

Research, part of a Special Feature on [Risk mapping for avian influenza: a social-ecological problem](#)
Wild Bird Movements and Avian Influenza Risk Mapping in Southern Africa

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ABSTRACT. Global analyses of the potential for avian influenza transmission by wild birds have ignored key characteristics of the southern African avifauna. Although southern Africa hosts a variety of migratory, Holarctic-breeding wading birds and shorebirds, the documented prevalence of avian influenza in these species is low. The primary natural carriers of influenza viruses in the northern hemisphere are the anatids, i.e., ducks. In contrast to Palearctic-breeding species, most southern African anatids do not undertake predictable annual migrations and do not follow migratory flyways. Here we present a simple, spatially explicit risk analysis for avian influenza transmission by wild ducks in southern Africa. We developed a risk value for each of 16 southern African anatid species and summed risk estimates at a quarter-degree cell resolution for the entire subregion using data from the Southern African Bird Atlas. We then quantified environmental risks for South Africa at the same resolution. Combining these two risk values produced a simple risk map for avian influenza in South Africa, based on the best currently available data. The areas with the highest risk values were those near the two largest cities, Johannesburg and Cape Town, although parts of Kwazulu-Natal and the Eastern Cape also had high-risk scores. Our approach is simple, but has the virtue that it could be readily applied in other relatively low-data areas in which similar assessments are needed; and it provides a first quantitative assessment for decision makers in the subregion.

Key Words: *anatidae; avian influenza; Botswana; ducks; influenza; landscape ecology; Namibia; pathogen; South Africa; virus; waterfowl; Zimbabwe.*

INTRODUCTION

Recent outbreaks of avian influenza in both domestic poultry and the human population are a source of considerable concern (Kaleta et al. 2005, Poland et al. 2007). Given their potential impacts on both humans, and domestic and wild bird populations, it is important that the dynamics of influenza viruses are assessed at a global scale, and that similarities and differences among potential transmission pathways in different regions are considered (Melville and Shortridge 2006, Olsen et al. 2006, Kilpatrick et al. 2006).

Avian influenza viruses fall into two groups, termed low pathogenicity (LPAI) and high pathogenicity (HPAI). LPAI viruses constitute the majority of viruses in wild birds (Olsen et al. 2006). HPAI viruses such as H5N1 have been primarily found in poultry, although the HPAI virus H5N2 has been isolated from common ostriches (*Struthio camelus*)

in South Africa, and an influenza virus of the H5N2 subtype was isolated from a wild Egyptian Goose (*Alopochen aegyptiaca*) in the Western Cape Province in 2004, 2 wk prior to an outbreak in ostriches in the Eastern Cape (Sinclair et al. 2005). There is currently little empirical evidence to suggest a major role for wild birds in moving H5N1 or other HPAI influenza viruses among populations of people or domestic poultry (Kilpatrick et al. 2006), but the possibility remains that migratory or nomadic wild birds could at some future date spread some form of HPAI rapidly over large distances.

There has been no previous synthesis of information about the potential role of wild birds as carriers of either HP or LP avian influenzas in southern Africa. We address this gap through a preliminary analysis of spatial variation in known HPAI risk factors in areas south of the Zambezi River, i.e., South Africa, Lesotho, Swaziland, Namibia, Botswana, Zimbabwe, and southern Mozambique, which together

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constitute an area larger than the United States of America. Southern Africa offers an interesting challenge for avian influenza research because populations of wild waterfowl behave very differently from those that breed in north-temperate latitudes (Fig. 1). The southern African environment is relatively arid, with considerable variation in precipitation magnitude and pattern, and does not experience particularly harsh winters. These factors are thought to have led to high levels of opportunism and nomadism in African anatids. Southern Africa largely lacks predictable flyways for anatids, and the movements of many species appear to be driven by a combination of nomadic responses to rainfall and annual aggregation at secure sites for flightless moult (Oatley and Prys-Jones 1986, Scott and Rose 1996, Petrie and Rogers 1997, Underhill et al. 1999, Hockey et al. 2005). Local southern African waterfowl are, however, indirectly linked to Europe and parts of Asia by migratory storks, waders, and terns. These species move south from a wide range of both latitudes and longitudes in the western and central Palearctic, and in a few cases the Nearctic, to spend the nonbreeding season south of the Equator (Sanderson et al. 2006). In addition, intra-African movements of African duck species (Underhill et al. 1999) have the potential to bring them into close contact with large numbers of Palearctic-breeding ducks at wetlands immediately south of the Sahara.

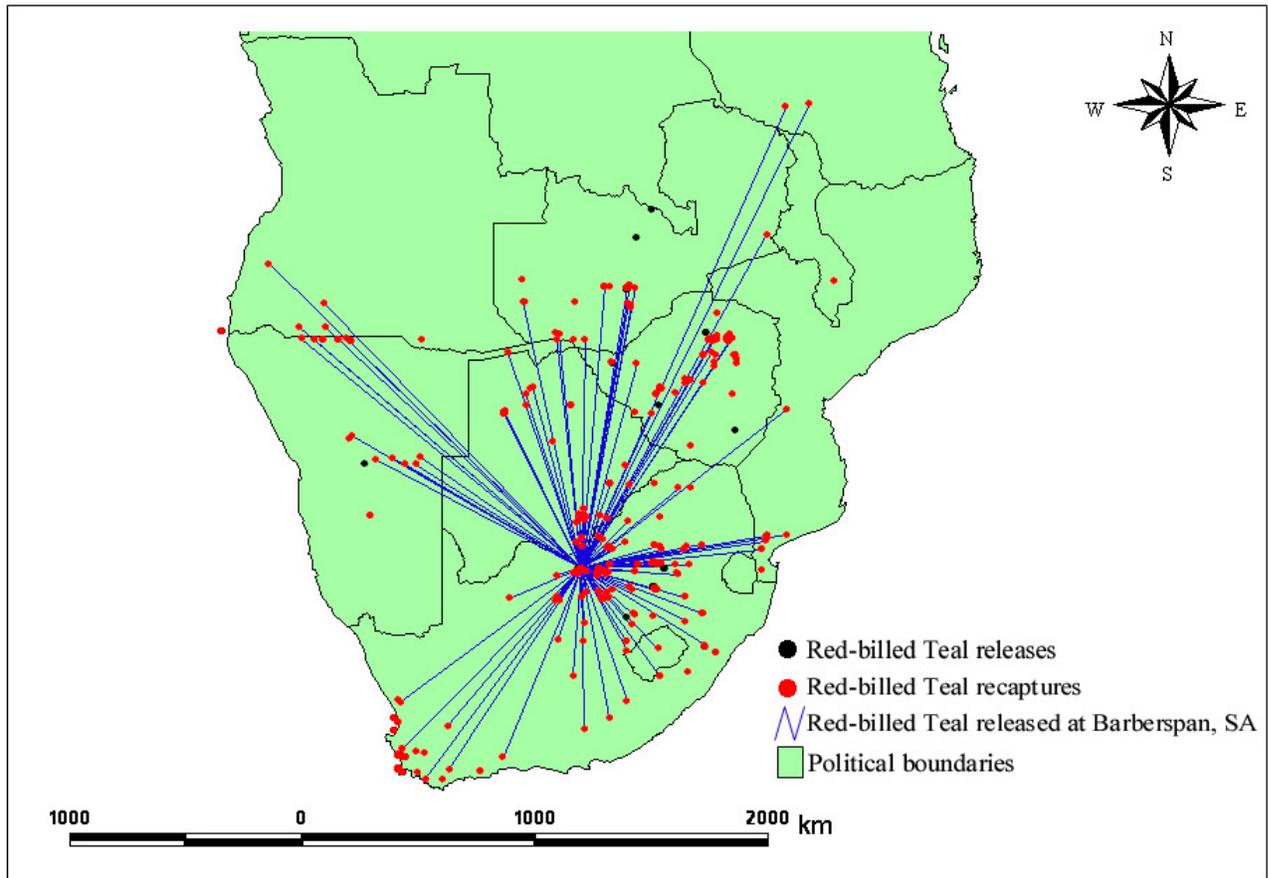
Southern Africa lacks the kinds of physical features that serve as barriers to bird movements in the Americas and Asia, making the movements of migrants less channeled by topography, and hence less predictable. Consequently, it is important to note that generalizations about the spread of avian influenzas along predictable pathways by migratory birds (Simonite 2005, Clark and Hall 2006) do not necessarily apply in the case of southern Africa. The closest analogue to the southern African situation is Australia (Tracey et al. 2004). Roshier et al. (2006) have argued that although nomadic Grey Teal (*Anas gracilis*) in Australia move in response to local changes, they may be responding to cues from events several hundred kilometers away. In a subsequent study, Roshier et al. (2008) identified two primary types of movement: ranging, and directed. Despite the potential for predictability of some aspects of directed movement, these systems remain vastly different from the regular migratory movements of northern-hemisphere birds. In the rest of this paper we summarize what we consider the most important available information relating to

understanding the potential role of wild birds as carriers in avian influenza dynamics in southern Africa. Our focus in this analysis is on what might happen after HPAI is introduced to southern Africa, rather than on the multitude of means by which it might either evolve from endemic LPAI strains or arrive in southern Africa from elsewhere.

METHODS

Because there have been relatively few published studies of avian influenza prevalence in the subregion (e.g., Pfitzer et al. 2000, Sinclair et al. 2005), an assessment of the potential role of wild bird carriers in avian influenza dynamics in southern Africa must of necessity be based on a set of a priori criteria. Several criteria appear to predispose a wild bird species to being a potentially important carrier of avian influenza, here termed a "risk species," as follows: (1) Risk species will be those that are closely related in terms of phylogeny and ecology to other species that are known to have naturally high susceptibility to influenza viruses, i.e., to readily harbor viruses as either asymptomatic carriers or individuals experiencing illness; (2) Risk species should be abundant and widespread. Range-restricted taxa are unlikely to move influenza viruses long distances; and, by the same token, given the apparent generality of the host preferences of influenza viruses, rare birds are unlikely to play a significant role in their transmission; (3) Risk species will be those that are far-ranging, whether migratory or nomadic, because long-distance movements will carry viruses into new areas and thereby increase the potential for spread; (4) Risk species will form daily or seasonal aggregations in which high densities of individuals occur. Clearly, the potential for bird-to-bird transmission, and the likelihood of at least one bird being stressed, and thus shedding a virus, is highest when large numbers of birds are in close association. Many southern African ducks aggregate to roost, both by day and by night, and many gather on large water bodies to undergo a period of postbreeding, flightless moult (Hockey et al. 2005); (5) Risk species will often occur in mixed-species flocks, facilitating the transmission of virus to species with different movement patterns and/or greater contact with domestic poultry. The degree of contact between wetland birds and the bird communities around farms is unknown, but there is the possibility that granivorous passerines could function as a link between water birds and domestic poultry because

Fig. 1. Ringing recovery data for Red-billed Teal (Underhill et al. 1999). Black dots indicate release localities; red dots indicate recapture localities; dark blue lines connect release and recapture points of birds ringed at Barberspan, South Africa (SA). This figure demonstrates that a Red-billed Teal ringed at Barberspan could subsequently visit almost any wetland south of the Congo forests.



passerines could frequently forage in association with poultry, yet may roost, drink, or breed in wetlands; (6) Because influenza is a droplet infection and is easily transmitted in water, birds that are strongly associated with fresh water for reproduction, foraging, and/or roosting are generally higher risk than birds that use water for drinking purposes only. Southern African ducks can be characterized as grazers, dabbling ducks, or diving ducks. Dabbling ducks are more likely to come into contact with influenza viruses when

feeding, because they forage in the surface strata of the water body in which influenza viruses are most commonly found and roost at the edges of water bodies in areas in which faecal matter is more commonplace. Grazing ducks commonly occur in farmlands and may feed next to domestic poultry and share food and water with them. For example, in the Western Cape, ostriches are often kept in open paddocks. Egyptian Geese, which are ducks, despite their common name, have easy access to such paddocks and frequently feed from ostrich food

trays and drink or swim in shared farm dams (Hockey et al. 2005). Grazing and dabbling ducks are higher-risk species than diving ducks, which spend most of their foraging time relatively asocially in deep water and hence are confined to a more restricted set of wetlands (Gilbert et al. 2006); and (7) Birds that have a strong association with human structures, such as sewage ponds, impoundments, farm dams, and livestock drinking troughs, are more likely to be risk species than birds that rely on less anthropogenic habitats.

Given these criteria, most of the long-distance migrants that enter the subregion cannot be considered high-risk species. The birds that have been documented with highest influenza prevalence in Europe and America, the anatids (Kaleta et al. 2005, Olsen et al. 2006), generally do not undertake long-distance migrations as far as southern Africa. Of the 12 species of Palearctic-breeding anatid whose migrations take them into sub-Saharan Africa, 9 species regularly reach as far south as the Equator; most penetrate a little further, but only 4 species reach southern Africa as vagrants. Thus, direct transmission of avian influenza from Palearctic-breeding ducks to southern African ducks would require transmission to the latter at East African wetlands (Simonite 2005), followed by southward movement of infected local birds to southern Africa. Other water birds that do migrate long distances into southern Africa include storks, terns, and waders. Coastal migrants such as marine terns seldom come into contact with people or poultry, and wading birds are not known to associate widely with ducks or poultry, although several species, such as Wood Sandpiper (*Tringa glareola*), are common at inland wetlands, in which they have the potential to receive or transmit viruses from and to anatids. Ruffs (*Philomachus pugnax*) are regularly found in farmlands and farmyards, and are perhaps the most likely shorebird to be implicated in avian influenza dynamics. As many as 200,000 Ruffs may spend the boreal summer in southern Africa (Hockey et al. 2005). Nonetheless, the known incidence of influenza viruses in most Palearctic-breeding migrants is relatively low (Olsen et al. 2006, Gaidet et al. 2007), and there are doubts about the ability of sick birds to complete long migrations successfully (van Gils et al. 2007).

Based on what is known about the transmission capabilities of wild birds, in general (Gaidet et al. 2007), the highest risk species for the dispersal of HPAI in southern Africa are the anatids, i.e., ducks. We have therefore focused on these species to

provide a preliminary quantification of the risks associated with wild birds. We have included all ducks, rather than just *Anas* species, because the few positive records collected to date suggest that birds in other genera such as *Alopochen* may be equally or more important as potential HPAI vectors. Obviously, other bird species will contribute to influenza risks, and will need to be added to this approach once more information on their relevance becomes available. We note also that for this first analysis, we ignore the distinction between populations or species that may move influenza viruses around, i.e., carriers, and populations or species that may maintain them in a location, i.e., reservoirs; the two are not necessarily the same, although the ducks are probably the highest risk group in both cases. We explored aspects of risk in a series of four steps:

Step 1: quantifying wild bird risks. To assess the relative importance of each species, we asked six expert ornithologists to score each of 16 southern African duck species on each of our seven a priori risk criteria using a simple ranking system that ranged from 1 (low risk under that criterion) to 5 (high risk under that criterion). The scores for each species were then averaged across all participating experts, summed, and converted to an overall percentage by species. To assess bird-associated risks, we then summed percentage risk scores by quarter-degree (15x15 minute) grid cell for all species reported by the Southern African Bird Atlas Project (Harrison et al. 1997) as occurring within the cell, and divided by 16, i.e., the maximum possible number of species, to produce a risk factor that potentially ranges from 0 to 100 (Table 1).

Step 2: testing whether the inclusion of abundance data would greatly influence the distribution of risks. The Southern African Bird Atlas Project (SABAP) data unfortunately have no true measure of sampling effort, and hence no true measure of abundance. To assess whether using an index of abundance would influence the map, we multiplied each risk factor by species by the relative reporting rate for that species in that cell, i.e., the proportion of total cards for an individual grid cell on which the species was reported as present, and summed these values for each cell. The data were strongly lognormal so we took logs of the summed risk proportions, standardized them to a zero mean and unit deviation, and re-scaled the data to a mean of 50 and a standard deviation of 20 to make them comparable to other data sets in the analysis.

Table 1. Risk evaluation by species for southern African anatids. Estimates have been rounded to the nearest 0.1. The risk score is calculated by summing the other columns, dividing by the maximum possible total of 35, and converting to a percentage. Note that all of the species commonly called "goose" in southern Africa are actually ducks. Further details of assessment categories and species names are provided in the Appendix.

Species	Range	Abundance	Mobility	Roost	Mixed f-locks	Foraging	Anthropogenic association	Risk score
Fulvous Duck	2	2.3	3.8	4.3	2.9	3.2	2.8	61
White-faced Duck	2.6	4.4	3.8	4.5	2.9	4.2	3.6	74
White-backed Duck	1	1.5	3	4.5	2.5	2	3	50
Maccoa Duck	2.2	2.3	2.8	3	2.2	1	3.3	48
Egyptian Goose	4.2	5	3.7	5	3.1	5	4.7	87
South African Shelduck	2.8	3.5	3.2	4	2.7	4.3	3.5	69
Spur-winged Goose	3	4	3.3	4	3	5	4	75
Comb Duck	2.2	3.5	5	4	2.6	4.2	2.8	69
African Pygmy-Goose	1.5	2.1	2.9	3	1.8	1.8	2.2	44
Cape Teal	2.9	3.8	3.8	3.7	3	2.7	3.5	67
African Black Duck	3.1	3.2	1.6	1.6	1.2	2.8	2	44
Yellow-billed Duck	3.1	4.4	3.8	4	2.8	3.8	4	74
Cape Shoveler	2.2	3.4	4	4.2	3.2	3	3.8	68
Red-billed Teal	3.5	4.5	4.8	4.5	3.33	3.7	3.9	81
Hottentot Teal	2	3.2	2.8	3.3	2.4	3	2.8	56
Southern Pochard	3	3.2	5	4	2.6	1	3.1	63

Step 3: analysis of spatial variation in the environment. Spatial variation in the southern African environment makes it unlikely that all areas of the subregion are at an equal risk of experiencing avian influenzas. Factors that will predispose areas toward being higher risk (see also Gilbert et al. 2006) include: (1) the presence of wetlands and water bodies; (2) location in higher rainfall regions; (3) location in cooler areas in which influenza viruses can persist for longer time periods in water

bodies, and areas in which ephemeral water bodies may persist for longer because of lower evaporation rates; (4) areas that contain relatively high densities of humans in a rural or semi-rural setting; (5) areas in which there is extensive rural poultry production; and (6) landscapes in which humans, wild birds, and water birds mingle, such as those used for irrigated agriculture, and in which small, constant food and water resources such as feeding troughs or borehole-filled water points are available.

These variables were quantified for southern Africa using the best data sets that we could find in each instance (Hutchinson et al. 1995, CSIR 2001, SSA 2001, CDSM 2006, FAO 2006). Because of the lack of suitably high-quality data for other southern African countries, we focused on South Africa for the quantification of environmental risk factors (Table 2). To adopt an approach that was consistent with the bird ranking exercise in the previous section, we divided each data set into five different classes and labeled them from 1—5 according to their risk level. In the environmental analysis, the determination of classes can be heavily influenced by outliers if a simple division of the range into five equal classes is used. To resolve this problem we standardized the data to a zero mean and unit deviation, rounded all values to the nearest 0.1, and defined the five classes as <-1 , -1 to <0 , 0 , >0 to ≤ 1 , or >1 . We then summed the total risk estimate across all data sets, divided by 7 to give a by-variable score, and multiplied by 100 to produce a map that shows an estimate of the percentage environmental risk associated with each grid cell. All criteria were ranked equally in this exercise because we had no quantitative basis for assigning justifiable relative weightings.

Step 4: linking environmental and wild bird risks. The final step was to link our assessment of risks from wild birds and our assessment of predisposing risk factors in the environment by adding the two percentage risk scores together and dividing by two. This yielded a single risk map for the potential occurrence of avian influenza in southern Africa.

RESULTS

Our results are presented as a set of maps indicating our HPAI risk index by quarter-degree cell. The results from our first step, wild bird risk mapping, are presented in Fig. 2. Figure 3 builds on this analysis to take into account a surrogate measure of abundance; this map is notably similar to Fig. 2 in terms of its overall pattern. The risks associated with spatial variation in the environment are shown separately in Fig. 4. Finally, Fig. 5 (Step 4) depicts the outcome of linking Figs 2 and 4. This represents our current "best guess" as to which areas of South Africa are at greatest risk from HPAI.

As one might expect, the areas that emerge as being most at risk from HPAI are the Western Cape and the densely populated highveld around Johannesburg.

Both are fertile areas with high water bird diversity, relatively high annual rainfall, high human population densities, and extensive agriculture. Ringing records suggest that these areas are linked by the movements of birds that exploit seasonal differences in summer vs. winter rainfall (Underhill et al. 1999), although little other evidence is currently available from which to test this hypothesis more directly. Additional potential high-risk areas include the mid-altitude regions of the Central Free State, the Eastern Cape, and central KwaZulu-Natal. Most of the high-risk areas also include substantial numbers of poultry farms, on which the potential for transmission between wild and domestic birds could be high.

Our focus on ducks means that areas near the coasts, in which the abundance and species richness of taxa that are strongly associated with the marine environment is high, do not necessarily emerge as high-risk zones. If terns or gulls, for example, were shown at some future date to be carriers of HPAI, this aspect of our analysis would need to be revisited.

DISCUSSION

Although this exercise is obviously influenced by the many subjective decisions taken in determining risk criteria and in developing a simple index, as well as the quality and kinds of available data, it does serve to provide a first, simple, quantitative description of the potential risks of HPAI outbreaks associated with wild bird movements in different parts of South Africa. It is also interesting that our maps do highlight the area of the Eastern Cape H5N2 outbreak, in which at least one wild Egyptian Goose tested positive for H5N2 (Sinclair et al. 2005), as a high-risk zone.

The risks associated each different variable in our analysis are obviously not identical. We have decided to follow a parsimonious approach to quantifying risk because most of the data that would be needed to weight different variables quantitatively, and hence, rigorously, are not available for southern Africa. It would obviously be possible to develop this risk-mapping approach to a far greater level of complexity. For instance, some bird populations will act primarily as pathogen carriers, whereas others will be more likely to act as reservoirs; the kinds of data on prevalence and movement that would be needed to distinguish

Table 2. Variables used in assessing environmental risk for avian influenza in southern Africa. Categories were assigned quantitatively, based on deviations from the mean of a standardised distribution. The reasoning behind the use of these risk factors is discussed in the text.

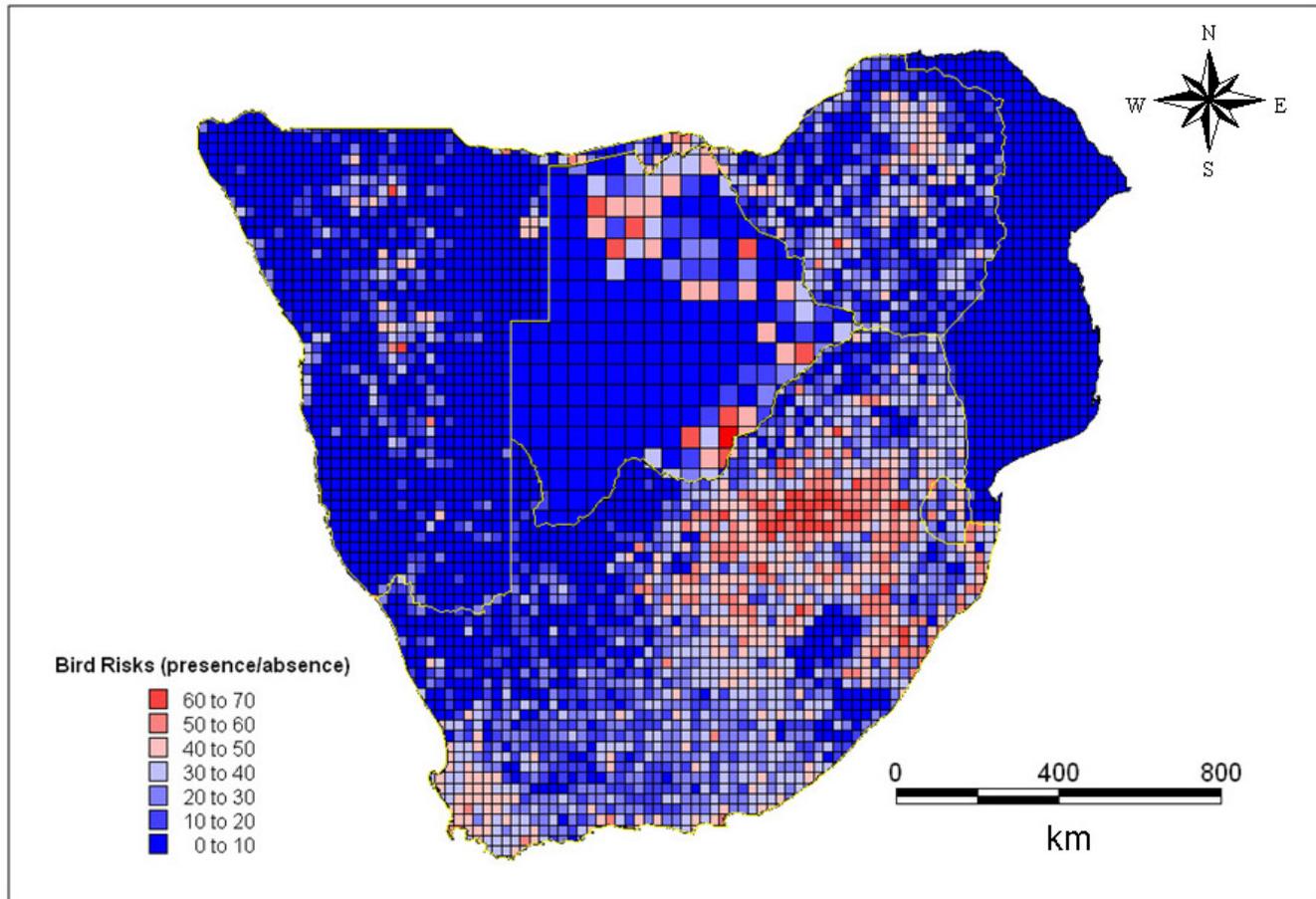
Variable	Description	Risk scale
FAOChix	Density of chickens per grid cell (FAO 2006)	1=low, 5=high
Popdens1	Human population density (SSA 2001)	1=low, 5=high
Mtemp00	Mean monthly temperature (Hutchinson et al. 1995)	1=warm, 5 = cool
Mrfall00	Mean monthly rainfall (Hutchinson et al. 1995)	1 =low, 5=high
RfallCV	Coefficient of variation in mean monthly rainfall (Hutchinson et al. 1995)	1=high (least predictable), 5=low
WL_area	Total area of wetlands as defined from 1:50 000 scale map falling into cell (CDSM 2006)	1 = small, 5 = large
WL_perim	Total perimeter of wetlands as defined from 1:50 000 scale map falling into cell (CDSM 2006)	1 = small, 5 = large
Grains	Area in cell classified as irrigated crops or grasslands in the South African National Land Cover data set (CSIR 2001)	1 = small, 5 = large

between these different roles are not available. Similarly, we were unable to obtain reliable statistics for the domestic bird part of the problem. Our results will be further influenced by a range of other complexities, including variation in bird numbers in time; anthropogenic factors that have not been accounted for, such as the movements of rural poultry and the locations of markets; and possible interactions among shorebirds, wading birds, and ducks. Unlike in Asia and northern Africa (Gaidet et al. 2007), our subjective impression from working at wetlands across the subregion is that southern African human populations do not generally use ducks as a frequent food source, with the possible exception of southern Mozambique, and that there are few or no markets at which live wild ducks are sold. Our impression is also that domestic ducks kept in rural settings are generally not southern African species. For instance, Mozambicans regularly keep Muscovy Ducks (*Cairina moschata*), but Mallards (*Anas platyrhynchos*) are kept in South Africa. In cases in which poultry are kept near to wetlands, a more likely transmission pathway would be from wild ducks to free-range domestic poultry, but few or no data are currently available on the degree to which such contact might

occur and the high prevalence of predators, e.g., crocodiles, monitor lizards, genets, caracals, mongooses, and raptors, around rural African wetlands means that most domestic poultry must remain close to a human homestead if they are to survive. One of the highest risk forms of poultry farming in the subregion is that of ostriches, in which wild ducks and domestic ostriches often mix freely at open feedlots and drinking troughs.

The lack of reliable data on the movement patterns of wild ducks makes it difficult to assess some aspects of risk, such as whether some wetlands are particularly likely to function as centers of disease transmission within a broader network. There is also a general lack of information about the dynamics of either HP or LP avian influenza transmission in natural environments, making it difficult to model such things as environmental influences on transmission rates or distinctions between pathogen carriers and reservoirs. Our relatively simplistic analysis of spatial variation in avian influenza risks in southern Africa does, however, provide a fact-based opinion that has the virtues of being interpretable by decision makers and readily repeatable for other areas or at a different scale of

Fig. 2. Map showing risk assessment for avian influenza occurrence based on expert opinion and known species presence/absence (Harrison et al. 1997) of 16 southern African anatids. Note that the data for Botswana were recorded at half-degree (30'x30') resolution in the southern African Bird Atlas, and that data for Mozambique (for completeness, shown here from south of the Zambezi) were not included in this analysis.



analysis. The map could usefully be used to select areas for active surveillance as well as to direct public health investment in response preparedness, e.g., personnel training, vaccination campaigns, or stockpiling sampling equipment and relevant drugs.

We conclude that surveillance for avian influenza in both poultry and wild birds in southern Africa should be centered on populated localities near to wetlands in the highveld, as well as in a subset of high-risk coastal areas. In closing, we would also like to stress that scientifically proven risks from wild bird transmission of HPAI remain low. The

primary factor increasing H5N1 risks in southern Africa is almost certainly the potential for long-distance commercial movements of infected domestic poultry, together with poor biosecurity at poultry farms. As suggested by Sinclair et al. (2005), the introduction of strict measures to ensure that wild and domestic birds do not come into contact on poultry farms will probably be the most effective approach to ensuring that HPAI does not enter the wild bird population.

Fig. 3. Map showing risk assessment for avian influenza occurrence based on expert opinion and quantified reporting rates for species of 16 southern African anatids (Harrison et al. 1997). Note that the data for Botswana were recorded at half-degree (30'x30') resolution in the southern African Bird Atlas, and that data for Mozambique (for completeness, shown here from south of the Zambezi) were not included in this analysis.

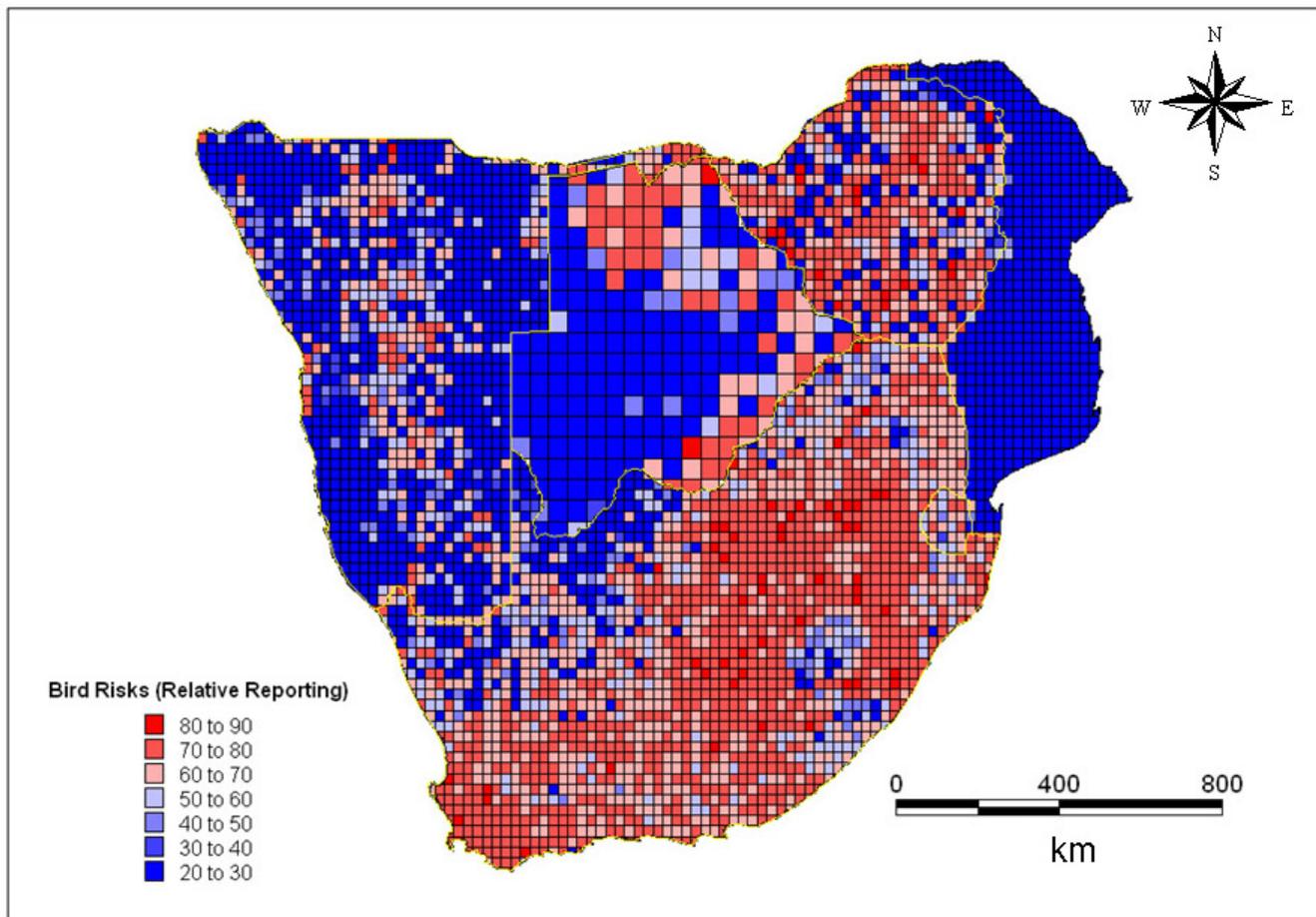


Fig. 4. Map showing environmental risks for avian influenza occurrence in South Africa and Lesotho, based on seven different environmental variables that were identified as increasing risk.

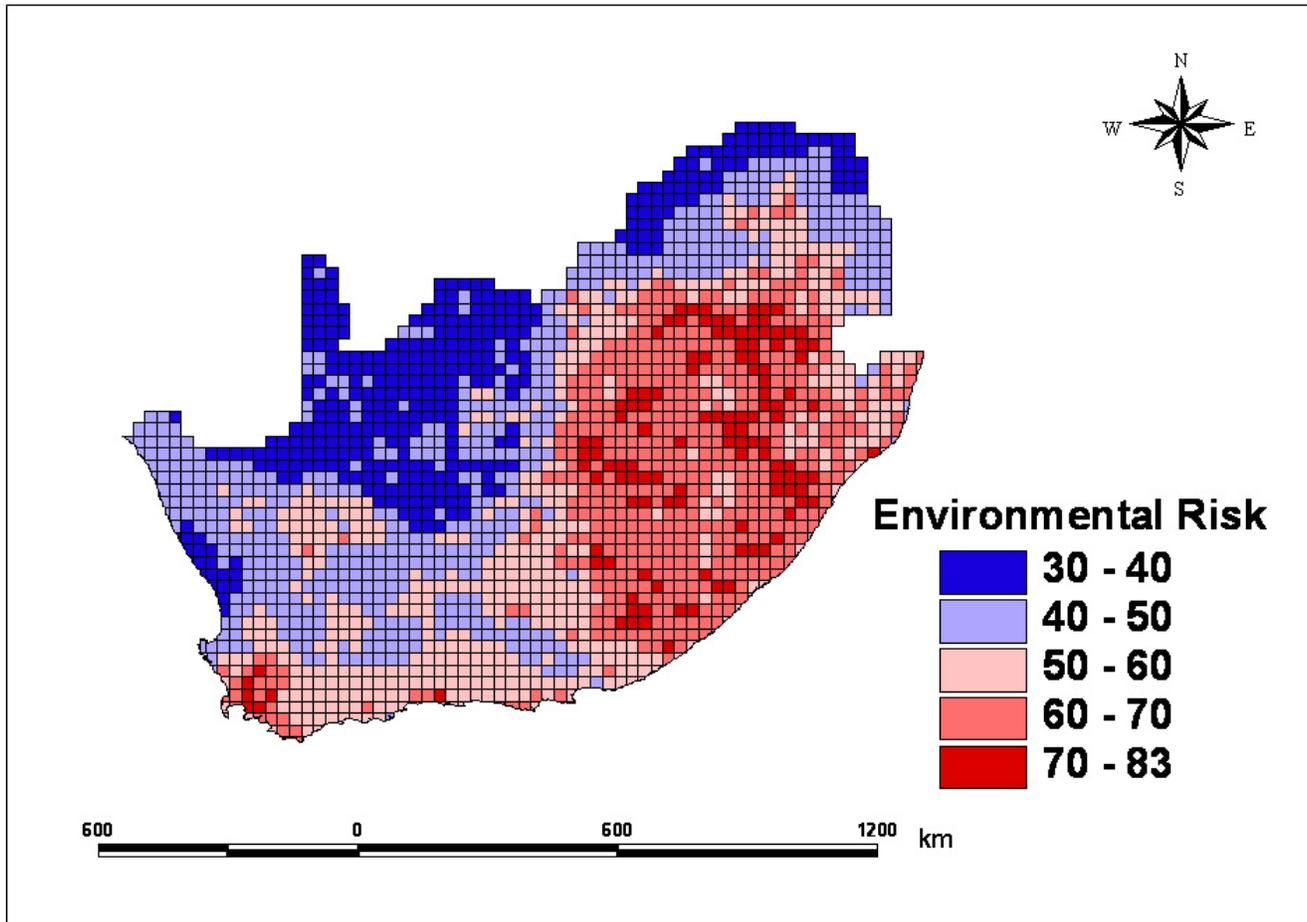
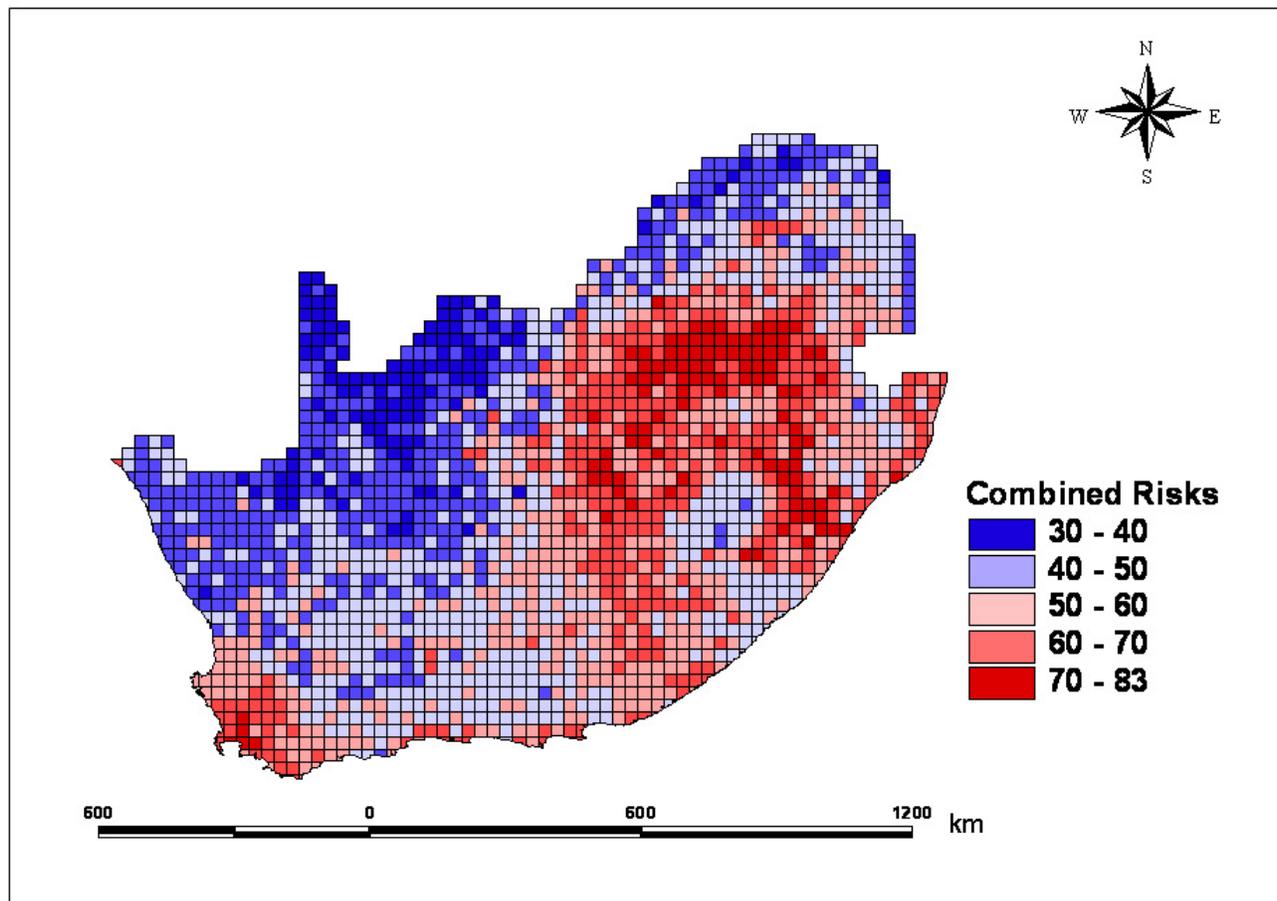


Fig. 5. Map showing summed risks for avian influenza occurrence in South Africa and Lesotho, based on assessment of wild birds and environmental variables. Further details in text.



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Appendix 1.

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