seven districts of Kenya: Baringo, Garissa, Ijara, Isiolo, Kilifi, Tana River, and Wajir. Metadata supplied with the data set described the methods used to geocode case locations when villages were specified. The village level latitude-longitude reading was first searched for in three gazetteers that each had a slightly different list of village names and locations; a note was provided if a village name was found, but the location did not appear to be in the correct province. However, no notation was entered if a village location was simply, for instance, on the wrong side of a river. If the village name was not found in any gazetteer, sublocation, location, or division centroids were recorded. For Kenya, of the 700 reported cases, 158 were deaths (CFR 22%) and 272 were confirmed RVF cases.

For the purposes of mapping human RVF cases for this study we ignored case categories of "not a case," leaving 412 cases requiring spatial data. Of these 412 cases 83 were missing latitude-longitude data. Although many of the 412 cases were

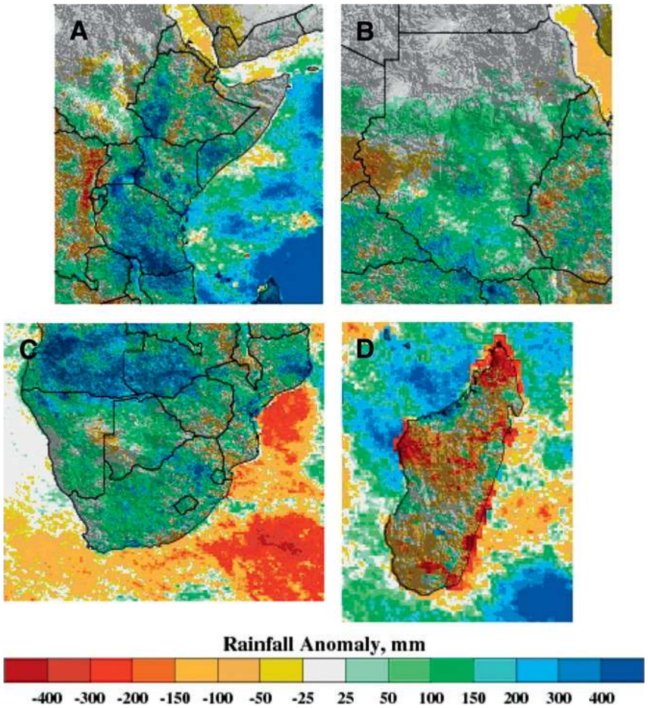

FIGURE 2. Cumulative rainfall anomalies for (**A**) East Africa: September 2006–May 2008. (**B**) Sudan: May–November 2007. (**C**) Southern Africa: September 2007–May 2008. (**D**) Madagascar: September 2007–May 2008. Except for Madagascar, all the regions received an excess of 200 to 400 mm of rainfall during the respective Rift Valley fever (RVF) outbreak periods.

listed with location information down to the village level, a large proportion was listed only down to the location or sublocation level. A cursory analysis also revealed that an irregular mosaic of spatial information existed in the data set, in accordance with the notations detailed in the metadata. For instance, the same latitude-longitude was assigned to several individuals who had a heterogeneous set of division and sublocation data; or an individual could be listed with a village name but no latitude-longitude. A more detailed analysis revealed individuals assigned to villages but with the wrong higher-level division assignment and revealed that some latitude-longitude data, when plotted in a Geographic Information System (GIS), placed the individual in a location incongruous with the assigned division. As far as possible, we corrected these irregularities and verified all locations with a detailed, cross-checked survey of digital/GIS gazetteer data obtained from the International Livestock Research Institute (ILRI), NASA WorldWind 1.4, and Google Earth 4.2. Detailed data regarding the ultimate source(s) of information for all cases were recorded in the spreadsheet throughout the process. Ultimately, many cases could not be spatially resolved below the centroid of division or location/sublocation, and of the 412 cases requiring spatial data, 61 could not be spatially resolved with confidence and were excluded, leaving 339 case locations. When the 339 locations were collated by latitude-longitude we produced a data set with 94 points each representing one to 35 cases, distributed among the seven Kenya districts. A similar set of human RVF case data was obtained from the WHO in May 2007, describing 64 points each representing one to 25 cases from early December 2006 to late April 2007 across Somalia, Kenya, and Tanzania. This dataset was a compilation of the epidemiological data that were shared by national authorities with WHO during field investigation and comprise only a confirmed RVF case or probable case with no laboratory results; cases with negative laboratory results were not included in the data set provided by WHO. In this data set, relatively more information was provided to the village level than the MoH-K/CDC-K data set, but in some instances no latitude-longitude data were present. We carried out a similar iterative geocoding search as was done for the CDC data set using several digital/Global Positioning System (GPS) gazetteers and we were able to assign latitude-longitude data to all cases. The two data sets were integrated for post outbreak evaluation. The Sudan Ministry of Health and WHO data set for Sudan, IPM data set for Madagascar, and NCID data for South Africa were evaluated for geo-coding accuracy in a similar manner. The data were all plotted on summary RVF risk maps for each region and are shown in Figure 3.

The overall performance, based on the specific location evaluations, show that the risk mapping performed the best in East Africa with 65% of the human case locations mapped to be in at risk areas, followed by Sudan with 50% of the cases, Madagascar 23%, and Southern Africa with 20%. The good performance of the risk prediction model in East Africa and its low performance for other regions should be interpreted as a combination of several factors including:

1. Livestock case data: A model performance assessment with livestock RVF case data would increase model performance

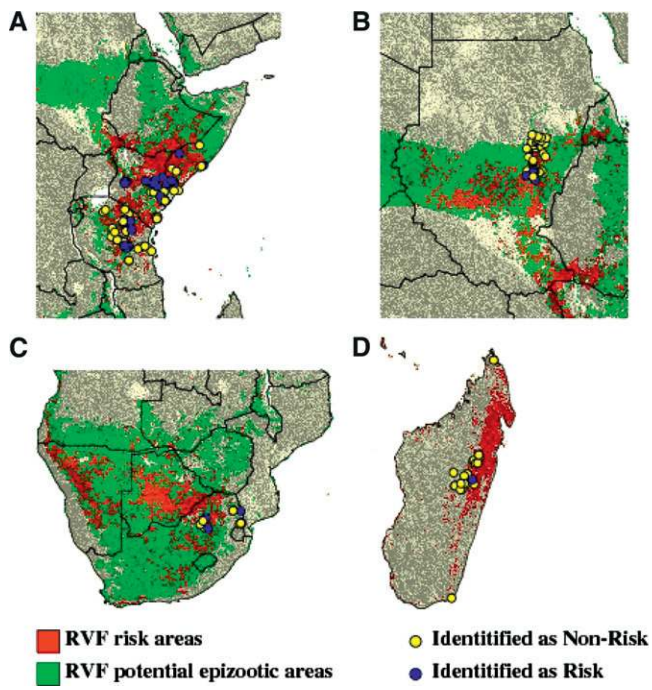

FIGURE 3. Summary Risk Valley fever (RVF) risk maps for (**A**) Eastern Africa: September 2006–May 2007. (**B**) Sudan: May 2007–December 2007. (**C**) Southern Africa: September 2007–May 2008. (**D**) Madagascar: September 2007– May 2008. Areas shown in green represent RVF potential epizootic areas, areas shown in red represent pixels that were mapped by the prediction system to be at risk for RVF activity during the respective time periods, blue dots indicate human cases identified to be in the RVF risk areas, whereas yellow dots represents human cases in areas not mapped to be at risk.

as livestock get primarily infected in the ecological zones where RVF outbreaks initially occur.

2. Human case data are not an optimum indicator of the spatial distribution of RVF cases because some human case data are collected at healthcare facilities, which in a number of these countries could be located as far as 30–100 km from the site of infection.
3. Animal movements and migration: Movement of viremic animals to other ecological zones, as it happened for example in the Ifakara irrigation area in Tanzania, the Gezira irrigation scheme in Sudan, and the irrigated area of Hauts Plateaux in Madagascar, amplified the outbreaks as such areas have large populations of *Culex* species that played a role in creating "secondary" foci of RVF outbreaks in these countries.
4. Livestock surveillance: Most of the countries affected by the outbreaks do not have dedicated operational livestock health surveillance systems therefore RVF animal outbreaks will have been missed in the absence of severe human cases in many locations.
5. RVF potential epizootic area mask (PEAM): Some of the RVF outbreaks along coastal Kenya in 2006–2007, in South Africa in 2008, or in central Madagascar 2008–2009 were outside of the PEAM. The current configuration of the PEAM is largely based on findings from East Africa and interannual variability in rainfall and vegetation associated with ENSO. The mask can be improved by an adjustment in the rainfall and NDVI thresholding and by incorporating more detailed land cover characteristics map information at the regional scale.

Although some of these factors could be addressed and the model performance improved, in some instances (2, 3, and 5) the model cannot realistically capture the other factors.

Additional evaluations were undertaken to examine the time gap between when the first warning was issued for each region versus the approximate time of the first human RVF case for each region. This was only evaluated for Kenya, Tanzania, and Sudan where case records could be used to develop a human epidemiological profile. The results are shown in Figure 4. In East Africa (including Kenya, Somalia, and Tanzania) the first warning alert for RVF outbreaks was issued in September 2006 (Week 38, 2006) and the first index human case in Kenya was reported in mid-December 2006 (Week 49, 2006), whereas in Tanzania the first index case was reported at the end of January/early February 2007 (Week 4, 2007). For Sudan, the first early warning alert was issued in early June 2007 (Week 25, 2007) and the first index human case was identified in early October (Week 41, 2007). For Southern Africa and Madagascar the first early alert was issued in early December 2007 with the first human case identified in South Africa in February 2008. Overall these results indicate that there was a 2–>4-month

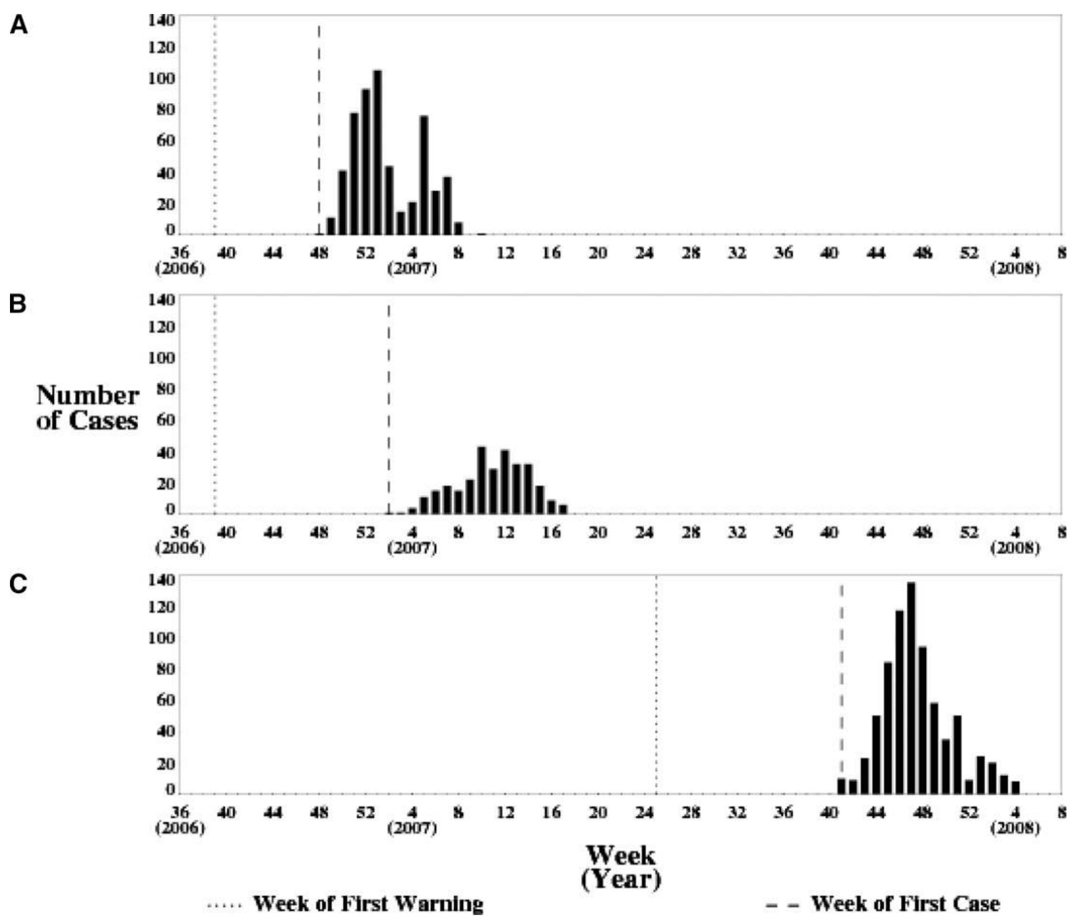

FIGURE 4. Comparison between the timing of the first Rift Valley fever (RVF) early warning alert and the first reported human case of RVF based on epidemiological reports for (**A**) Kenya, (**B**) Tanzania, and (**C**) Sudan. In this case there is a 2–4 month time gap between the early warning alert and the first index human case, which would allow for preventive control and mitigation measures to be undertaken.

period before the first recognized human case during which preventive and control measures could be undertaken to mitigate disease transmission, with the largest lead times for East Africa and Sudan. The long lead time in Sudan might reflect the less efficient surveillance in that region.

Using forecasting information to mitigate RVF impacts during the pre-outbreak period. In East Africa, especially in Kenya and Tanzania, the national governments in collaboration with international partners including WHO, FAO, and CDC created response task forces to deal with the outbreak situation. This was enabled in the first phase by the U.S. Department of Defense – Global Emerging Infections System (DoD-GEIS) Unit of the U.S. Army Medical Research Unit in Nairobi Kenya, Kenya Medical Research Institute and CDC teams in Kenya, which rapidly deployed vector surveillance teams in suspect areas to gauge the extent of virus circulation in mosquito vector populations. Subsequent response and mitigation efforts in at risk areas included: initiation of enhanced surveillance activities, imposition of animal movement restrictions/quarantines, distribution of mosquito nets, dissemination of public information to mobilize social and cultural activities directed at reducing human contact with infected animal products and mosquito vectors, implementation of specific domestic animal vaccination, and mosquito control programs. Table 1 shows a summary of reported human cases and mortality.

Overall, for East Africa the early warning information provided in 2006 enabled country preparedness and early detection and response activities to be undertaken ~2 months earlier compared with the previous epidemic/epizootic of 1997–1998.[8] However, there were additional preventive and control measures that could have been implemented and should be considered for implementation in the future based upon the prediction time line shown in Figure 4. During the pre-outbreak period, measures to mitigate the impact of RVF and reduce its transmission to domestic animals and human populations by mosquito vectors should include:

a. The implementation of a vector control program based on entomological surveys.
b. Dissemination of information about the disease to the public and especially targeted professions at risk (farmers, veterinarians, slaughter house personnel, veterinary laboratory workers etc.) with a focus on behavior at risk and protection measures that people can individually implement to avoid infection. Public health messages for risk reduction should focus on:
   - reducing the risk of animal-to-human transmission as a result of unsafe animal husbandry and slaughtering practices;
   - reducing the risk of animal-to-human transmission arising from the unsafe consumption of fresh blood, raw milk or animal tissue; and
   - the importance of personal and community protection against mosquito bites through the use of impregnated mosquito nets, personal insect repellent if available, by wearing light colored clothing (long-sleeved shirts and trousers) and by avoiding outdoor activity at peak biting times of the vector species.
c. The implementation of health education and social mobilization programs that promote behavior to reduce infection.
d. The enhancement of standard precautions in health care settings to avoid possible nosocomial transmission.
e. The reinforcement of animal and human surveillance and national diagnostic capacity to permit very early detection of both animal and human cases.
f. Strengthening of collaboration between ministries/departments of public/human health and livestock development.

Table 1

Summary of estimated reported number of human cases, and reported deaths during the 2006–2008 Rift Valley fever (RVF) outbreak period

Years	Countries	Number of human cases estimated	Number of human cases reported	Number of human deaths reported
2006–07	Kenya	75,000	700	158
2006–07	Somalia	30,000	114	51
2006–07	Tanzania	40,000	264	109
2007–08	Sudan	75,000	673	214
2007–08	Madagascar	10,000	476	19
2007–09	South Africa		15	0

Vector control programs should include: *1. Adult mosquito control.* Control of adult mosquitoes can be accomplished by directly targeting flying or resting adults with either thermal fogging or ultra-low volume (ULV) spraying, or by targeting resting adults through barrier spraying of vegetation or artificial substrates. Various types of thermal fogger equipment aerosolize the insecticides by heat and are usually mounted on ground vehicles. The ULV applications involve breaking up the insecticide into very small droplets by various mechanical methods, and can be made by commercially available machines mounted on trucks or trailers, or by aircraft (both helicopter and fixed-wing) configured with specialized spray systems. Barrier perimeters of vegetation common in most pastoral areas that are impacted by RVF can be treated with residual insecticides such as bifenthrin that has been shown to provide protection from mosquito disease vectors.[9] Treatment of artificial substrates including interior and exterior walls, suspended sheets, bed nets, and livestock fencing might be effective in controlling adult mosquito vectors of RVFV.

2. Immature mosquito control. Control of larval mosquitoes can be accomplished by applying insecticide to water habitats where mosquitoes develop. Larval control for larger areas, which would be needed for control of RVFV vectors, can be accomplished by airplanes and helicopters. For both adulticiding and larviciding, chemical insecticides should only be used if they have an approved label from the country's appropriate Environmental Protection or similar Agency and at international level by approval of WHO and FAO showing them to be approved for that use. Label directions must be carefully followed when applying these insecticides to assure safety and to minimize negative non-target effects. Adult and larval control applications have been shown to cause few, if any, non-target deleterious effects.[10] Application methods and pesticides described subsequently here for RVFV mosquito vector control strategies are recognized as effective by the WHO Pesticide Evaluation Scheme. Proper insecticide use always involves application at the lowest concentrations that will accomplish the appropriate control. Insecticides should be used only when absolutely necessary and not on a routine basis.

3. A comprehensive health education program. To ensure a successful mosquito control effort it is very important that the general public must be made aware of the need for mosquito control, the methods by which it is accomplished, and the need for their support and cooperation. This can be accomplished through meetings organized by social mobilization experts with the local communities in RVF areas at risk, press briefings by relevant government authorities, radio and television broadcasts.

4. Entomological surveys to guide vector control measures. Pre-treatment and post-treatment surveillance strategies with regard to human and animal populations require that disease and mosquito surveillance must be conducted before insecticide treatment to properly determine the appropriate use of insecticides. Post-treatment surveillance is important to determine if insecticide application was efficacious and to determine if retreatment is warranted. Additionally, the use of personal protection methods such as commercial or natural insect repellents and insecticide-treated bed nets for humans and potential use of insect repellents for animals could provide immediate protection from infected vector mosquitoes during a RVF outbreak.

5. Monitoring RVF areas at risk during the outbreaks. Even though an outbreak has occurred or is prevented it is important that surveillance efforts are continued through time using the current DOD GEIS-National Aeronautics and Space Administration–U.S. Department of Agriculture, Agricultural Research Service RVF monitoring and mapping system over the whole of Africa and Middle East.[7] Given that above normal rainfall conditions may change from one region and shift to other areas across the continent with the movement of the intertropical convergence zone, there is always a high probability RVF high-risk areas will also change and shift through time. Mapping of such areas in real-time will identify likely areas for RVF transmission and permit planning for targeted surveillance and control efforts. Using both current and empirical historical information from eco-climatic data, maps can be plotted of the likelihood of currently unaffected regions to have transmission within the next 30, 60, and 90 days. Such areas can be prioritized for targeted surveillance and mosquito control activities.

6. Use of high spatial resolution mapping of areas at risk. Using the risk maps outputs in (e) above, selective high spatial resolution satellite data for example from LANDSAT, MODIS, or IKONOS can be used to identify flooded regions in RVF endemic areas of any target region. Radar data can be particularly useful during periods of high cloud cover, which are likely over the next several months during a high-risk period.[11] Flooded areas will likely serve as the source of new RVFV transmission and can be targeted for immature and adult mosquito control.

7. Use most efficient state-of-the-art adult mosquito traps and mosquito attractants for mosquito surveillance.

Mosquito control strategies. Adult mosquito control is useful for a quick knockdown of adults. However, it is important to recognize that adulticide application must be performed at the time when potential mosquito vectors are active, and under appropriate weather conditions so that the insecticide reaches the target mosquitoes near the ground or in vegetation. In the case of RVFV vectors, *Aedes* species are active during the day and in crepuscular periods, whereas *Culex* species are primarily active in crepuscular and night conditions. Adult control can temporarily reduce RVFV transmission to animals and humans by interrupting the epidemic cycle as depicted in Figure 1. Reducing the number of infected adult mosquitoes able to transmit RVFV to animals and humans (Figure 1, at critical pathway 3×) and reducing the number of adults able to deposit eggs after a blood meal into immature habitats (Figure 1, at critical pathway 1×) is critical to success. Larval mosquito control is useful for preventing any emergence of adult mosquitoes if used prior to flooding or stopping additional production of adults if applied after flooding (Figure 1, at critical pathway 2×).

1. Conduct adult mosquito control in areas with elevated threat of RVF disease.

a. Appropriate use of ground and aerial ULV products should be very effective in the quick knockdown of mosquito vectors and could be used to impede or stop RVFV transmission over small or large areas. The organophosphate Naled produced as Dibrom™ (Amvac Chemical Corp., Axis, AL) is inexpensive and effective. Synthetic pyrethroids including synergized sumithrin as Anvil™ (Clarke, Roselle, IL) are almost as inexpensive as Dibrom and are effective in quick knockdown.
b. Effective use of barrier sprays to homes and adjacent vegetation can be used to protect animal and human populations. New barrier sprays have been developed, such as the microencapsulated pyrethroids like Suspend™ (Bayer Environmental Science, Research, Triangle Park, NC) (deltamethrin) and Demand™ (Syngenta Professional Products, Basel, Switzerland) (lamda-cyhalohthrin) and can be effective for up to 1 month.

2. Conduct immature mosquito control in areas at elevated or potentially elevated risk of RVFV transmission. Immature control products known as insect growth regulators (IGRs), such as methoprene in sustained release Altosid™ Pellets (Wellmark International, Schaumberg, IL), have been demonstrated to be extremely effective in controlling both *Aedes* and *Culex* vectors of RVFV, even when placed into immature mosquito habitats several months before flooding.[12] Although initially expensive, sustained release products control mosquitoes for an extended period of time (1–2 months) without retreatment. Recent studies using pyriproxyfen (Sumilarv™ 0.5G [Sumitomo Chemical Co., Osaka, Japan]) have shown that adult *Aedes aegypti* mosquitoes contaminated with this IGR can transfer the material to larval habitats.[13] This product could be applied by ULV techniques (as NyGuard™ IGR Concentrate [MGK, Minneapolis, MN]) to adult mosquito vectors and possibly transferred to larval habitats, significantly increasing efficiency and reducing cost of immature control of RVFV mosquito vectors. The *Bacillus thuringiensis israelensis* (Bti)-based products have not been used as successfully for RVFV vectors in some situations.[14] Other products such as the organophosphate Abate™ (BASF, Ludwigshafen, Germany) could be used effectively as a liquid or as pellets to prevent adult mosquito emergence after flooding. However, Abate cannot be applied to pastures, which may be a prime target in RVF areas in Kenya. Abate pellets could be used for pretreatment of areas prior to flooding. Products based on *Bacillus sphaericus* such as Vetolex CG™ (Valent Biosciences Corp., Libertyville, IL) would be expected to provide good control against *Culex* mosquitoes.

3. Cost estimates for mosquito control for mitigation of RVFV transmission in domestic animals and humans. The following discussion of cost estimates for aircraft flying costs and chemical costs are broad estimates derived from data

TABLE 2
Estimated mosquito control aircraft operation costs

Aircraft	Control activity	Calculation	Cost
U.S. Air Force C-130	Ferry costs for 3 aircraft from U.S. to Kenya	\$7,000/hr × 18 hr × 3 aircraft	\$378,000
	Transport of support staff and supplies to Kenya on an additional aircraft	\$7,000/hr × 18 hr	\$126,000
	Per diem cost in Nairobi for 40 crewmembers for 14 days	\$230/day × 40 staff × 14 days	\$128,800
	Flights for adult ULV treatment/aircraft		\$0.09/acre
	Flights for liquid larvicide treatment/aircraft		\$0.90/acre
Local Agricultural Air Tractor 401B	Liquid larvicide/aircraft		\$2.77/acre
Local helicopter (Hughes 500D)	Adult ULV treatment/aircraft		\$0.09/acre
	Liquid larvicide/aircraft		\$5.00/acre
	Granular larvicide treatment/aircraft		\$8.00/acre

* ULV = ultra-low volume.

acquired from mosquito control districts in the United States and discussions with the U.S. Air Force's 910 Airlift Wing in Youngstown Ohio. These estimated overall costs are actually operating costs, which may be offset by other funding/factors. The contracting of Air Tractor and Helicopter services from local vendors will certainly be significantly higher. Contracting of services outside of Africa will also involve ferrying charges. Note that the C-130 aircraft currently cannot fly at night and cannot deliver granule larvicides.

Table 2 lists estimated operation costs for various aspects of three potential mosquito control aircraft: 1) U.S. Air Force C-130 fixed-wing aircraft, 2) local Agricultural Air Tractor 401B fixed wing aircraft, and 3) local helicopter, such as a Hughes 500D rotary wing aircraft. Note that we are considering that the Air Tractor is not configured to apply ULV adulticide and only the helicopter can apply granular larvicide. Once the aircraft are at the site of application (i.e., East Africa) adult control operation costs/acre are the same for the C-130 and the Local helicopter (\$0.09/acre). Aircraft operation costs to apply liquid larvicides are lowest for the C-130 (\$0.90/acre) with Air Tractor and Helicopter costs 3- and 5-fold higher/acre, respectively. Estimated costs for potential chemicals for adulticide and larvicide applications are listed in Table 3. Typically adulticides are applied at an active ingredient concentration of less than 1 oz/acre, and costs are significantly less than \$1/acre. Larvicides ranged from \$2.00/acre for Abate liquid to \$93/acre for Altosid pellets, which can provide excellent control for 60 to 90 days.

To properly assess the overall cost of applying an adulticide to a large area we calculated the cost for aerial ULV application of 1,000,000 acres with the organophosphate Dibrom and these calculations are shown in Table 4. Estimates shown here illustrate how up to one million acres can be treated with a single ULV dose of the adulticide Dibrom for less than \$1.3 million depending upon the aircraft used. An aircraft like the C-130 could cover very large areas targeted for adult control in a very short period of time compared with the helicopter. It is very likely that repeated applications of adulticides will be required to interrupt transmission; however, increased knowledge of the most important target mosquito vector species and their distributions will likely reduce the area needed for adulticide treatment. In Table 5 we show cost estimates for larvicide treatments of 100,000 acres with the chemical Abate. Larvicide treatment of 100,000 acres could potentially cost less than \$700,000 depending upon the aircraft used. Knowledge of the spatial distribution of specific immature habitats could enhance efficiency of larval control operations over large areas.

TABLE 3
Estimated chemical costs

Adulticides	
Dibrom concentrate	\$0.50/acre
Synergized Permethrin	\$0.08/acre
Synergized Sumithrin	\$0.71/acre
Larvicides	
Abate 4E liquid	\$2.00/acre
Abate Pellets	\$50.00/acre
Altosid liquid 5%	\$7.27/acre
Altosid Pellets 5%	\$93.00/acre
Bti liquid	\$5.00/acre
Bti granules	\$12.00/acre
Vectolex CG	\$43.50/acre

CONCLUSIONS

The RVF monitoring and prediction system[8] produced forecasting information that was used operationally during the most recent RVF outbreaks in East Africa, Sudan, Southern Africa, and Madagascar. This information provided significantly improved spatial and temporal warnings of imminent RVF transmission, and permitted early disease detection and implementation of multiple control strategies. The forecasting of RVF activity in these regions of Africa could have been used to potentially enhance various preparedness activities such as by targeting both adult and immature stages of the most important mosquito vector species. Costs of mosquito control are significant but have been shown to be effective in suppressing arbovirus transmission,[15] potentially reduce human and animal morbidity and mortality, and diminish economic impacts. Theoretically, the use of sustained release methoprene or other immature mosquito larval control products would be more costly than post outbreak control measures but massive applications at the earliest indications of elevated rainfall and before flooding would decrease the quantity of RVFV introduced into the environment by killing the majority of the mosquito reservoir before they are able to transmit the virus to domestic animals, thus diminishing the magnitude of the outbreak and potentially prevent more than \$60 million in trade losses alone and losses in human and animal lives.

While for the most part the predictions were correct on a regional scale, there are a number of elements in the model that need to be improved going into the future. Currently, the model uses NDVI as the primary data input as a proxy for both ecological dynamics and rainfall. The explicit incorporation of real-time rainfall data that is now readily available in the risk mapping model will provide a back-up check on the NDVI anomalies and enable the improvement of the risk mapping through a ranking of risk based on accumulated rainfall.

TABLE 4
Total cost estimate for ultra-low volume (ULV) adulticide treatment of 1,000,000 acres with Dibrom

Aircraft	Calculation	Total cost
C-130	Ferry costs ($378,000) + transport cost ($126,000) + application costs ($0.09/acre × 1,000,000 acres + chemical costs ($0.50/acre × 1,000,000 acres)	$1,222,800
Local helicopter (operating costs, not contracting costs for Hughes 500D)	Operating cost ($0.09 /acre × 1,000,000 acres) + chemical costs ($0.50/acre × 1,000,000)	$590,000

The current RVF epizootic area mask is based on a RVF literature survey to identify countries where there have been episodes of RVF activity.[6] These maps are then improved through climate variable (rainfall and NDVI) thresholding to derive the PEAM.[6] Some of the RVF outbreak cases along coastal Kenya in 2006–2007, in South Africa (January–February 2008), in Sudan within the Gezira irrigation scheme, and some areas in Madagascar were just outside of the PEAM area and were not identified as occurring in non-RVF risk zones (yellow dots in Figure 3). Despite applying a strict ecological/historical definition for the calculation and mapping of the PEAM, most of the RVF cases that we missed occurred proximal to the PEAM and hence were effectively predicted from both a temporal and spatial perspective. Additionally, it is not possible to know the exact location of human case exposure to RVFV. The distances from where human cases were reported at the margin of RVF risk zones were well within common and feasible human movements, especially if the cases traveled to seek health care.

Any potential improvement in the PEAM will involve either a change in the rainfall and NDVI thresholding values or incorporation in the model of detailed land cover maps with input from FAO, WHO, and in-country experts. Inclusion of livestock and human-population data will enable improved risk ranking of potential areas of RVF activity and improved and early targeting of locations of vector-virus surveillance by entomological and veterinary teams. For the purposes of real-time monitoring of rainfall and ecological conditions, creation of a Sentinel Monitoring Sites (SMS) database that contains locations of foci or epicenters of recent and previous RVF outbreaks can be identified and be used to monitor rainfall, and NDVI to serve as area-specific indicators of early warning information. The plotted series from the SMS location can be published along with risk maps on a monthly basis to provide additional value-added information to the response planning component teams at country and international levels. In addition, application and refinement of early warning models outside of East Africa, based on the improvements above, will make it possible to take specific regional landscape characteristics into consideration. This will require the building of regional models for each target region.

To improve both response planning and model prediction performance there are several priorities that need to be addressed including; 1) coordination of government resources and development of an international epidemiology database; 2) enhanced communication with appropriate medical, veterinary, and entomology control officials in coordination with WHO, FAO, and Office International des Epizooties (OIE); and 3) integration of veterinary, medical, and entomology surveillance data into risk assessment models. Finally, governments and their international partners need to lead the way in the development of informational materials and standard operating procedures for human and veterinary public health for use before, during, and after an outbreak based on the current risk prediction timeline.

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TABLE 5
Total cost estimate for larvicide treatment of 100,000 acres with Abate 4E liquid

Aircraft	Calculation	Total Cost
C-130 (ferrying, transport, and per diem not included here)*	Application costs ($0.90 × 100,000 acres) + chemical costs ($2.00/acre × 100,000 acres)	$290,000
Local agriculture Air Tractor 401B	Application costs ($2.77/acre × 100,000 acres) + chemical costs ($2.00/acre × 100,000 acres)	$477,000
Local helicopter (Hughes 500D)	Application costs ($5.00/acre × 100,000 acres) + chemical costs ($2.00/acre × 100,000 acres)	$700,000

* U.S. Air Force C-130 only sprays Altosid liquid and will not spray Abate liquid. Cost comparisons shown here are to illustrate relative estimations of application costs for larval control using different aircraft.

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