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REMOTE SENSING, ECOLOGICAL VARIABLES, AND WILD BIRD MIGRATION RELATED TO OUTBREAKS OF HIGHLY PATHOGENIC H5N1 AVIAN INFLUENZA[1]

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ABSTRACT: Outbreaks of highly pathogenic avian influenza (HPAI) H5N1 subtype have occurred in many countries across Asia, Europe, and Africa since 2003. Better understanding of the ecology and risk factors of HPAI is critical for surveillance, risk assessment, and public health policy. We introduce satellite remote sensing as one important tool, and highlight the potential of using satellite images to monitor dynamics of climate and landscapes that are related to wild bird migration and agriculture in the context of avian influenza transmission.

Key words: Avian influenza, land surface temperature, MODIS images, paddy rice.

Since late 2003 several Southeast Asia countries experienced outbreaks of highly pathogenic avian influenza (HPAI) H5N1 subtype. The emergence of this virus in Southeast Asia had dramatic consequences. Direct impacts in the affected countries include death of infected people, mortality in poultry and birds culled for disease control, and economic effects on the local and international trade of poultry and poultry products. HPAI H5N1 outbreaks in Southeast Asia resulted in the death of 76 people (as of 10 January 2006) (World Health Organization [WHO], 2005), and nearly 140 million domestic poultry.

In May 2005, the first major outbreak of HPAI H5N1 virus in wild waterbirds took place in Lake Qinghai, western China (Liu et al., 2005). The Lake Qinghai area is an important breeding site for many wild waterbirds that overwinter in Southeast Asia, Tibet, and India. During fall/winter of 2005 and spring 2006, HPAI H5N1 virus spread rapidly over Asia, Europe, and Africa, with a total of 192 human cases (109 human deaths) by April 6, 2006. One hypothesis for the global patterns and dynamics of the spread of HPAI H5N1 virus is that seasonally migratory wild waterbirds may carry the virus and spread it along migratory flyways. Understanding the role of wild birds in HPAI epidemiology is probably one of the most challenging tasks of HPAI disease ecology because of the multiplicity of bird species potentially involved, their unknown range of susceptibility to different virus strains, the diversity of their habitats, and their diffuse patterns of migration. A pragmatic approach to predict the risk of HPAI transmission from wild birds is therefore to explore where and when wild birds are most likely to be in contact with domestic poultry, which may then allow the virus to enter the domestic poultry population (Fig. 1). To examine the hypothesis on wild waterbirds fully, one needs comprehensive knowledge of seasonal migration of wild waterbirds, including timing of migration and locations of breeding, moulting, stopover, and wintering sites.

Migration timing and flyways of wild waterbirds are affected by weather, climate, and land-surface types (Fig. 1). We are living on the human-dominated planet

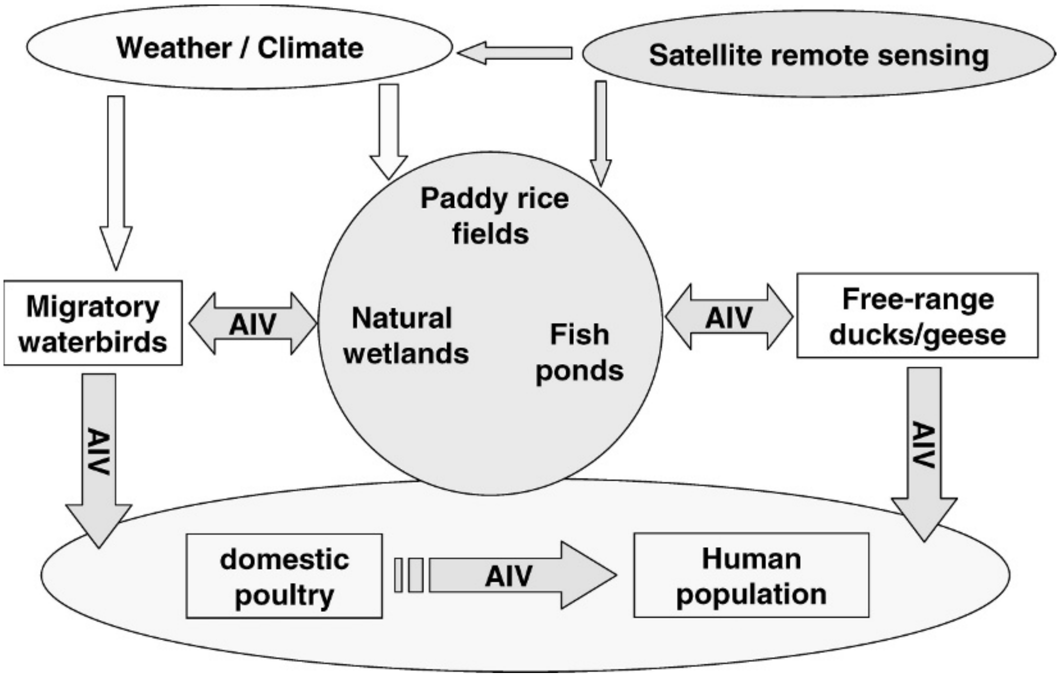

FIGURE 1. The schematic diagram that illustrates the role of satellite remote sensing for studying bird migration, agriculture, natural wetlands, and epidemiology of avian influenza virus (AIV).

Earth and human activities in land use and water use have dramatically changed the land surface types and their temporal dynamics. We aim to illustrate the potential of satellite remote sensing for quantifying ecological variables that are relevant for bird migration, and to propose a research framework that could integrate satellite-derived geospatial databases into risk assessment and decision support tools.

Routine observations from meteorological satellites (namely, the National Oceanic and Atmospheric Administration [NOAA] Advanced Very High Resolution Radiometer [AVHRR] sensors) have been widely available since the early 1970s. For example, thermal bands of the NOAA AVHRR sensors have been used to estimate land surface temperature (LST), and the resultant LST data have been used for studying ecology of infectious disease (e.g., malaria), risk assessment, and early warning (Hay et al., 2000; Rogers et al., 2002).

On 18 December 1999 the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) program launched the Terra satellite that carries several advanced optical sensors, including the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. The MODIS sensor records image data in 36 spectral bands ranging from 0.4 to 14.4 μm. Two spectral bands (red and near infrared) are imaged at a nominal resolution of 250 m at nadir, five bands (blue, green, near infrared, and two shortwave infrared bands) are imaged at 500 m, and the remaining 29 bands at 1 km. For its orbit around the Earth, MODIS/Terra passes from north to south across the equator in the morning (around 10:30 AM) and the evening (about 10:30 PM). The MODIS/Aqua satellite was launched on 4 May 2002, and Aqua passes from south to north across the equator in early afternoon (around 1:30 PM) and late evening (1:30 AM). Therefore, both MODIS/Terra and MODIS/Aqua provide daytime and nighttime observations of the entire globe every 1–2 days. Both systems provide unprecedented data for improving our understanding of land, oceans, and the atmosphere, and thus offer improved capacity for monitoring the atmosphere and landscapes that are related to wild birds and poultry as well as transmission of avian influenza.

To facilitate the wide use of MODIS data, the NASA EOS program organized four MODIS science discipline teams related to the atmosphere, land, ocean, and calibration. The land science team provides a suite of standard products to users, including Land Surface Reflectance, and Land Surface Temperature (LST) (Wan et al., 2004). Detailed information about the science teams and data-processing procedure are described at http://modis.gsfc.nasa.gov/. These data products are freely available to users.

Many factors determine when wild waterbirds start their migration from their breeding sites in the northern territories to their overwintering sites in the south, thus affecting the possible spread of bird-transmitted diseases. In addition to internal biological clocks (e.g., daylight length) and physiological status (e.g., body fat/weight ratio), a number of weather and climate factors may play important roles in bird migration, including wind, temperature, as well as snow and ice cover of the land surface and water bodies. Arrival of snow and/or ice in the early fall makes it difficult for some birds to find food and water, forcing them to migrate southward. Low temperature (particularly frost events at night) in the autumn may trigger migration of some wild waterbirds in northern territories. These climate-driven temperature triggers can be monitored and modeled with high-temporal-resolution remote-sensing data such as MODIS.

The spatial and temporal distribution of LST can be estimated from thermal imagery (Wan et al., 2004). In comparison to AVHRR sensors, the MODIS sensor offers improved capacity to estimate LST for the globe (Wan et al., 2002, 2004). The MODIS Land Science Team produced a standard product of LST at 1-km spatial resolution and daily to 8-day temporal resolution, including both daytime and nighttime LST. With the use of time-series data of nighttime LST, one can quantify the traveling wave of frost. We used nighttime LST in 2004 to delineate the traveling wave of frost in the fall and spring seasons over the western Palearctic ecoregion (Fig. 2).

In the fall, the traveling wave of first frost shows a distinct spatial gradient from the Western Siberian Lowlands to the Mediterranean region (Fig. 2a). Populations of wild waterfowl are composed of individuals of different ages likely to have different capacities for tolerance of cold temperature and thus different response strategies to frost. Part of the Western Siberian Lowlands experienced frost in July, and frost is generally considered as one of the triggers to initiate migration of young wild birds to their moulting sites south of the Western Siberian Lowlands. By late September to early October, most of the Western Siberian Lowlands experienced the first frost, and it is likely that most migratory waterfowl started to move out of their breeding sites and begin their long journey to wintering sites in the south.

In the spring, the traveling wave of the last frost also shows a distinct spatial gradient from the Mediterranean region to the Western Siberian Lowlands (Fig. 2b). Rapid retreat of the frost line during April and May suggests that this is the spring migration season for a large number of wild birds moving towards the Western Siberian Lowlands. By late May to early June, the Western Siberian Lowlands is mostly frost-free and serves as a major breeding site for millions of wild birds. Spring migration may potentially result in replenishment and transmission of avian influenza virus at breeding sites.

Highly pathogenic H5N1 virus has established an ecological niche or reservoir in domestic poultry (WHO, 2005).

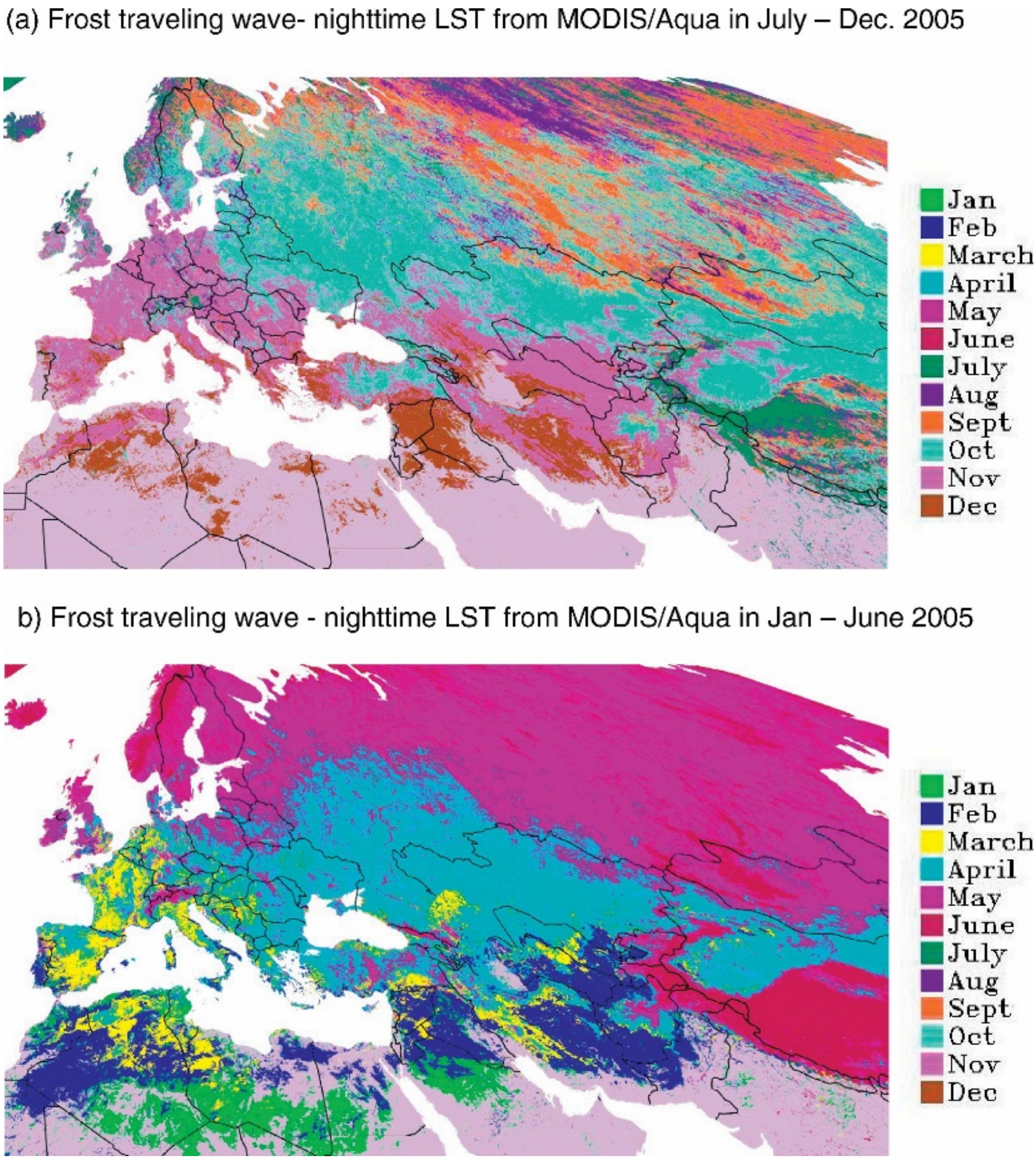

FIGURE 2. Traveling wave of frost from nighttime land surface temperature in 2005 (MODIS/Aqua). (a) The date of the first 8-day frost in July–December. (b) The date of the last 8-day frost in January–June.

Domestic ducks play an important and silent role in the persistence and spread of HPAI, as the ducks can remain relatively healthy whilst excreting a sufficient amount of HPAI H5N1 virus to sustain transmission (Hulse-Post et al., 2005; Sturm-Ramirez et al., 2005). Geospatial analyses of HPAI outbreaks in Thailand corroborate these laboratory findings by showing that the spatial distribution of HPAI outbreaks in chicken and ducks is strongly associated with that of free-grazing ducks (Gilbert et al., 2006).

Husbandry of free-grazing ducks in Thailand occurs extensively in the rural areas where multiple cropping systems dominate throughout a year. Southeast Asia has a monsoon climate with distinct dry (fall/winter) and wet (spring/summer) seasons. In order to meet rising needs of food and fiber for an increasing human population, irrigation infrastructure has been constructed to make it possible to cultivate second and/or third crops in the dry season (mostly in fall/winter months). Multiple-cropping agricultural systems provide essential food sources for large flocks of free-grazing ducks that move frequently from one post-harvested field to the next to feed on leftover rice grains, as well as insects and snails, as part of integrated pest management strategies. It is important to note that when wild waterbirds migrate to Thailand in the fall/winter, they likely use the post-harvested rice fields and second rice crop fields as their food and water resources. Therefore, rural landscapes with a double- or triple-paddy rice cropping system provide an opportunity for mixing wild waterbirds with domestic poultry, an important precondition for transmission of avian influenza virus among waterbird populations, and between wild waterbirds and domestic poultry (see Fig. 1).

The spatial distribution and timing of crop cultivation in the fall/winter seasons vary substantially in Thailand, due to changes in the length and timing (starting and ending dates) of the dry season, as well as effects of markets, policy, and infrastructure. In recent years, substantial progress has been made in both remote sensing technology and data analysis methods. For example, it is now possible by using MODIS satellite images to map and monitor paddy rice agriculture (Xiao et al., 2005, 2006) and cropping intensity in Asia. Here we used 8-day composites of MODIS land-surface reflectance product (MOD09a1) in 2004 as input data to a temporal-profile analysis algorithm (Xiao et al., 2005, 2006) to map cropping intensity, crop calendar, and irrigation (inundation) in Thailand. The resultant cropping intensity map has a spatial resolution of 500 m (Fig. 3).

Spatial distributions of HPAI H5N1 outbreaks in ducks and chickens in 2004 agreed well with those of free-range ducks and multiple-cropping areas in Thailand (Fig. 3). Similar geospatial associations between the paddy rice production system and free-range duck production system are expected in other affected countries in Southeast Asia. In other words, agricultural land-use intensification (multiple cropping) provides necessary habitats and food resources for domestic ducks and wild migratory waterfowl to interact and potentially transfer infection during the fall/winter months.

In response to the emerging and continuous outbreaks of HPAI H5N1 in East and Southeast Asian countries, the Global Strategy for the Progressive Control of HPAI was developed (Ferguson et al., 2005; Food and Agriculture Organization of the United Nations [FAO], 2005). Strengthening surveillance capacity in affected counties and evaluating those most at risk are key priorities identified by the Food and Agriculture Organization (FAO) of the United Nations and the World Organization for Animal Health (OIE). At present, risk assessment and early warning systems are based largely on agricultural census data that are often out of date and of coarse spatial (e.g., national or provincial) and temporal (e.g., annual) resolutions.

We have briefly discussed the potential of satellite remote sensing for quantifying ecological variables that are relevant to bird migration at a spatial resolution of 1 km or finer and a temporal resolution of daily to weekly. It is important to note that many of those ecological variables (e.g., temperature, snow) also are important to agriculture, another important component for understanding epidemiology of avian influenza. Significant progress in geospatial technologies (i.e., remote sensing, geographic information systems, and global positioning systems) occurred over the last decade, and enormous amounts of satellite imagery are available free or at low cost. It is now

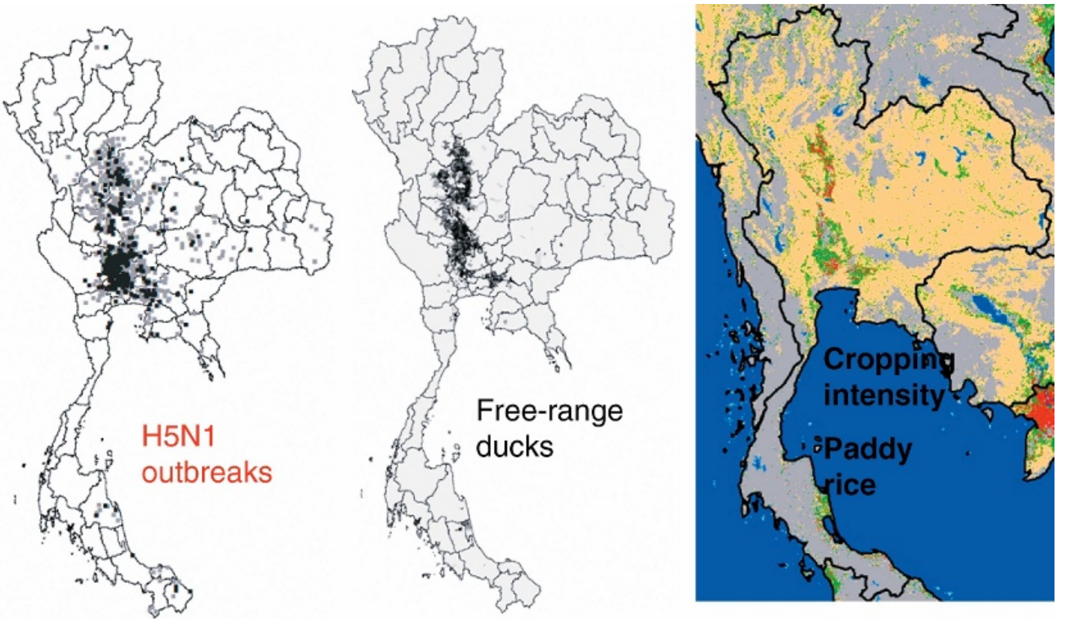

FIGURE 3. Spatial distributions of (1) HPAI outbreaks in domestic ducks and chickens in Thailand during the second wave of outbreaks in 2004–2005 (lab-confirmed outbreaks reported in ducks from 3 July 2004 to 5 May 2005), (2) free-range duck density, and (3) cropping intensity map. In the H5N1 outbreaks map, the solid black circle represents outbreaks of ducks, and the gray square represents outbreaks of chicken. The cropping intensity map is derived from 8-day composite MODIS imagery in 2004 at 500-m spatial resolution, where green and red colors represent double or triple cropping per year.

possible to apply the satellite-based algorithms to map and monitor crop intensity, crop calendar (planting and harvesting dates), and irrigation at moderate spatial resolution (250–500 m) in near-real-time fashion. The resultant geospatial data can, therefore, be used to assess where year-round availability of harvested crop fields may sustain free-range duck husbandry and wild waterbirds. Satellite imagery can be used to track the seasonal dynamics of wetlands where wild migratory waterbirds live. This can be combined with both in situ observations and satellite telemetry tracking data of bird migration for studying spatial patterns, temporal dynamics, behavior, and ecology of wild waterbirds. Satellite imagery also can be used to track the temporal dynamics of water temperature, a factor in the survival rate of H5N1 virus in water bodies (Stallknecht et al., 1990). Therefore, the geospatial data derived from satellite remote sensing, once incorporated into HPAI epidemiological models and decision support systems, will substantially improve their functionality and effectiveness. Geospatial technology, such as the emerging Global Earth Observation System of Systems (GEOSS), that will encompass a variety of remote sensors can play an important role in identifying likely hot spots (location-varying risk) and hot times (time-varying risk) for efficient and intelligent deployment of limited resources for surveillance, risk assessment, and early warning.

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