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Spatial ecology, landscapes, and the geography of vector-borne disease: A multi-disciplinary review

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ABSTRACT

According to the World Health Organization, more than half the world's population is at risk for vector-borne illnesses such as malaria and Lyme disease. Climate change and other anthropogenic factors have further increased the incidence of vector-borne diseases in several parts of the world. To prevent the spread of these devastating diseases, scientists have focused their efforts on controlling the ever-expanding distributions of arthropod vectors. Since arthropod vectors are dependent on environmental factors, geospatial technologies, such as geographic information systems and remote sensing, may assist in their control and eradication by allowing researchers to collect, manage and analyze environmental data with greater precision and accuracy than ever before. Many studies of vector-borne disease have begun to integrate geospatial technologies, such as remote sensing-derived vegetation indices, with traditional ecological data. Here we review the use of multidisciplinary research incorporating climate, geospatial technologies, and ecology in the study and control of disease vectors. Suggestions for future research combining these disciplines are discussed.

1. Introduction

In the last century, rapid advances in the performance, accessibility and affordability of computer hardware and software has allowed researchers to collect data with greater speed, sophistication, sensitivity, and accuracy. As a prime example, the development of geographic information science (GIScience) has resulted in new multidisciplinary specializations that use geographic information systems (GIS) as a spatial framework in their analysis tool (Clarke, McLafferty, & Tempalski, 1996; Goodchild, 1992; Ostfeld, Glass, & Keesing, 2005). Interdisciplinary studies now commonly incorporate GIScience, allowing the visualization of data at scales not previously possible without this "birds-eye" view. As a result, geospatial technology has become a powerful tool in biological, medical, and ecological studies (Aplin, 2005; Auchincloss, Gebreab, Mair, & Diez Roux, 2012; Dijkstra, Hak, & Janssen, 2013; Dominy & Duncan, 2002; Fuller, Troyo, Alimi, & Beier, 2014; Roughgarden, Running, & Matson, 1991; Skog, 2014; Suhaida, Sood, & Saaban, 2015; Wang, Franklin, Guo, & Cattet, 2010).

In addition, geospatial technologies themselves have evolved as technology has become more sophisticated. In the past, remote sensing applications were used exclusively to detect changes in habitat or environmental conditions; however, more recently these methods have been used to address a wide range of biological questions (Broadbent et al., 2008; Chambers et al., 2007; Formica, Gonser, Ramsay, & Tuttle, 2004; Jensen, Gonser, & Joyner, 2014; Kalluri, Gilruth, Rogers, & Szczur, 2007; Nair et al., 2008; Valavanis et al., 2008). Past studies were also restricted to large-scale analyses and the most coarse spatial resolution, but as technology has become more sensitive, even smaller scales (e.g. $\leq 1\ m^2$) can be investigated (Birk et al., 2003; Dhinwa et al., 2010; Mumby & Edwards, 2002; Roughgarden et al., 1991; Sahu, ObiReddy, Kumar, & Nagaraju, 2015; Tanaka & Sugimura, 2001). Finally, with the development of information technology and cloud resources, multidisciplinary spatial research can answer many large-scale ecosystems questions. For example, over the past decade researchers have been able to pinpoint the evolutionary and ecological effects of global climate change in a variety of biological systems (Dallas & Rivers-Moore, 2014; Michelutti et al., 2015; Patz

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& Olson, 2006; Purse et al,. 2005; Roessig, Woodley, Cech, & Hansen, 2004). Geospatial technology can link disease distribution, vector ecology, and climate change to provide insight into the many factors contributing to transmission (Bouzid, Gonzalez, Lung, Lake, & Hunter, 2014; Gauly et al., 2013; Githeko, Lindsay, Confalonieri, & Patz, 2000; Hongoh, Berrang-Ford, Scott, & Lindsay, 2012; McIver et al., 2015; Purse et al., 2005).

These rapid advancements in geospatial technology and techniques over the last two decades cannot be understated. Satellite data can detect reflectance of electromagnetic radiation at resolutions of one meter or less from commercial sources (Birk et al., 2003; Mumby & Edwards, 2002; Read, Clark, Venticinque, & Moreira, 2003), are applied to various anthropomorphic applications (Cleckner, Allen, & Bellows, 2011; Narumalani, Mishra, & Rothwell, 2004; Seelan, Laguette, Casady, & Seielstad, 2003; Smith & Thomson, 2003; Zhu et al., 2005; Zomeni, Tzanopoulos, & Pantis, 2008), and used to reveal global and local changes from disturbance to disasters (Ledrew, 1992; Myint, Yuan, Cerveny, & Giri, 2008; Nemani & Running, 1995; Potter et al., 2003; Ramsey, Chappell, & Baldwin, 1997; Sambah & Miura, 2014), and employed to investigate global climate change (Hinzman et al., 2005; Masek, 2001; Rosenqvist, Milne, Lucas, Imhoff, & Dobson, 2003; Silapaswan, Verbyla, & McGuire, 2001; Simas, Nunes, & Ferreira, 2001; Stow et al., 2004). These data have been used to predict environmental variables, or connect changes in the environment to biological patterns from food availability (Wilmers & Post, 2006), habitat quality (Valavanis et al., 2008; Wiegand, Naves, Garbulsky, & Fernandez, 2008), movement (Chapman, Reynolds, & Smith, 2003), and the abundance or outbreak of insects (Hurley, Watts, Burke, & Richards, 2004; Reisig & Godfrey, 2006). However, the connections between climate and vector biology may be correlative. Much work on the connections between biology and geography focus on ecology, where typical ecological measurements are used and compared with disease prevalence. Various single environmental measurements in ecology have connected changes in animal life history or biodiversity, such as temperature and rainfall (Barrientos, Barbosa, Valera, & Moreno, 2007; Li & Brown, 1999; Lysyk & Danyk, 2007), while others connect to extreme events that occurred after El Niño (Perriman, Houston, Steen, & Johannesen, 2000), including disease outbreaks (Ward & Johnson, 1996; Yang & Scherm, 1997). In epidemiology studies, researchers commonly draw connections between aspects of climate, such as precipitation and temperature, and disease outbreaks. Population cycles of red grouse, which are heavily connected to parasitic infection (Hudson, Dobson, & Newborn, 1998), are well simulated by climate-parasite models based on precipitation and temperature (Cattadori, Haydon, & Hudson, 2005). Similarly, cholera has been found to cycle with climatic factors including ENSO (Pascual, Rodo, Ellner, Colwell, & Bouma, 2000). Connecting vector borne disease to environmental variables, particularly climatic factors, has led to an effort to incorporate new technology and new analysis with the goal of identifying hot spots, or areas of potential outbreak, in at-risk regions (Clarke, Osleeb, Sherry, Meert, & Larsson, 1991; Young & Jensen, 2012). Hot spot data are readily available online (Demelle, Tang, & Casas, 2014; Houghton, Prudent, Scott, Wade, & Luber, 2012). While many parasites lack an animal vector, many diseases need an accomplice to actively spread; therefore understanding the natural history of a vector may help us understand the transmission of the disease.

These studies suggest that vector ecology can be used as an indirect factor to explain cycles of vector-borne disease outbreaks and prevalence. Several vectors are arthropods (Phylum *Arthropoda*), which include ticks, fleas, mosquitoes, black flies, and biting midges (see Table 1, Barbour & Fish, 1993; Durden & Page, 1991; Fallis & Bennett, 1961; Kiszewski & Cupp, 1986; Mellor, Boorman, & Baylis, 2000; Valkiūnas, 2005; Werden et al., 2014). Many Dipteran insects (including the families *Cuculidae*: mosquitoes, *Simuliidae*: black flies, and *Ceratopogonidae*: biting midges) require a minimum temperature and moisture content in order to cycle through their various larval stages (Adler, Currie, & Wood, 2003; Darsie & Ward, 2005; Focks, Haile, Daniels, & Mount, 1993; Mellor et al., 2000). Detecting or modeling levels of precipitation and temperature may assist in the prediction of insect outbreaks and current and/or possible expansion of disease range(s) (Cook, Folli, Klinck, Ford, & Miller, 1998; Lindsay, Parson, & Thomas, 1998; Purse et al., 2005; Ward, 1996). The ability to prevent or predict the next epidemic is particularly important in developing countries with populations that experience the highest rates of infection, and the lack of medicinal resources (Barat et al., 2004) and where vectors to pesticides and disease are resistant to medication (Greenwood & Mutabingwa, 2002; Lenormand, Bourguet, Guillemaud, & Raymond, 1999; Montagna, Anguiano, Gauna, & de d-Angelo, 2003). Moreover, changes in ecosystems in response to shifts in climate may explain expansion of the distribution patterns of vector borne diseases across the world, emphasizing the importance of vector ecology (Barbour & Fish, 1993; Harrus & Baneth, 2005; Hongoh et al., 2012; Sallares, 2006).

In this review we discuss the current status of multidisciplinary geospatial research in relation to vector-borne disease. We divide the review according to vector family.

2. Family: *Culicidae* – mosquitoes

Mosquito species are of great concern worldwide as they can spread many diseases, ranging from unicellular protists (i.e. malaria) to viruses (e.g. Dengue fever, Yellow fever, and West Nile Virus (encephalitis)) that affect human populations (Cianci, Hartemink, & Ibanez-Justicia, 2015; World Health Organization, 2015; Goddard, 1998; Khaemba, Mutani, & Bett, 1994; Kulasekera et al., 2001; Romero-Vivas, Leake, & Falconar, 1998; Ruiz et al., 2010; Vanderberg & Gwadz, 1980). A mosquito's ability to reproduce is directly related to the presence of still water (Focks et al., 1993; Kelly-Hope, Purdie, & Kay, 2004; Koella, Agnew, & Michalakis, 1998; Mabaso, Kleinschmidt, Sharp, & Smith, 2007; Singh & Sharma, 2002); thus, standing water and precipitation, and changes in moisture and precipitation, are used in models predicting disease outbreaks (Cleckner et al., 2011; Hopp & Foley, 2003; Schaeffer, Mondet, & Touzeau, 2008a; Schaeffer, Mondet, & Touzeau, 2008b; Zhou, Minakawa, Githeko, & Yan, 2004). Often remote sensing is used to detect the presence of moisture or water in the environment using vegetation indices such as NDVI (Normalized Differential Vegetation Index), a metric that correlates with vegetation in arid environments. These studies can incorporate climatic aspects as well, confirming the relationship between increased temperature and rain prior to mosquito and disease outbreaks (Battalán et al., 2015; Brown, Diuk-Wasser, Guan, Caskey, & Fish, 2008; Duchemin et al., 2006; Gleiser, Gorla, & Almeida, 1997; Kawamura et al., 2005; Pope et al., 1994; Rogers, Randolph, Snow, & Hay, 2002; Stockli & Vidale, 2004; Young, Tullis, & Cothren, 2013).

NDVI is based on the ratio of near-infrared to red reflectance that is calculated with the following equation:

$$\mathrm{NIR} - \mathrm{Red}/\mathrm{NIR} + \mathrm{Red}$$

Standardized NDVI values range from -1 to 1, where values closer to 1 indicate more robust vegetation. The United States Geological Survey and other government agencies calculate and maintain NDVI maps throughout the world using relatively coarse