Remote Sensing of Environment 137 (2013) 226–233

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Airborne imaging spectroscopy to monitor urban mosquito microhabitats

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ARTICLE INFO

Article history:
Received 5 December 2012
Received in revised form 20 June 2013
Accepted 22 June 2013
Available online 28 July 2013

Keywords:
Imaging spectroscopy
Disease vector control
West Nile virus
Green swimming pools
Matched filter detection
Urban environments

ABSTRACT

West Nile (WNV) is now established in the continental United States with new human cases occurring annually in most states. Mosquitoes in the genus *Culex* are the primary vectors and exploit urban stagnant water and swimming pools as larval habitats. Public health surveys to monitor unmaintained pools typically rely on visual inspections of aerial imagery. This work demonstrates automated analysis of airborne imaging spectroscopy to assist *Culex* monitoring campaigns. We analyze an overflight of Fresno County, CA by the Airborne Visible Infrared Imaging Spectrometer instrument (AVIRIS), and compare the spectral information with a concurrent ground survey of swimming pools. Matched filter detection strategies reliably detect pools against a cluttered urban background. We also evaluate remotely sensed spectral markers of ecosystem characteristics related to larval colonization. We find that commonly used chlorophyll signatures accurately predict the probability of pool colonization by *Culex* larvae. These results suggest that AVIRIS spectral data provide sufficient information to remotely identify pools at risk for *Culex* colonization.

Published by Elsevier Inc.

1. Introduction

Remote sensing has long contributed to infectious disease prediction and warning systems (Linthicum, Bailey, Davies, & Tucker, 1987; Washino & Wood, 1994). Spatial epidemiological studies have used satellite data to map environmental conditions associated with disease vector habitats. They typically correlate environmental variables such as land use, vegetation indices, temperature, and elevation with relative vector abundance or pathogen transmission (Beck, Lobitz, & Wood, 2000; Kalluri, Gilruth, Rogers, & Szczur, 2007). Instruments used for this purpose include the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Moderate Resolution Imaging Spectroradiometer (MODIS). Urban areas pose a special challenge: they are heterogeneous collections of residential and commercial areas, parks, and other land use types with potential vector habitats on much smaller spatial scales (Reisen, 2010). Characterizing these sparse microhabitats requires different remote sensing techniques.

A particular concern is West Nile Virus (WNV), which spreads in urban areas by transmission between birds and mosquitoes in the genus *Culex*. These mosquitoes often colonize stagnant water during their aquatic immature stages, and features such as open containers or unmaintained swimming pools provide key habitats (Caillouët, Carlson, Wesson, & Jordan, 2008; Reisen, Takashi, Carroll, & Quiring, 2008). Unmaintained residential swimming pools, or *green pools*, are especially problematic. These neglected pools become stagnant with accumulated organic matter, and often harbor *Culex pipiens* mosquito larvae (Fig. 1).

Current WNV mitigation efforts generally rely on street-level monitoring and treatment campaigns. Previous work has used remote sensing products such as airborne images to monitor individual pools, enabling more effective *Culex* treatment programs by identifying risk areas and flagging specific households for direct intervention. For instance, Reisen et al. (2008) demonstrate an airborne survey of Bakersfield, CA with high resolution color imagery. These images clearly reveal neglected green pools. However, manual inspection is necessary to catalog these habitats, so the approach is better suited for a single snapshot in time than sustained monitoring campaigns that track the evolution of the vector habitats. Since then, local providers have continued to refine the manual image inspection using GIS pool catalogs and higher spatial resolution (Franklin, 2013). There have also been efforts to automate the image analysis. Kim et al. (2011) propose a fully automated method to locate pools in GeoEye satellite images, detecting pools from a *Normalized Difference Water Index* (NDWI) score followed by a morphological classification. This is effective at finding pools, but assessing their condition still relies on manual inspection. To our knowledge no previous study has quantified a link between remotely sensed pool color and *Culex* colonization that would permit automated assessment of pool condition from airborne instruments.

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0034-4257/$ – see front matter. Published by Elsevier Inc.
http://dx.doi.org/10.1016/j.rse.2013.06.015

Fig. 1. *Culex* mosquitoes in urban areas often use unmaintained "green pools" as larval habitat.
Image: Santa Clara Vector Control District (2013), Franklin (2013).

This study contributes to the literature in two ways. First, we evaluate a new class of sensor – airborne imaging spectrometers – to assist *Culex* monitoring campaigns. These instruments, such as the Airborne Visible Infrared Imaging Spectrometer (AVIRIS), typically measure reflected light over large areas in wavelengths from 370 nm to 2500 nm. The wide bandwidth and high spectral resolution permit a suite of powerful approaches for pool detection and classification. In this work, we apply a matched filter approach to identify pool locations. Our second contribution is to quantify the relationship between remotely observed spectral attributes and the presence of *Culex* larvae. To this end, we combine AVIRIS imagery of an urban environment with reference surveys by vector control authorities. We construct models relating pool health to common spectral indicators of water quality. The results indicate a strong relationship between typical signatures of algal chlorophyll and *Culex* colonization.

2. Methodology

2.1. Data acquisition

Our study analyzed a survey overflight of Fresno, California (USA) that took place on 30 Sept. 2011. WNV is endemic in the area; the 2012 year had 24 confirmed infections in Fresno County and 479 in the state at large, resulting in 19 fatalities (California Department of Public Health West Nile Website, 2012). The Airborne Visible Infrared Imaging Spectrometer (AVIRIS) (Green, 2008) overflew the city on a Twin Otter turboprop aircraft under clear atmospheric conditions, acquiring spectra in the 370–2500 nm range with 10 nm spectral resolution and 3.7 m ground sampling distance. It imaged 60 km^2 of urban terrain with residential communities and commercial districts with occasional parks, canals and open reservoirs. Fig. 2 (Left) shows a typical orthorectified subframe. We applied the Atmospheric/Topographic Correction for Airborne Imagery (ATCOR) algorithm (Richter & Schläpfer, 2012) to compensate for scattering and absorption. At the same time the AVIRIS measured radiances were normalized with the solar irradiance to produce Hemispherical Directional Reflectance Factors (Schaepman-Strub, Schaepman, Painter, Dangel, & Martonchik, 2006), hereafter "reflectance."

In the weeks before and after the overflight, the Consolidated Mosquito Abatement District (MAD) conducted field surveys of suspect swimming pools in the area. Inspectors recorded pools as *breeding* or *nonbreeding* depending on whether mosquito larvae were found. They also categorized pool conditions as one of: *dry*, if the pool was empty; *light green*, if the pool had low algal density indicative of a recent lack of maintenance; *dark green*, if the pool had high algal density indicative of a long-term lack of maintenance; and *Blue*, if the pool was in normal condition. The breeding pools were always associated with the dark or light green conditions, while nonbreeding pools were always blue. Inspectors recorded the GPS location of the household and the date of the visit.

We began the analysis by matching the MAD survey entries to specific pixels in the AVIRIS image. This was complicated by the fact that the GPS records did not exactly correspond to pool locations; instead, they typically fell on the households' front driveways. We determined the precise pixel position of each pool by inspecting high-resolution commercial satellite imagery (Google, 2012; Nokia/DigitalGlobe, 2012). Almost all pools were visually apparent both in the high-resolution satellite images and the AVIRIS data. Occasionally a small, dark, or shadowed pool was not obvious in the lower-resolution AVIRIS image. In these cases we located the appropriate AVIRIS pixel by referencing nearby landmark features. Our data set consists of the first 25 pools from both breeding and nonbreeding groups based on the incidental ordering of the Consolidated MAD database.

It was necessary to skip some database entries to preserve the quality of this sample. We ignored entries for pools that could not be seen in the high-resolution images (6 pools). This may have been caused by modifications between the time of the survey and the unknown date of the satellite image. It is also possible that some database entries referred to spas which were under patio covers and therefore invisible. We also skipped pools whenever neighboring landmarks were not clear enough to identify the corresponding AVIRIS pixel (7 pools). Finally, some pools visited very early had obviously dried out by the time of the AVIRIS overflight so that only the bright bottom was visible (4 pools). We continued to label valid pixels until reaching the total number of 25 from each category. Most pools were inspected within two weeks of the overflight and it is reasonable to expect they did not change significantly during this period.

2.2. Matched filters for pool detection

We sought an automated procedure to transform an AVIRIS reflectance cube into a map of colonized and clean pools. This involves several distinct challenges. Finding pools requires suppressing false positives from urban spectral clutter. Then, assessing colonization potential requires an interpretable statistical prediction. Consequently we formulated the problem as two sequential steps of *pool detection* and *pool characterization*. We used different methods for each objective and then validated the two stages independently. The two steps appear in the center and right panels of Fig. 2.

The detection step identifies pixels containing pools. Previous work in pool detection by Kim et al. (2011) uses high-resolution imagery containing color and morphological information. They use the Normalized Difference Water Index (NDWI), a ratio of green and near-infrared channels, to flag water pixels. In contrast, we used a full-spectrum detection algorithm to analyze a wide spectral range. We excluded atmospheric absorption bands, analyzing all channels within the intervals from 400–1206 nm, 1433–1732 nm, and 1957–2500 nm. We used a matched filter, a classical strategy for subpixel target detection in spectral data (Manolakis, Siracusa, Marden, & Shaw, 2001). A linear mixing model treats the observed spectral reflectance in d channels, $\mathbf{x} \in \mathbb{R}^d$, as convex linear combination of a background distribution with the target spectrum $\mathbf{t} \in \mathbb{R}^d$. It models the background as a multivariate Gaussian distribution with mean μ and covariance matrix Ψ, ignoring independent additive measurement noise (Stocker, Reed, & Yu, 1990). It is most common