

Risk Mapping for HPAI H5N1 in Africa  
Improving surveillance for virulent bird flu

## Final report and risk maps

Under Early Detection, Reporting and Surveillance  
– Avian Influenza in Africa Project – USAID



K.B. Stevens, S. Costard, R. Métras, W. Theuri, S. Hendrickx, D.U. Pfeiffer

February 2010



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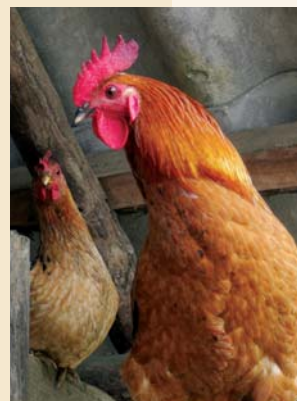
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# Executive Summary



## Project rationale and methods

More than 85 percent of households in rural Africa raise poultry for food, income, or both, and many people live in close contact with their birds. The possibility of an epidemic of highly pathogenic avian influenza (HPAI) H5N1 is therefore a major concern. Since 2006 bird flu has been introduced into at least 11 countries in Africa, and over 600 outbreaks reported.

Vigilance is key to limiting the disease but animal health personnel cannot monitor everywhere at once. This risk-mapping project was designed to help prioritize their efforts by showing in which places outbreaks are more likely to occur.

A risk map is a complex, computer-generated image that shows the spatial distribution of the predicted risk of a disease. It is based on the spatial distribution of “risk factors” associated with an increased risk of disease, and the relative importance of each of these factors. In the case of virulent bird flu, risk factors include major transport routes, markets where poultry may be traded, and wetlands with the possibility of contact between poultry and wild birds.

Researchers in this project have prepared risk maps for bird flu in Africa using multi-criteria decision modeling (MCDM). In this way they have integrated data and information from such diverse sources as published scientific literature, maps available in the public domain, field surveys and expert consultations.

## Methodology

An initial set of risk maps were prepared using MCDM in 2009 (see Initial Bird Flu Risk Map Report [3]). The maps were then refined as follows to produce the final maps contained in the current report:

- 1) Ground-truthing of risk factors in selected countries. For instance, researchers ensured that trade routes and ports found on maps in the public domain are actually used. When discrepancies were identified the maps of the risk factors were revised using the information collected.
- 2) Improving the resolution of the satellite imagery used for the computer models, from thirty square kilometers, to one square kilometer.

- 3) Eliciting of expert opinion—incorporating the judgment of those most experienced with bird flu on the continent helped refine the maps.
- 4) Validation of the risk maps. Researchers compared actual outbreaks on the ground with what the risk maps predicted.

## Project findings

- 1) While most of the literature emphasizes the role of wild birds in the introduction and spread of the disease, experts judged that trade in poultry and poultry products (including eggs) is at least as, if not more, important.
- 2) The density of poultry production was considered a major risk factor for the spread of bird flu.
- 3) Risk is cumulative based on the number and potency of risk factors in a given place. So for instance, densely populated areas adjacent to wild-bird flyways and where poultry trade is active, would be more vulnerable than isolated rural areas near flyways.
- 4) The computer models identified only 2.5% of Africa's land mass to be in the "most likely" category for outbreaks of virulent bird flu. Areas in the top three at-risk categories (out of ten categories) cover 21.8% of the continent.
- 5) The maps have proven highly accurate. Researchers compared them with actual outbreaks from 2006-09 and found that 97.4 % of the 605 outbreaks occurred in areas shown to be in the top three at-risk categories. Furthermore, 34.3% of reported outbreaks were located in the 2.5% of land area ranked as having the highest risk.
- 6) Places at greatest risk for the introduction of virulent bird flu include:
  - West Africa and the North African coastline, though not the Sahel
  - Along the Nile River, though not the Nile Delta
  - Parts of Uganda, Rwanda, Burundi, and southern Kenya that feature a combination of wild-bird flyways, wildlife areas and trade routes
  - Eastern South Africa, which hosts concentrations of wildlife near large cities with commercial poultry farms, and airports through which poultry may be traded.
- 7) Places where the spread of HPAIV is most likely once introduced are:
  - Similar to those places at higher risk of introduction
  - Plus the Nile Delta.

## Risk map limitations: Cautions for the reader

The risk maps are as accurate as possible at this point, but are still only guides to relative likelihood of disease outbreaks. They cannot predict particular outbreaks. Yet they can serve as an indicator to where bird flu is more or less likely to be introduced or spread, and thus help target surveillance activities.

A limitation with all risk maps is that, by definition, they show only things that are mappable. For instance, the proximity of poultry farms to wild-bird flyways can be mapped. However, human behavior such as hand-washing or a custom of letting chickens into living quarters, cannot be mapped.

In addition, data taken from the public domain could in some cases be incomplete, out of date, or inaccurate thereby reducing the accuracy of the resulting risk map. Risk maps should therefore always be used with judgment and in conjunction with local knowledge and other decision support tools such as risk assessment.

## The researchers and funders:

These risk maps represent the work of dozens of people—biologists, geographers, cartographers, Geographic Information System (GIS) specialists, veterinarians and animal health specialists, epidemiologists, farmers, and government officials at all levels.

Project partners include the U.S. Agency for International Development (USAID), the International Livestock Research Institute (ILRI), the African Union - InterAfrican Bureau for Animal Resources (AU-IBAR), the World Organisation for Animal Health (OIE), regional animal health centres, and other national animal health services and veterinary authorities throughout Africa and abroad.

The project was funded by the American people through USAID.



# Introduction







## Introduction

### What is a risk map?

Increasingly used in epidemiology, a risk map is a complex, computer-generated image that shows the spatial distribution of the predicted risk of a disease. It is based on the spatial distribution of “risk factors”—elements associated with the disease, such as the location of main transportation routes and wetlands — and the relative importance of each of these risk factors.

### Introduction to risk-mapping of virulent bird flu

During the last decade, virulent bird flu—highly pathogenic H5N1 avian influenza—has spread to most continents on the globe, with heavy impacts on the poultry industry and significant threats to human health.

In Africa, H5N1 has occurred in at least 11 countries since it was first reported in 2006: Nigeria, Egypt, Niger, Burkina Faso, Ivory Coast, Sudan, Cameroon, Djibouti, Benin, Ghana and Togo. More than 600 outbreaks have been reported, and as of May 2010 Egypt is still suffering ongoing outbreaks. Bird flu is a concern since the majority of the population—over 85 percent—raise poultry for income and/or food.

The disease can enter a country by one or more of three routes, according to a study of all countries that have reported highly pathogenic avian influenza (HPAI) [1]:

- migration of wild birds
- legal trade of domestic poultry, poultry products and wild birds, and
- illegal trade of the same.

The relative importance of the different routes for disease introduction differs between continents and countries. Most (20 of 23) European countries have probably been infected through migratory birds. In Africa, however, HPAI infection can be attributed to both migratory birds and trade in poultry and poultry products.

We lack adequate knowledge so far about the epidemiology of bird flu in Africa, concerning both introduction and spread—“introduction” refers to a first occurrence in a place; “spread” refers to disease movement once introduced.

## Why are risk maps needed?

An epidemic of virulent bird flu could devastate both livelihoods and food sources, as well as raise the risk of disease transmission to humans.

Veterinary services usually have scarce resources for surveillance and are thus unable to check for disease everywhere at all times. Therefore it makes sense to focus surveillance efforts on places where an outbreak is most likely to occur.

The risk maps produced as part of this project help to identify:

- 1) where bird flu is most likely to enter a given region or country and
- 2) where it has more potential for spread once introduced.

Combined with other tools and assessed critically, the risk maps can thus help policymakers target surveillance activities and prepare management plans for disease control.

## Can risk maps tell us where bird flu will occur next?

Risk mapping is only one tool in the complex effort of risk management. Although based on the best data and calculations we have, the maps are not oracles. They show only where outbreaks are more **LIKELY** to happen. They must be used in conjunction with other tools such as risk assessment and socio-economic studies.

For instance, many economic, social and cultural influences (informal trade, how people live with and manage chickens, hygiene, cooking habits, and traditional beliefs) can have an impact on the course of a disease. However, for the most part such influences are difficult to map. In addition, some of the spatial data are themselves incomplete or out of date, leading to inaccuracies. Finally, we only have a limited understanding of the epidemiology of the disease in Africa, and may thus not have considered all mappable factors that influence the distribution of the disease.

## Can risk maps be improved over time?

The risk mapping team worked hard to refine and verify the risk factor data, and validate the final maps. In addition, as our understanding of the epidemiology of bird flu improves, and more accurate and up-to-date data is collected, the risk maps could be further refined and enhanced.

### What can bird flu risk maps do for decision-makers?

- Show the locations where bird flu outbreaks are more likely to occur
- Provide a tool that—in combination with ground-truthing and other tools—alerts animal-health specialists to areas vulnerable to the introduction and spread of bird flu
- Help allocate resources for surveillance and manage plans by highlighting high-risk areas

### What can risk maps NOT do?

- Take into account all variables that influence bird flu introduction and spread, especially human practices and beliefs
- Be more reliable than the data on which they are based
- Indicate how best to manage the disease if it arrives.

## Methodology: Producing the bird flu risk maps

The methodology for generating the risk maps is based on multi-criteria decision modelling (MCDM) [2]. MCDM is driven by our best epidemiological understanding of the different factors associated with an increased risk of the disease, and their interrelationships.

## MCDM involves the following 8 steps:

### *Step 1: Defining the objective(s)*

The objectives of the multicriteria decision model are:

- a) To identify areas in Africa with a high likelihood for the introduction of bird flu
- b) To identify areas in Africa with a high potential for bird flu to spread, once introduced.

### *Step 2: Defining the risk factors*

A systematic search of peer-reviewed, published studies on avian influenza helped researchers identify risk factors for the introduction and spread of bird flu in Africa. Of the risk factors that emerged, the team selected those that can be mapped. For instance, proximity to waterbodies and main roads can be mapped, while cooking practices or cultural beliefs regarding poultry cannot be mapped. In the selection process, the risk mapping team was also careful not to select collinear risk factors (i.e. factors that have a similar spatial distribution).

Risk factors for bird flu considered in the MCDM model include:

#### *Places where poultry is imported, traded (legally or illegally), produced, and consumed*

- Main roads
- Major markets and major metropolitan areas—places of dense human populations where poultry is likely to be concentrated, traded and consumed
- Ports
- Airports

#### *Major global flyways for migratory birds*

At their resting places, wild birds that might carry the virus could transmit it to domestic birds, including poultry. The higher the concentration of birds, the more likely this is to happen. Places of concern include:

- Wetlands
- Lakes, rivers and other water bodies, whether standing or flowing
- Irrigated fields

### *Step 3: Producing risk factor layers for introduction and for spread*

After identifying the major risk factors, the risk-map team sourced maps for them, in the public domain whenever possible. They produced 13 layers representing risk factors associated with poultry trade and transportation, and migratory flyways.

Some layers were later refined via studies conducted in some countries, as described in Step 8.



#### *Step 4: Converting the layers into “raster” maps*

This is a digital manipulation of the maps required to convert them into the correct format for inclusion in the MCDM. Indeed, digitized raster maps allow researchers to assign relative importance or “weight” of risk factors at any particular point or “pixel.” Raster maps of risk factor layers can be combined to show how risk changes when more than one risk factor is present.

The complexity of the conversion varied greatly: sometimes it was simple, but in some cases the risk factor maps required extensive manipulation to produce raster maps. (See Initial Bird Flu Risk Map Report [3])

#### *Step 5: Defining the relative importance of each risk factor*

To determine the relative importance of risk factors, risk factors were weighted in pairs: specifying first whether Factor A was more or less important than Factor B regarding the introduction or spread of bird flu in Africa and second, the degree of importance. Factor A could be (i) Equally, (ii) Moderately, (iii) Strongly or (iv) Very Strongly, more or less important than Factor B.

These weightings were initially based on each team member’s judgment, and were performed for each pairwise combination of factors. The weightings were then refined using expert opinion elicitation, as described in Step 8.



### *Step 6: Combining factors and weights to produce risk maps*

The raster maps for individual risk factors were combined using weighted linear combination (WLC). Factors with a higher weight exert greater influence on the final risk estimate. This combination is done for each individual pixel in the map, which generates a numeric risk score on a scale of 0 (lower risk) to 255 (higher risk) (See Appendix 1). The resulting risk maps identify areas at highest risk of introduction and spread of bird flu in Africa. The resolution (or size of a pixel) for these risk map initially represented 30 square kilometers.

### *Step 7: Performing a sensitivity analysis to test accuracy*

Sensitivity analysis is a statistical check on the calculations underlying the risk maps. It showed that even if weighting for any individual risk factor was changed by 25 percent, (in other words, was “off” by 25 percent), the results in terms of risk level for the regions remained the same.

See Appendix 2 for more discussion of sensitivity analysis of risk factors and weights.

### *Step 8: Validating and improving the maps.*

After publishing the initial set of risk maps, we validated and refined the maps:

- 1) by ground-truthing geographical data, such as the location of border crossings, with information and observations from the field.
- 2) through eliciting the experience and judgment of experts in the field,
- 3) by field observations of actual outbreaks in Africa, and
- 4) by increasing the resolution of the maps to one square kilometer (from thirty) and generating a larger number of likelihood categories. Finer resolution enables more finely tuned risk-based surveillance strategies.

Points 1-3 are further described in the following section. Results have been incorporated in the maps of risk factors as well as the final risk maps.







## Refining and validating the bird flu risk maps

### *Revisions of the risk factor layers based on ground-truthing:*

Studies centred on specific, “focus” countries were conducted in three African sub-regions: Western Africa, Eastern Africa, and Southern Africa. For each focus country, researchers identified both (i) the major flows of poultry and poultry products entering the country, and (ii) major poultry markets. They also collected data on the location of airports, ports and border crossings.

For all countries, researchers collected all relevant data available in the literature, including on the internet. For “primary data” countries, they also interviewed key informants. For “focus” countries, research further included field visits.

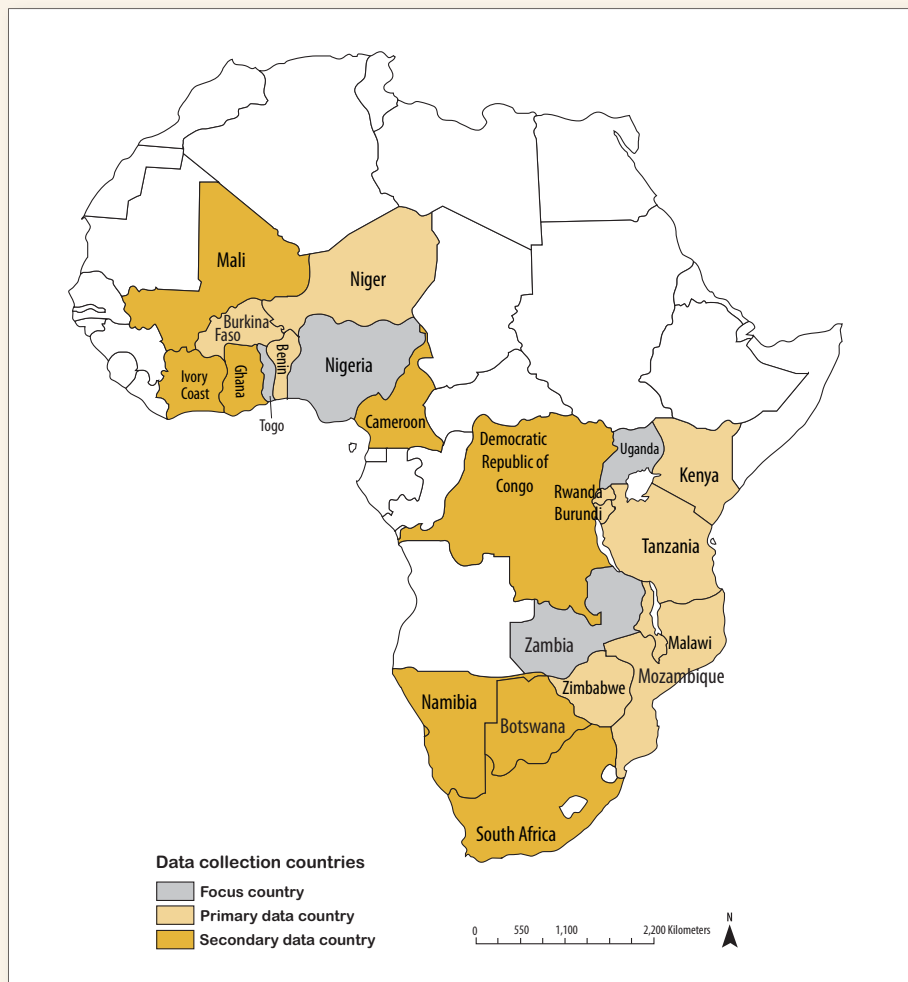


Figure 1: Countries included in the data collection in Eastern, Western and Southern Africa and the level of detail gathered from each.

<sup>1</sup> In East Africa, surveys were conducted as planned except that little information was available for Uganda, and none for the Democratic Republic of Congo (DRC) due to political instability.

<sup>2</sup> In Western Africa, time prevented secondary-data desk-studies for four countries: Ghana, Cote d’Ivoire, Cameroon and Mali.

Questionnaires were centralized and data collated in a Microsoft Access database. The information obtained was then plotted on maps and compared with the layers used for the production of the initial risk maps. In case of discrepancy, the layers were revised according to the information collected in the field (See Appendix 3).

Further details on methodology are provided in the Appendix as well as individual country and regional reports available on request from Saskia Hendrickx (s.hendrickx@cgiar.org).

### *Revisions of relative importance of risk factors, based on expert opinion*

The importance of risk factors was determined using a structured expert opinion elicitation process. The objective was to use the knowledge and expertise currently available to derive weights for each of the factors included in the MCDM model.

Experts were identified from literature review and a relevant international veterinary conference. The resulting 23 experts were contacted by email and asked to weight the different risk factors for introduction and spread of HPAIV in Africa using pair-wise comparison tables provided in Excel documents. Six experts replied as requested, and their judgments incorporated in the final risk maps. (Tables 1 and 2). See Appendix 4 for more detail and individual responses.

*Table 1:  
Average weights for risk factors associated with the introduction of highly pathogenic avian influenza into Africa as determined by the expert opinion elicitation.*

<b>Risk factor</b>	<b>Mean weight</b>
Proximity to cross-border roads	0.2705
Proximity to water / wetlands	0.2428
Presence of Black Sea/Mediterranean flyway	0.1489
Proximity to airports	0.1225
Presence of East Africa / West Asia flyway	0.1200
Proximity to ports	0.0578
Presence of East Atlantic flyway	0.0374

*Table 2:  
Average weights for risk factors associated with the spread of highly pathogenic avian influenza into Africa as determined by the expert opinion elicitation.*

<b>Risk factor</b>	<b>Mean weight</b>
Poultry density	0.2692
Proximity to markets	0.2400
Proximity to primary roads	0.1924
Proximity to water or wetlands	0.1375
Proximity to secondary roads	0.0879
Proximity to irrigated areas	0.0436
Proximity to navigable rivers	0.0294

## Improving the risk maps

The final risk maps presented in this report differ in the following ways from the initial risk maps published previously.

Revisions of the maps based on ground-truthing (the corresponding figures are in Appendix):

- In Southern Africa, poultry and its products enter only a small proportion of airports. But in the West African countries for which data were available, all or nearly all the airports were points of entry (Figure 9).
- In contrast, nearly all ports surveyed handle poultry and poultry products (Figure 10).
- Not all cross-border roads see the legal passage of poultry or poultry products--again resulting in an overestimation of points of entry (Figure 8).
- **The layer for points of entry was revised accordingly for countries where data were collected on airports, ports and cross-border roads used for poultry or poultry products.**
- However, there remains the risk of illegal entry of poultry through the un-manned cross-border roads.
- Although the use of cities with populations of greater than 50,000 was a reasonable proxy for the location of poultry markets, markets were not actually present in all these cities--resulting in an overestimation of locations from which HPAI could spread. This was more apparent in the western countries surveyed (Figure 8) than in the southern countries (Figure 4).
- **The layer on poultry markets was revised for countries where data were collected using the recorded locations of poultry markets.**

Revisions of relative importance of risk factors, based on expert opinion

- Expert respondents were divided as to whether migratory birds or poultry trade provided the predominant route of entry of HPAI into Africa. In general, however, entry points associated with poultry trade --particular cross-border roads — received higher weights than entry points associated with migratory birds.



### *Validation of the final risk maps*

Researchers compared what the risk maps showed with actual outbreaks from 2006-09 (See Appendix 5). Only 2.5 % of the total land mass of Africa falls into the risk maps' "most likely" category. Yet, out of ten categories shown on the risk maps, 34.3 % (n = 213) of reported outbreaks were located in areas ranked most likely (Figure 13).

In addition, 97.4 % (n = 605) of outbreaks occurred in the three highest categories of risk (Table 5).

Therefore the model and underlying assumptions appear to be highly accurate.



## Final risk maps based on updated layers and weights

Based on the entire process of MCDM, the risk maps finally produced are guides to locations where bird flu is most likely to be introduced into Africa, and where it has most potential for spread once introduced.

The risk maps are based on our current understanding of risk factors and their relative importance. They are only guides: they do not incorporate all possible risk factors and should always be used in conjunction with ground-truthing and other tools such as risk assessment.

### Risk of introduction of virulent bird flu

Most of West Africa, parts of southern Africa, and the North African coastline show the highest likelihood for introduction of HPAIV (Figure 2).

The model also shows land around the Nile River show high likelihood, yet the Nile Delta appears at low or moderate risk.

The Sahel and eastern Somalia appear to share a low likelihood of disease introduction.

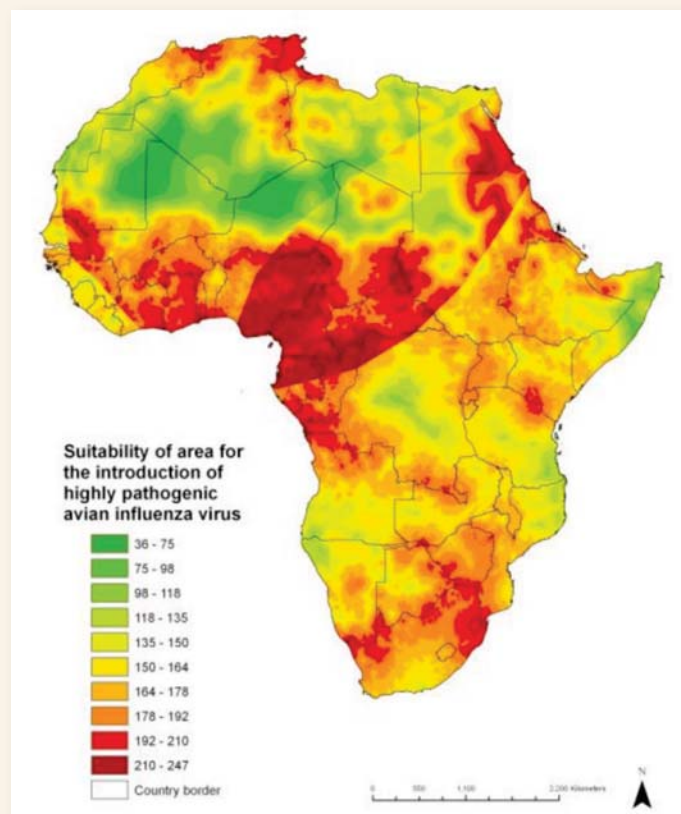
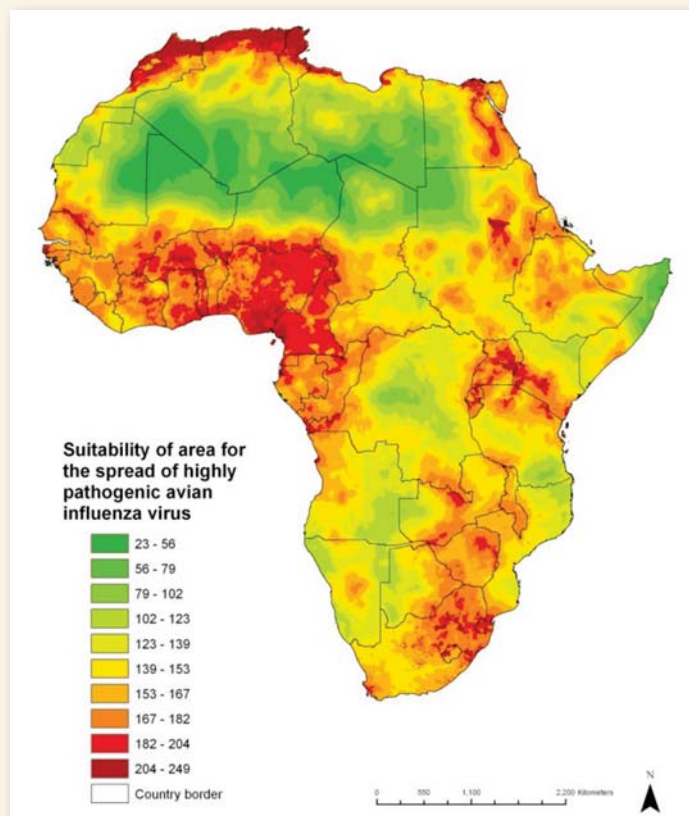


Figure 2: Risk map showing the likelihood of introduction of highly pathogenic avian influenza virus via a combination of poultry trade and migratory birds. The scale ranges from least (green) to most (red) likely.

## Risk of spread of virulent bird flu

Areas most likely to be affected by spread of bird flu once introduced appear to be:

- West Africa
- the North African coastline,
- along the Nile River—including the Nile Delta
- Uganda, Rwanda, Burundi
- southern Kenya
- and eastern South Africa (Figure 3).



*Figure 3: Map showing the degree of risk in parts of Africa for the spread HPAIV into the domestic poultry population via a combination of poultry trade and migratory birds. The scale ranges from least likely (green) to most likely (red).*

## Likelihood of overall occurrence of virulent bird flu

Areas that appear likely for HPAI to occur follow a similar pattern to areas suitable for spread. Most likely areas are again West Africa, the North African coastline, along the Nile River (and including the Nile Delta), Uganda, Rwanda, Burundi, southern Kenya and eastern South Africa (Figure 4).

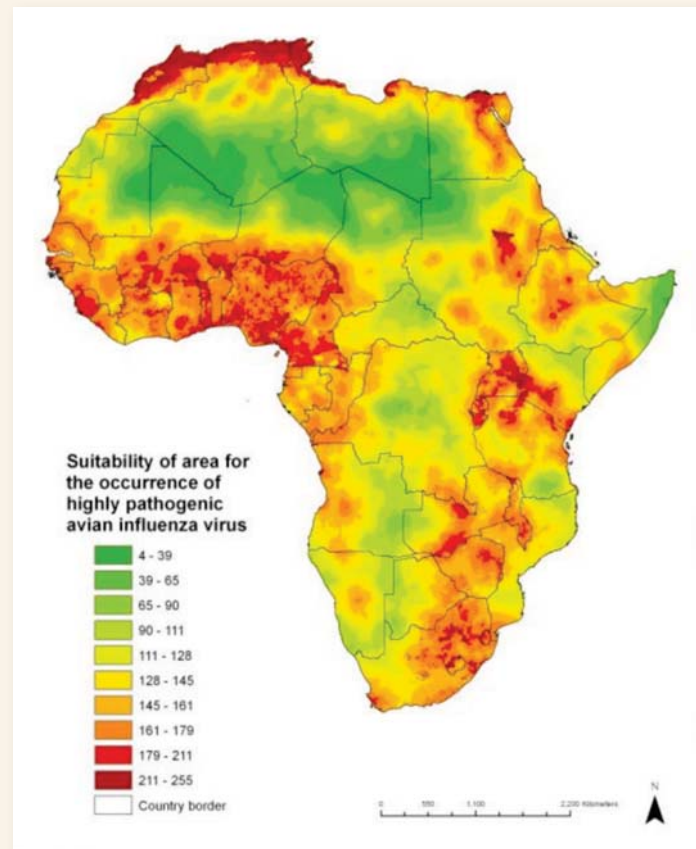


Figure 4: Map showing likelihood in Africa of occurrence of virulent bird flu outbreaks in domestic poultry. The scale ranges from least likely (green) to most likely (red).

## Discussion

The maps presented in this report show the relative likelihood in different parts of Africa for the introduction, spread and overall occurrence of outbreaks of HPAIV H5N1. Compared to the maps initially produced under the EDRS-AIA project, three main improvements have been made.

First, country-level surveys featuring data on the poultry trade helped researchers update the vector maps used in the production of the risk maps. Some of the vector maps used for the initial risk maps probably overestimated the number of entry points for poultry and poultry products in countries, thus the surveys conducted were useful to ground-truth the initial proxies used and adjust as needed wherever possible.



Then, a structured expert opinion elicitation was performed to weight the factors of the MCDM model for relative importance—using the best knowledge and expertise available. The variation in weights given by different experts is likely due to the general lack of understanding of the epidemiology of the disease—resulting in each expert rating factors based on his own experience with the disease. Incorporating these rates into the suitability maps reflects these uncertainties.

Finally, the resolution of the maps was increased to one square kilometer, and a larger number of suitability categories were generated. The objective of these refinements was to ensure that the maps could be used at regional and country levels to inform the development of risk-based surveillance strategies.

Results of the sensitivity analysis indicate that the MCDM model developed was robust, as the suitability scores for pixels of the map (1 km<sup>2</sup>) were not affected by a 25% change in the weights of the individual risk factors.

Another critical step of the process was to validate the maps produced. The validation performed using outbreak data for Africa shows that the model appears to predict areas suitable for the occurrence of HPAI with a high level of accuracy.

In addition to these analyses assessing the quality of the MCDM model used to generate the risk maps, a recent publication by Paul et al [4] highlighted the importance of anthropological factors for the occurrence of HPAIV H5N1 in addition to agro-environmental ones. This recent analysis supports the weights used for individual risk factors in this study.

Advantages of such suitability maps include the possibility to amend the MCDM model as knowledge of the disease increases, and the fact that they are not dependent on disease occurrence data, which can be difficult to obtain.



## Limitations of the risk maps

### Data considerations

- **Data quality:** The quality of the data used as geographical inputs for the model varies. For example, available road maps displayed only primary, secondary and tertiary roads; data on minor roads, which could play an important role in the illegal trade of poultry, were unavailable.
- **Proxies:** When data for specific risk factors were unavailable, proxy data were used. For example, as there are no available data on the location of markets in Africa, cities with human populations of more than 50,000 were used as proxies for the location of markets. This may bias the results since rural markets or collection points, too, might play an important role in legal or illegal trade.
- **Cultural influences:** Hygiene, cooking practices, beliefs, and habits such as living in proximity with poultry also influence risk, but cannot be mapped.

### Weighting considerations

- **Influence:** Weighting of the different risk factors was performed by only 6 experts out of 23 contacted. The weights obtained reflect their opinion based on current knowledge and personal experience.
- **Lack of knowledge:** There is a general lack of knowledge regarding the introduction and spread of bird flu, not only in Africa, but worldwide. The disagreement between experts is likely to reflect this uncertainty on the epidemiology of the disease. Our access to the most up-to-date scientific information on the subject translates, we hope, into a better assessment of the risk factors involved and their relative importance in the introduction and spread of bird flu in Africa.

Finally, risk maps may only represent a relative likelihood of disease spread, and not absolute probability or risk.

Each of these considerations should be taken into account when interpreting the risk maps.

Despite these limitations, in conjunction with risk assessment and other tools, these MCDM risk maps can help policymakers target areas with greater confidence for strengthened surveillance and/or control activities.



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# Appendices



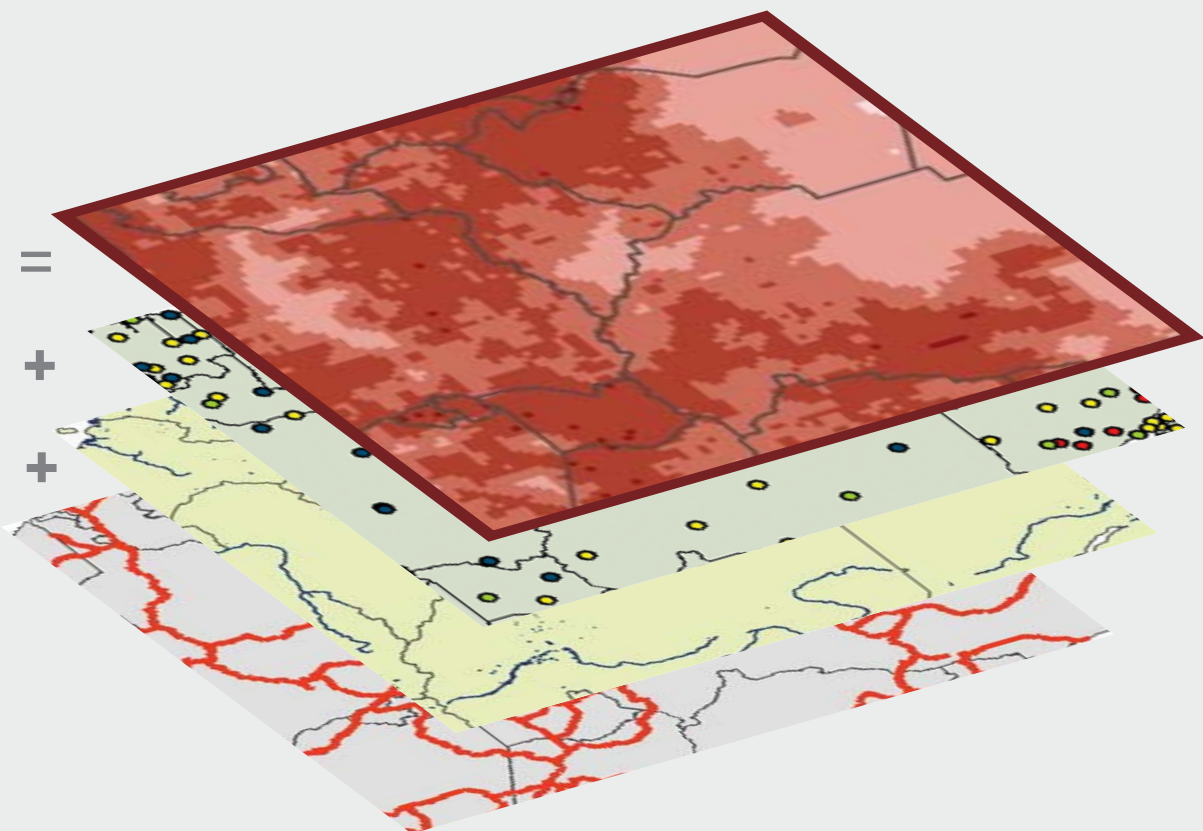


## Appendix 1

### Creating a risk map

The procedure for producing knowledge-driven risk maps is to:

- 1) Review the current scientific literature and knowledge to identify risk factors known to be associated with the disease of concern, and to determine their degree of association with the risk of disease.
- 2) Map the spatial distribution of the individual risk factors.
- 3) Combine these maps, giving them weights (scores) according to their relative importance in contributing to the overall risk of disease (Figures 5 and 6)
- 4) Present, in a risk map, the resulting spatial variation in disease risk.



*Figure 5:*  
Building process of a knowledge-driven risk map. The spatial distributions of the different risk factors (bottom four layers) are combined in order to produce the risk map (topmost layer).

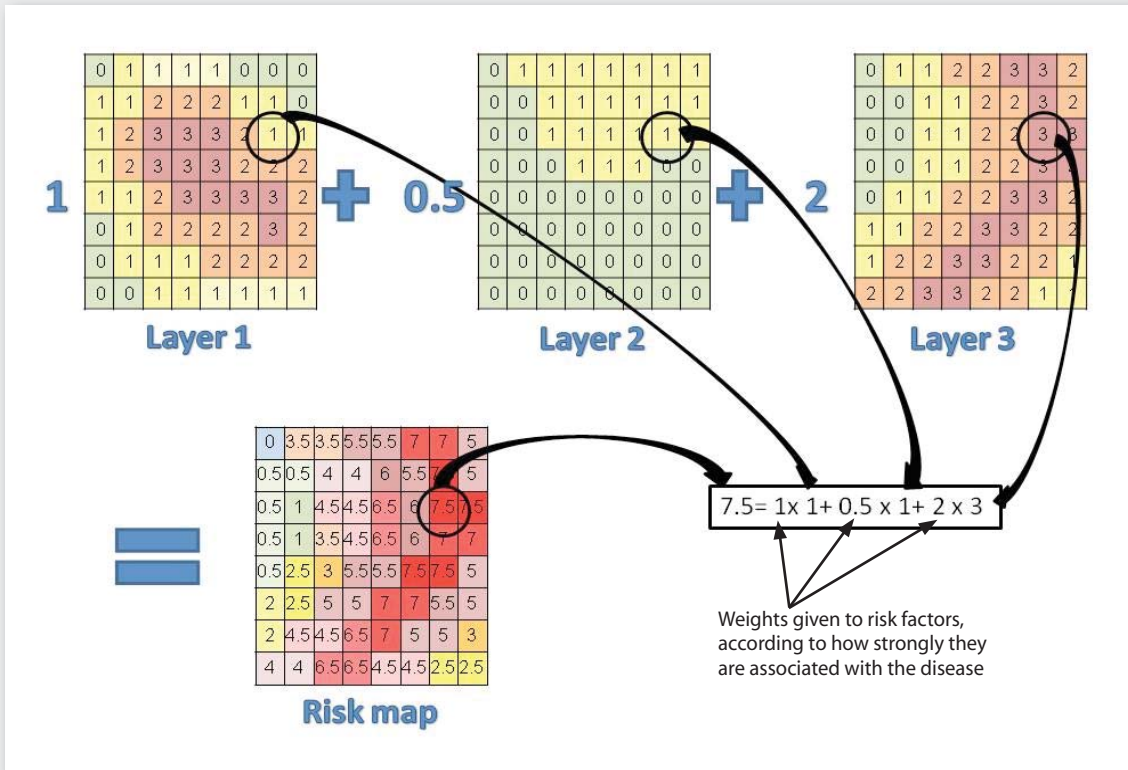


Figure 6: Building process of a knowledge-driven risk map. For each pixel of the area considered, the risk score of all risk factors are combined according to their relative importance, resulting in an overall risk score for each pixel of the risk map.



## Appendix 2

### Collecting data and creating the risk-factor layers

All digital maps used to create the raster maps required for the final model were sourced from the public domain. Where necessary, the public-domain maps were modified for inclusion in the MCDM model as detailed below.

### Markets

Markets for poultry and poultry products were mapped in the surveyed countries (Figure 7). For other countries, cities with a population greater than 100 000 were used as a proxy for the location of markets. These cities were extracted from the Global-Rural Urban Mapping Project (GRUMP) dataset (<http://sedac.ciesin.columbia.edu/gpw/index.jsp>). Euclidean distance to markets/cities was calculated and the results displayed as a raster map with a resolution of 1 km<sup>2</sup>.

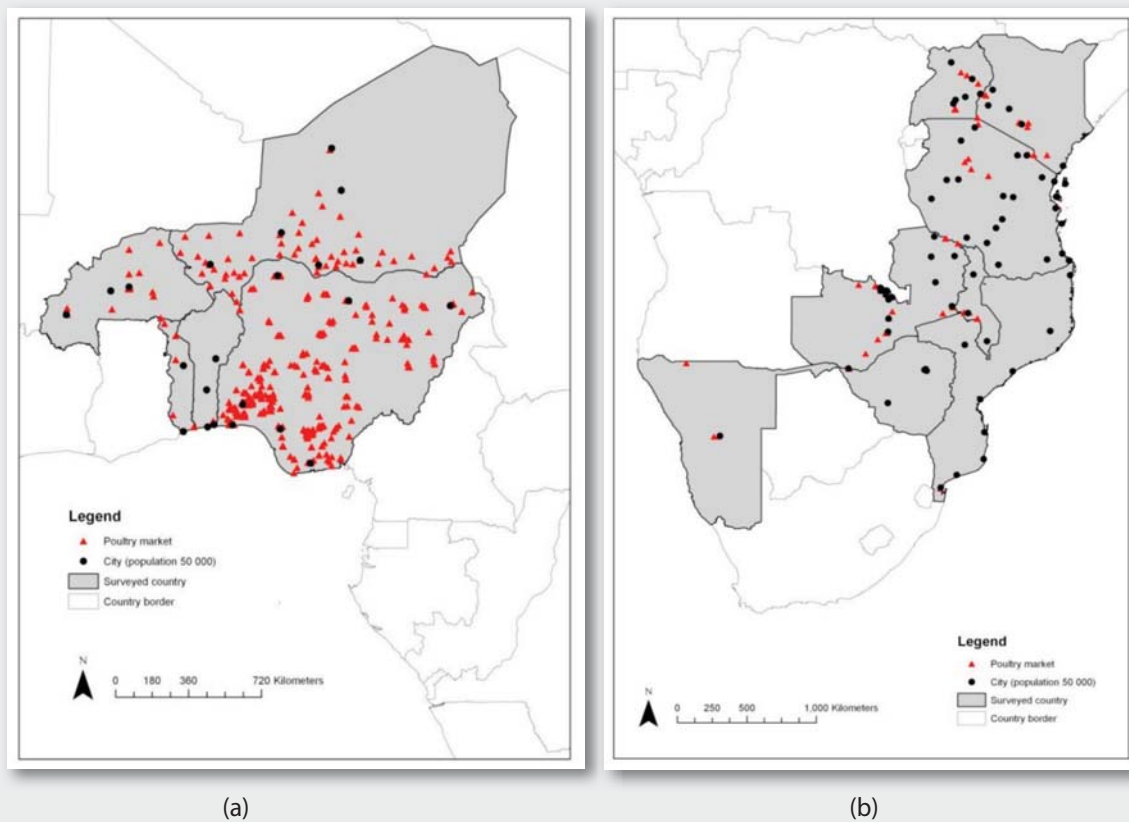


Figure 7:  
Map showing the location of markets dealing in poultry and poultry products in the surveyed countries in (a) western and (b) southern Africa.

## Roads

A map showing primary, secondary and tertiary roads was created by combining road location data from two websites; FAO GeoNetwork (<http://www.fao.org/geonetwork/srv/en/main.home>) and Global Mapping (<http://www.iscgm.org/cgi-bin/fswiki/wiki.cgi>). Although Global Mapping data were more current than those on GeoNetwork, they were available for only 15 African countries (Algeria, Botswana, Burkina Faso, Republic of Congo, Democratic Republic of Congo, Ethiopia, Guinea Bissau, Ghana, Mozambique, Niger, South Africa, Senegal, Sudan, Swaziland and Tunisia). GeoNetwork data were used for the other countries.

Individual maps were created to show (i) primary roads, (ii) secondary and tertiary roads and (iii) cross-border roads. For the latter, the point of intersection was converted to a point location using the Intersect Lines Tool available from Hawth's Analysis Tools for ArcGIS (<http://www.spatial ecology.com/htools/tool desc.php>). For survey countries only cross-border roads identified as control points for poultry or poultry products (Figure 8) were included. Euclidean distance to each of the three categories of road was calculated and the results displayed as raster maps with a resolution of 1 km<sup>2</sup>.

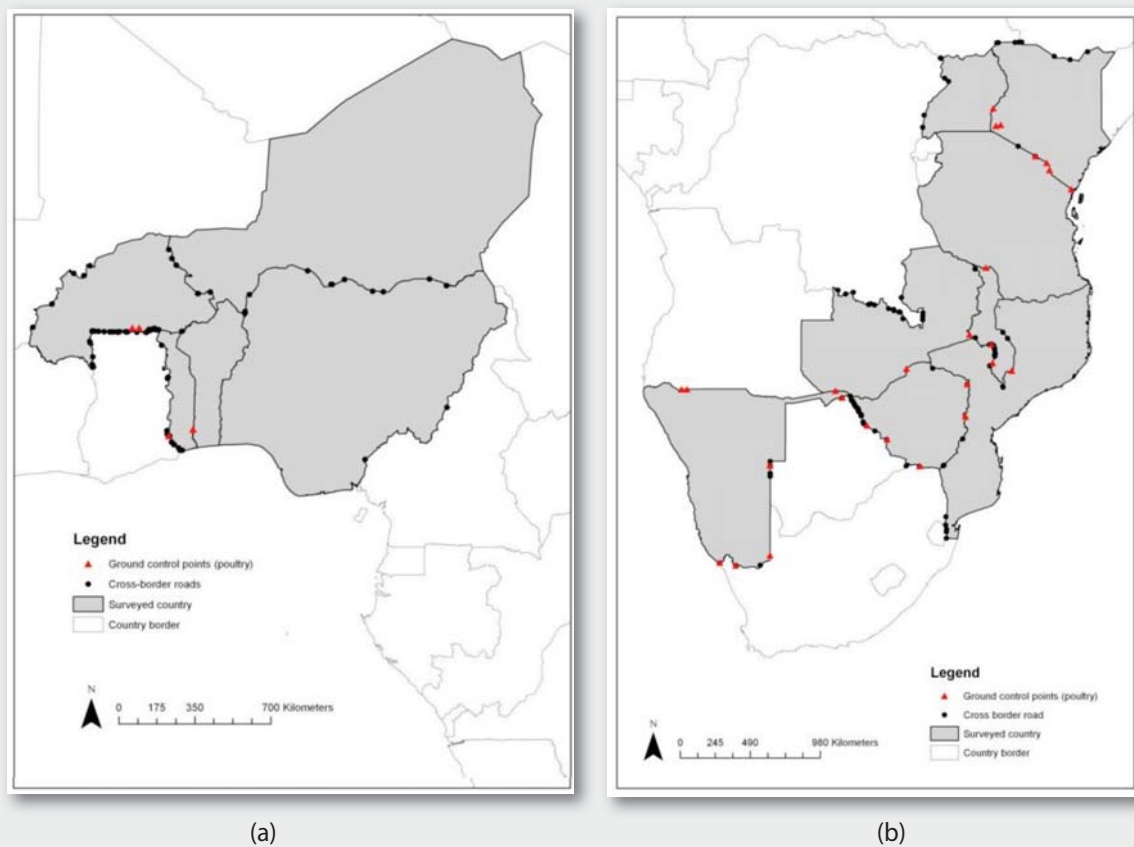


Figure 8: Map showing the location of border crossing points through which poultry and poultry products pass in the surveyed countries in (a) western and (b) southern Africa.



## Airports

Point locations of all civilian airports and airfields were obtained from the Global Mapping website for Algeria, Republic of Congo, Democratic Republic of Congo, Guinea Bissau, Mozambique, Niger, South Africa, Senegal, Sudan, Swaziland and Tunisia. Civilian airport and airfields in the remaining African countries, plus all joint military/civilian airports and airfields were extracted from VMap0 Airports (<http://www.fao.org/geonetwork/srv/en/main.home>). For the surveyed countries, airports not dealing in poultry products (Figure 9) were removed from the map. Euclidean distance to airports was calculated and the results displayed as a raster map with a resolution of 1 km<sup>2</sup>.

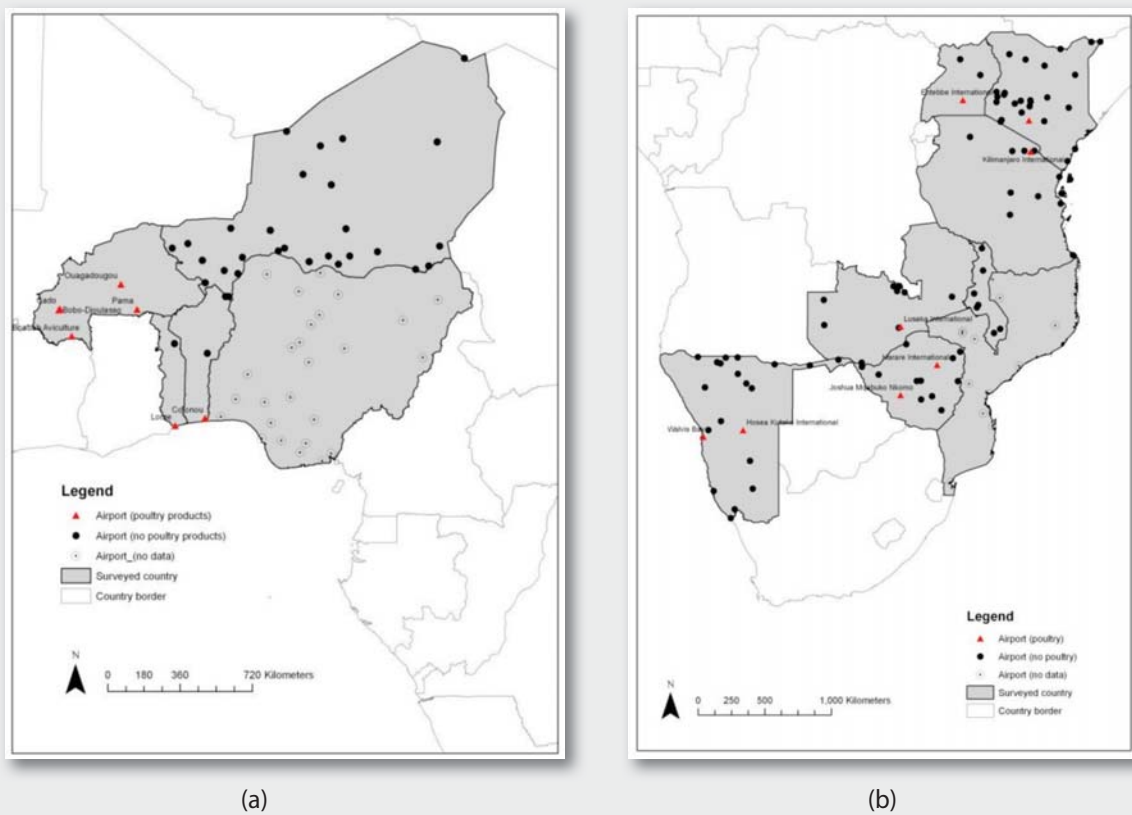


Figure 9:  
Map showing the location of airports dealing in poultry and poultry products in the surveyed countries in (a) western and (b) southern Africa.

## Ports

Port locations were taken from the RWDB2 Ports and Harbours map (<http://www.fao.org/geonetwork/srv/en/main.home>). For the surveyed countries, ports not dealing in poultry products (Figure 10) were removed from the map. Euclidean distance to ports was calculated and the results displayed as a raster map with a resolution of 1 km<sup>2</sup>.

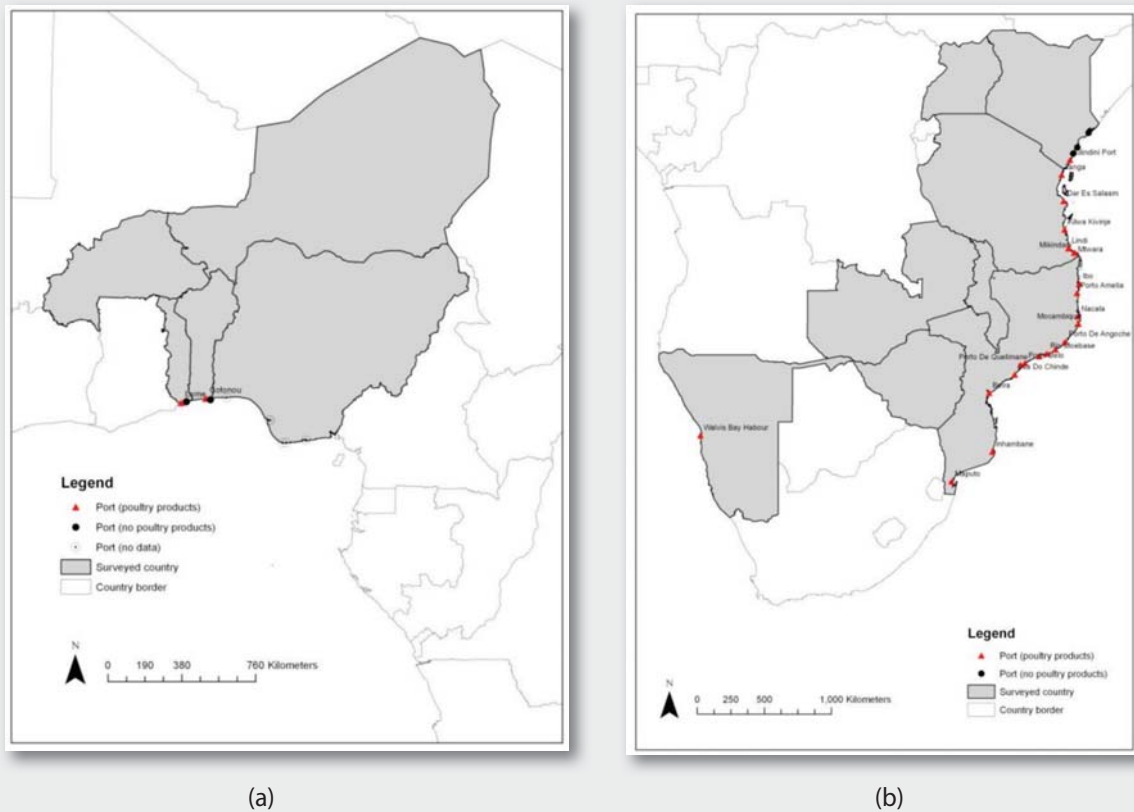


Figure 10: Map showing the location of ports dealing in poultry and poultry products in the surveyed countries in (a) western and (b) southern Africa.

## Rivers, wetlands, lakes, and irrigated areas

Data on the location of permanent or seasonal water were taken from the Global Maps dataset for Algeria, Burkina Faso, Republic of Congo, Democratic Republic of Congo, Egypt, Ghana, Guinea Bissau, Mozambique, Niger, Senegal, South Africa, Sudan and Tunisia. Rivers in other countries were provided by VMap0 Perennial Water Courses (Rivers) of the World (<http://www.fao.org/geonetwork/srv/en/main.home>).

For wetlands, researchers consulted the DCW Land Cover (Hydrological Features) map. Irrigated areas were extracted from the AQUASTAT Global Map of Irrigated Areas (version 4.0.1). Researchers later merged the shapefiles for rivers, wetlands, and irrigated areas. Euclidean distance to water was calculated and the results displayed as a raster map with a resolution of 1 km<sup>2</sup>.

## Flyways

Three major wild-bird flyways traverse Africa: the East Atlantic, East Africa/West Asia and Black Sea/Mediterranean flyways. They were imaged using ArcMap's Georeference tool, and extracted as polyline features. These were converted to polygons, with the three flyways displayed on separate maps. These vector maps were converted to raster maps with a binary scale (flyway present or absent).

## Poultry density

Poultry density for Africa was extracted from FAO's Gridded Livestock of the World raster map and converted from a resolution of 5 km<sup>2</sup> to 1 km<sup>2</sup>.

All maps were represented as a continuous scale positively correlated with the model outcome (risk of HPAI introduction or spread) and standardized using a byte binary scale ranging from 0 to 255.



## Appendix 3

### Calculating weights for relative importance of risks

The importance of each risk factor to the introduction or spread of HPAIV in Africa was decided using a structured expert-opinion elicitation process. The objective was to use the knowledge and expertise currently available to derive weights for each of the factors included in the MCDM model.

Relevant experts were first identified from the original literature review. Presenters on HPAIV H5N1 in Africa at the twelfth conference of the International Society for Veterinary Epidemiology and Economics (ISVEE) in August 2009 were then included, since their work was more recent than that reflected in the literature review. First authors and co-authors of three or more articles were selected; scientists involved in the EDRS-AIA project were excluded.

Researchers contacted the resulting 23 experts by email. They explained the objective and principles of the expert opinion exercise and asked the experts to weight the risk factors for introduction and spread of HPAIV in Africa using pair-wise comparison tables provided in Excel documents. Additional information was given, including journal articles from the literature review, key notes on methodology, and links to the EDRS-AIA risk maps. The corresponding documents are available on request from Saskia Hendrickx (s.hendrickx@cgiar.org).

Six experts replied within the timeframe. The mean of their individual weights for each risk factor was used in the production of the risk maps presented in this report. The individual weights of the six respondents and the average weight for each risk factor are presented in **Table 3 (introduction) and Table 4 (spread)**.

The respondents were divided as to whether migratory birds or poultry trade was the predominant route of entry of HPAI into Africa although in general, entry points associated with poultry trade, in particular cross-border roads, received higher weights than entry points associated with migratory birds (Table 3). There was reasonable agreement between the six respondents as to the weighting of the risk factors for spread of HPAI. Four of the six experts rated poultry density as the most important risk factor, and three of the six rated proximity to markets as the next most important (Table 4). In general, points of contact between traded poultry and the domestic poultry population received higher weights than contact between migratory birds and domestic poultry.



Table 3:

Individual and average weights for risk factors associated with the introduction of highly pathogenic avian influenza into Africa as determined by six respondents of the expert opinion elicitation. In each instance the risk factor with the highest weighting is highlighted in grey.

Risk factor	Mean weight	Individual weights					
		1	2	3	4	5	6
Proximity to cross-border roads	<b>0.2705</b>	0.2322	0.2807	0.1085	0.1770	0.3868	0.4380
Proximity to water/wetlands	<b>0.2428</b>	0.3738	0.0703	0.3673	0.2994	0.2192	0.1268
Presence of Black Sea/Mediterranean flyway	<b>0.1489</b>	0.1137	0.0487	0.1716	0.2994	0.0949	0.1653
Proximity to airports	<b>0.1225</b>	0.0274	0.3839	0.0185	0.0273	0.1391	0.1386
Presence of East Africa/West Asia flyway	<b>0.1200</b>	0.1688	0.0675	0.2476	0.0755	0.0949	0.0657
Proximity to ports	<b>0.0578</b>	0.0291	0.1207	0.0372	0.1025	0.0245	0.0328
Presence of East Atlantic flyway	<b>0.0374</b>	0.0550	0.0282	0.0493	0.0188	0.0406	0.0328

Table 4:

Individual and average weights for risk factors associated with the spread of highly pathogenic avian influenza in Africa as determined by six expert respondents. In each instance the risk factor with the highest weighting is highlighted in grey.

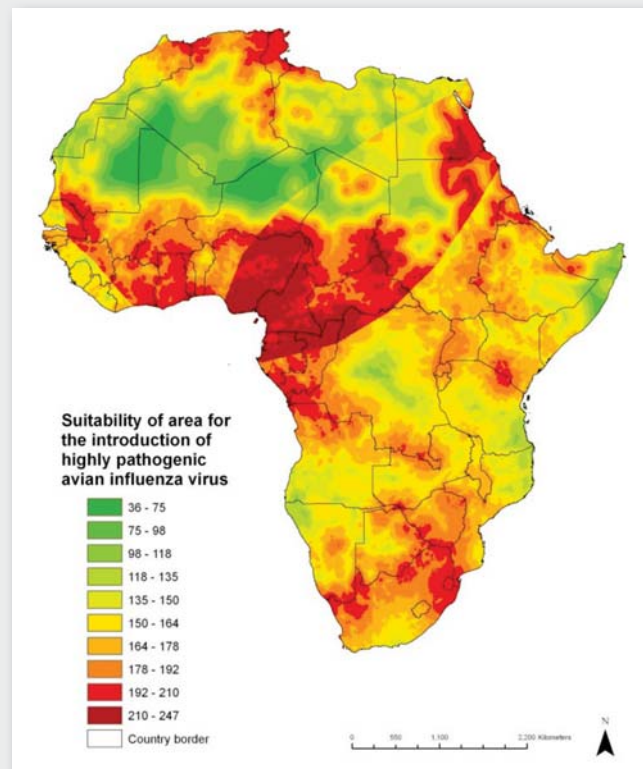
Risk factor	Mean weight	Individual weights					
		1	2	3	4	5	6
Poultry density	<b>0.2692</b>	0.3088	0.2963	0.2412	0.2415	0.3738	0.1535
Proximity to markets	<b>0.2400</b>	0.3088	0.1960	0.2412	0.3120	0.1372	0.2447
Proximity to primary roads	<b>0.1924</b>	0.1337	0.0818	0.2412	0.2284	0.1077	0.3618
Proximity to water or wetlands	<b>0.1375</b>	0.0374	0.2963	0.1384	0.0459	0.2232	0.0839
Proximity to secondary roads	<b>0.0879</b>	0.1209	0.0617	0.0772	0.0991	0.0781	0.0903
Proximity to irrigated areas	<b>0.0436</b>	0.0691	0.0403	0.0181	0.0543	0.0401	0.0396
Proximity to navigable rivers	<b>0.0294</b>	0.0214	0.0277	0.0425	0.0187	0.0401	0.0262

## Appendix 4

### Multi-criteria decision modeling

Mean weights derived from the expert consultation were combined with the raster maps using weighted linear combination (WLC). Risk was then calculated for either introduction (Figure 11) or spread (Figure 12) of HPAIV for each square kilometre mapped. The introduction and spread maps were then combined using WLC and weights of 0.333 (introduction) and 0.666 (spread) to determine the suitability of areas for the occurrence of HPAI outbreaks (Figure 13). The justification for these relative weights was that without potential for spread, then after introduction in an area HPAI would die out and not create secondary outbreaks.

In all instances likelihood was expressed on a continuous scale ranging from 0 (lowest likelihood) to 255 (highest likelihood). The continuous scale was then grouped into ten categories using the Jenk's natural breaks method.



*Figure 11: Map showing the suitability of Africa for the introduction of highly pathogenic avian influenza virus via a combination of poultry trade and migratory birds. The scale ranges from least (green) to most (red) suitable.*

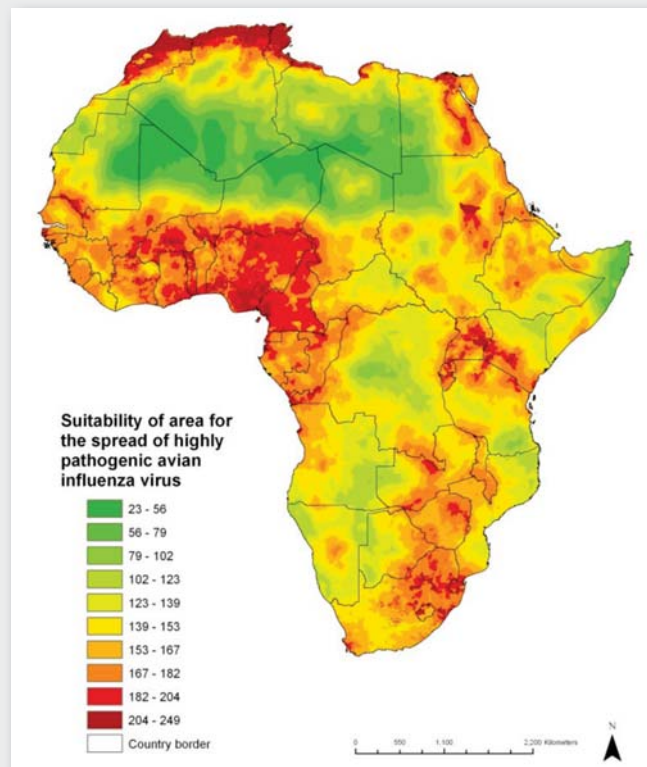


Figure 12: Map showing the suitability of Africa for the spread of highly pathogenic avian influenza virus (HPAIV) into the domestic poultry population via a combination of poultry trade and migratory birds. The scale ranges from least (green) to most (red) suitable.

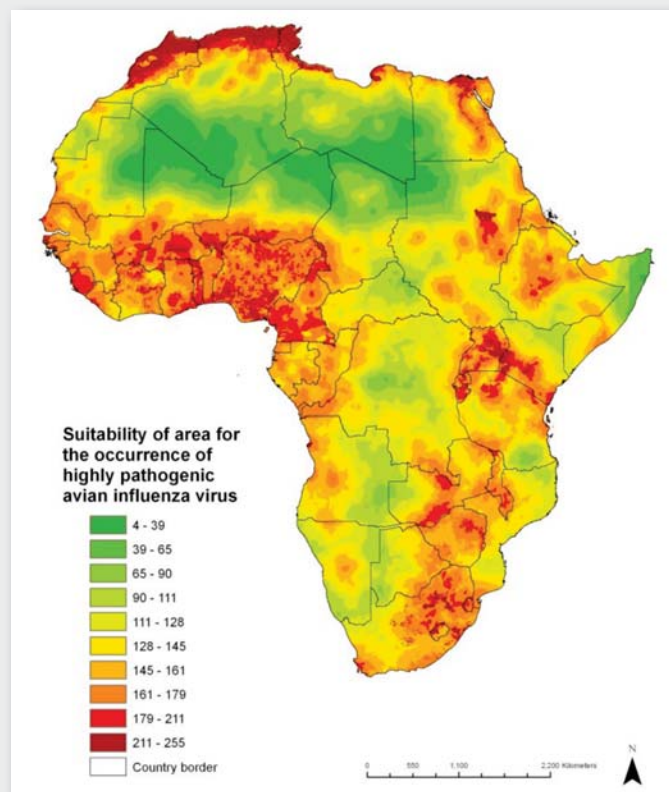


Figure 13: Map showing the suitability of Africa for the occurrence of highly pathogenic avian influenza virus (HPAIV) outbreaks in domestic poultry. The scale ranges from least (green) to most (red) suitable.

## Appendix 5

### Map validation

What the risk maps predicted was compared with actual outbreaks from 2006-09. Only 2.5 % of the total land mass of Africa was modeled as most suitable for the occurrence of HPAI (Table 5), and 34.3 % (n = 213) of reported outbreaks were located in these areas (Figure 14). In addition, 97.4 % (n = 605) of outbreaks occurred in the three highest categories of risk (Table 5).

*Table 5:*

*Proportion of total land area in Africa predicted as being suitable for the occurrence of highly pathogenic avian influenza (HPAI) outbreaks and the number of reported H5N1 outbreaks occurring in these areas between 2006 and 2009.*

<b>Suitability</b>	<b>Total land area (km<sup>2</sup>)</b>	<b>Percentage of total land area (%)</b>	<b>Expected outbreaks (n)</b>	<b>Actual outbreaks (n (%))</b>
1 (least)	1721971	5.9	37	0
2	1762068	6.0	37	0
3	1690978	5.8	36	0
4	3143914	10.7	66	0
5	4429599	15.1	94	1 (0.2)
6	5288511	18.1	112	6 (1.0)
7	4861501	16.6	103	9 (1.4)
8	4186964	14.3	89	252 (40.6)
9	1454751	5.0	31	140 (22.5)
10 (most)	724885	2.5	16	213 (34.3)
<b>Total</b>	<b>29 265 142</b>	<b>100</b>	<b>621</b>	<b>621 (100)</b>

The total area of Africa and the area covered by each of the ten likelihood, or risk, categories—from least to most likely-- were determined in square kilometres. The area (km<sup>2</sup>) of each risk category was then converted into a proportion of the total land area.

Pearson's chi-square test for goodness-of-fit was used to compare the proportion of outbreak locations that occurred in areas of suitability with the proportions that might be expected to occur in the these



areas if they were randomly distributed across suitability categories. Unlike Pearson's chi-square test of independence which assesses whether observations on two variables are independent of each other, the test for goodness-of-fit compares the distribution of the observed data with a theoretical or hypothesized distribution.

Chi-squared tests for goodness-of-fit indicated that both these proportions were significantly ( $p < 0.001$ ) greater than the hypothesized 2.5 % ( $n = 16$ ) and 21.8 % ( $n = 135$ ) of outbreaks that might have been expected to occur in these areas if their distribution was random ( $X^2 = 2576.25$ ,  $df = 1$  and  $X^2 = 2065.55$ ,  $df = 1$ , respectively). Thus, the map appears to predict areas suitable for the occurrence of HPAI with a high level of accuracy.

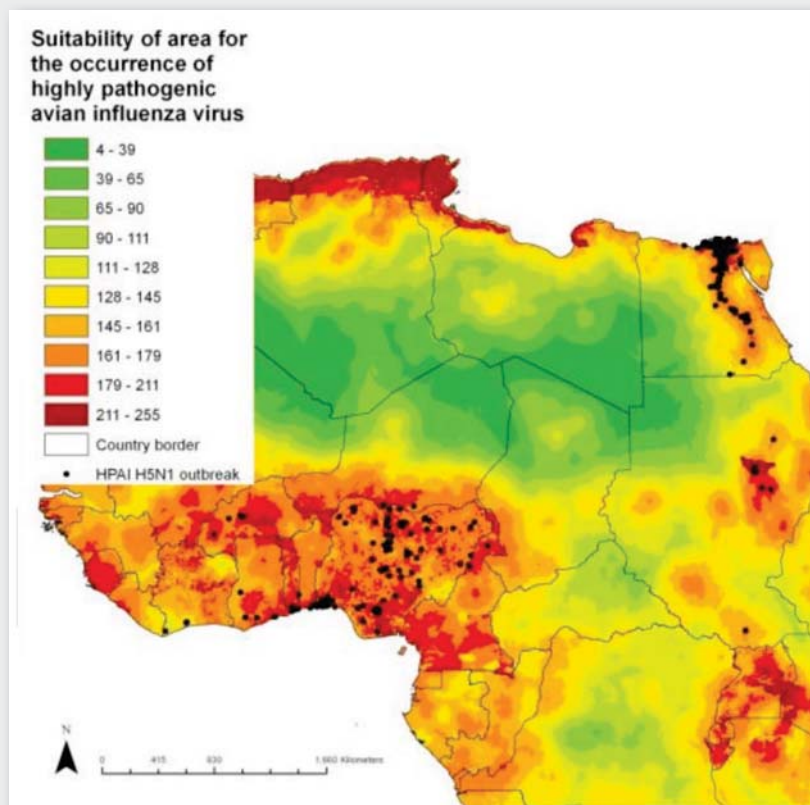


Figure 14:  
Map showing the suitability of Africa for the occurrence of outbreaks of highly pathogenic avian influenza virus (HPAIV) overlaid with the locations of all outbreaks of H5N1 reported between 2006 and 2009.

## Appendix 6

### Sensitivity Analysis

This statistical check showed that even if weighting for any individual risk factor was changed by 25 percent, the results in terms of risk level for the regions remained the same. Each of the newly calculated weights was individually incorporated into the MCDM model, while holding all other factor weights constant.

The risk score was measured at 50,000 randomly-generated point locations, and mean change in the suitability estimate as a result of altering each factor weight was calculated. At the aggregate level, regions identified as being at higher or lower risk for the introduction or spread of disease would therefore remain as such even when the weights of the different risk factors are increased or decreased by as much as 25%.

Risk estimates for disease introduction (Table 6) and spread (Table 7) were highly robust, as increasing or decreasing the weights of the individual risk factors for disease introduction resulted in negligible changes to the individual pixel risk scores.

*Table 6:*

*Sensitivity analysis of weights used to estimate the suitability of Africa for the introduction of the highly pathogenic avian influenza virus (resolution: 1 km<sup>2</sup>). The average change in risk estimates was calculated from 50,000 randomly-generated point locations.*

Risk factor	Mean change in suitability estimate (+ std. dev)	
	Factor weight increased by 25%	Factor weight decreased by 25%
Proximity to cross-border roads	1.97 ± 5.66	0.28 ± 2.97
Proximity to airports	1.09 ± 3.45	1.28 ± 3.46
Proximity to ports	1.45 ± 2.95	0.91 ± 3.39
Presence of Black Sea flyway	2.11 ± 6.74	0.18 ± 4.64
Presence of East Africa flyway	1.00 ± 3.06	1.37 ± 5.72
Presence of East Atlantic flyway	1.29 ± 3.01	1.07 ± 3.09
Proximity to water or wetlands	0.62 ± 2.37	3.21 ± 6.12

*Table 7:*

*Sensitivity analysis of weights used to estimate the suitability of Africa for the spread of the highly pathogenic avian influenza virus into the domestic poultry population (resolution: 1 km<sup>2</sup>). The average change in risk estimates was calculated from 50 000 randomly-generated locations.*

Risk factor	Mean change in suitability estimate ( $\pm$ std. dev)	
	Factor weight increased by 25%	Factor weight decreased by 25%
Proximity to markets	4.51 $\pm$ 3.43	1.90 $\pm$ 3.60
Proximity to secondary roads	4.93 $\pm$ 2.68	1.56 $\pm$ 2.78
Proximity to irrigated areas	3.61 $\pm$ 2.61	2.96 $\pm$ 2.49
Proximity to primary roads	5.10 $\pm$ 4.75	1.29 $\pm$ 0.99
Proximity to water or wetlands	5.31 $\pm$ 2.69	5.31 $\pm$ 2.69
Proximity to navigable rivers	3.53 $\pm$ 2.37	3.04 $\pm$ 2.66
Poultry density	3.78 $\pm$ 2.17	11.37 $\pm$ 5.03













Final report and risk maps