

Satellite Vegetation Index Data as a Tool to Forecast Population Dynamics of Medically Important Mosquitoes at Military Installations in the Continental United States

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ABSTRACT The United States faces many existing and emerging mosquito-borne disease threats, such as West Nile virus and Rift Valley fever. An important component of strategic prevention and control plans for these and other mosquito-borne diseases is forecasting the distribution, timing, and abundance of mosquito vector populations. Populations of many medically important mosquito species are closely tied to climate, and historical climate-population associations may be used to predict future population dynamics. Using 2003–2005 U.S. Army Center for Health Promotion and Preventive Medicine mosquito surveillance data, we looked at populations of several known mosquito vectors of West Nile virus, as well as possible mosquito vectors of Rift Valley fever virus, at continental U.S. military installations. We compared population changes with concurrent patterns for a satellite-derived index of climate (normalized difference vegetation index) and observed instances of population changes appearing to be direct responses to climate. These preliminary findings are important first steps in developing an automated, climate-driven, early warning system to flag regions of the United States at elevated risk of mosquito-borne disease transmission.

INTRODUCTION

Faced with mosquito-borne diseases such as West Nile virus (WNV) and emerging threats such as Rift Valley fever (RVF) virus, which could arrive in the United States at any time along a variety of pathways,^{1,2} we should constantly improve our ability to predict the population dynamics of the mosquito vectors of these pathogens.³ Predictions of changes in mosquito populations would greatly enhance estimates of the risk of spread of mosquito-borne viruses.^{4–6} For instance, regions predicted to have larger populations of competent vectors during outbreaks would likely experience more severe mosquito-borne virus transmission. Classic range maps⁷ display the total region where a mosquito species might be found but are not designed to show long-term annual or seasonal trends, habitat patchiness, or spatial variations in population density. Military and civilian public health and vector-control agencies have surveillance systems to sample mosquitoes at the local level, which capture much of this heterogeneity,^{8,9} but these data are not analyzed temporally on larger scales or used to forecast population abundances.¹⁰

Many potentially confounding, varying factors may influence measurements of mosquito population changes from one time period to another. On one hand, an array of constantly interacting and changing abiotic environmental parameters, including a suite of climate effects, perpetually affect mosquito population samples. On the other hand, human factors such as irrigation, application of pesticides, or particular surveillance methods may variously affect our perception of a mosquito population. Finally, population samples vary with the outcomes of the bionomic properties of the mosquito species themselves, such as flight range, quality and availability of breeding habitat and hosts, and presence and abundance of predators. Despite these challenges, a proven method for predicting mosquito population dynamics is to examine climate-population relationships. In Africa, climate data measured by satellites are used to predict conditions preceding production of large populations of mosquitoes and thus the earliest stages in a RVF epizootic.^{11,12} This effective early warning system in Africa was developed by looking at long-term associations between outbreaks of RVF, the mosquitoes that transmit RVF virus, and climate. In this report, our objective was to look at short-term climate-population associations for selected U.S. mosquito species, to assess the potential for a similar in-depth analysis. We focused on populations being influenced by climate, not to discount the effects of confounding factors but as a starting point in identifying potential predictive factors. We explored relationships between a satellite climate index and mosquito populations in selected regions of the United States, using mosquito surveillance data gathered by the U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM).¹³

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In particular, we sought to identify instances of population patterns that suggested a response to climate. If such responses exist, then we can build on those instances in ongoing analyses to determine whether similar current or future climate conditions lead to expected population abundances or whether other factors need to be identified.

METHODS

USACHPPM mosquito surveillance data were available for 2003–2005 from three regional commands, that is, Center for Health Promotion and Preventive Medicine-North, Center for Health Promotion and Preventive Medicine-South, and Center for Health Promotion and Preventive Medicine-West. The raw data were in an electronic spreadsheet format, divided according to year, and presented the number of adult female mosquitoes collected and trap-night values in daily, weekly, or monthly reports according to installation. There was variation among installations in sampling months, but sampling was generally performed in spring, summer, or autumn months. Collections were conducted by using Centers for Disease Control and Prevention light traps with or without carbon dioxide, New Jersey light traps, gravid traps, or counterflow-geometry traps baited with octenol. No installation sampled throughout the year, and approximately one-third of installations submitted data in all 3 years. Because the satellite climate data we used were in a monthly format, we compiled mosquito surveillance reports and calculated a trap-night metric for each species in each month at each installation. All mosquito catch numbers were logarithmically transformed before analysis. Although many dozens of mosquito species were detected at USACHPPM installations, we limited analyses to small groups of species known to be important in WNV transmission¹⁴ and hypothesized to be important in RVF virus transmission in the United States^{15–17} (Table I).

We used a subset of the USACHPPM data to investigate climate-population relationships across an operationally and ecologically meaningful cross-section of the United States.

We chose four installations in Georgia, namely, Fort Benning, Fort Stewart, Fort Gillem, and Fort McPherson, because this region could be particularly susceptible to the arrival of emerging mosquito-borne pathogens. Factors contributing to this susceptibility include nearly year-round mosquito climate, high concentrations of seaports and airports, frequent military mobilizations, and geographic proximity to island nations outside the continental United States. We chose three other installations, that is, Fort Riley, Fort Lewis, and Yuma Proving Ground, because they could provide insights regarding potential climate-population relationships in widely separated regions (the Midwest plains, the Pacific Northwest, and the desert Southwest, respectively). Data from Fort Gillem and Fort McPherson were combined because the installations are close (<20 km) and data were sometimes reported as pooled values for the two installations.

We obtained monthly North American normalized difference vegetation index (NDVI) satellite climate data sets for 1981–2005 from the Goddard Space Flight Center.^{18–20} The NDVI measures the greenness of the earth, capturing in one index the combined effects of temperature, humidity, insolation, elevation, soils, land use, and precipitation on vegetation. There is an almost-linear relationship between NDVI values and precipitation in semi-arid areas of Africa,^{21,22} and relationships between NDVI values and increases in locust²³ and mosquito²⁴ populations in Kenya have been documented. In ecological terms, vegetation is the productivity on which all animal life depends directly or indirectly and should correlate with temporal and spatial variations in mosquito populations. The NDVI is unitless, with a theoretical range of –1 to +1, but most values fall between 0 and 0.7. Positive values near 0 indicate bare soil with little or no vegetation, whereas values near 0.7 indicate dense vegetation. Raw NDVI data are reported in the form of a matrix, or coverage, of measurements taken from 8-km squares of the earth's surface. To provide a view of the relative long-term magnitude of NDVI, we also calculated the numerical difference

TABLE I. Focal Species Drawn from 2003–2005 USACHPPM Mosquito Surveillance Data

Mosquito Species	Typical Habitat	WNV	RVF Virus	Location	Case
<i>Aedes albopictus</i>	Tree holes; peridomestic	X		Fort Gillem/Fort McPherson	2
<i>Aedes vexans</i>	Floodwater pools	X		Fort Lewis, Fort Riley, Fort Gillem/Fort McPherson	1, 4
<i>Anopheles crucians</i>	Vegetated pools and ponds		X	Fort Stewart	2
<i>Coquillettidia perturbans</i>	Heavily vegetated bodies of water	X		Fort Stewart	2
<i>Culiseta melanura</i>	Tree holes and swamps	X		Fort Gillem/Fort McPherson, Fort Stewart	1, 2
<i>Culex erythrothorax</i>	Cattail marshes and ponds	X		Yuma Proving Ground	3
<i>Culex pipiens</i>	Stagnant water pools	X		Fort Lewis	2
<i>Culex salinarius</i>	Fresh or foul water pools	X	X	Fort Gillem/Fort McPherson, Fort Benning	3
<i>Ochlerotatus sollicitans</i>	Salt marshes	X	X	Fort Gillem/Fort McPherson, Fort Stewart	1
<i>Ochlerotatus triseriatus</i>	Tree holes; peridomestic	X	X	Fort Riley	2

Species were studied because of their status as either competent vectors for WNV in the United States or potentially competent vectors for RVF virus in the United States. It should be noted that most potential RVF virus vectors listed here are also vectors of WNV. Except for the bird-feeder *Culiseta melanura*, which is important in maintaining WNV in the wild, all species in this table feed on and potentially transmit viruses to humans. Case refers to one of the four kinds of climate-population patterns observed in this study.

(i.e., the anomaly value) between the observed NDVI and a 25-year mean NDVI for each month. For the anomaly NDVI, 0 indicates no difference from the 25-year average for that month, negative numbers indicate below-average greenness (dry periods), and positive numbers indicate above-average greenness (wet periods).

With a combination of geocoded data from the Bureau of Transportation Statistics²⁵ and the U.S. Geological Survey National Atlas,²⁶ we mapped polygons of USACHPPM military installations in a geographic information system with all raw and anomaly North American NDVI coverages. Using geoprocessing tools in the geographic information system, we calculated average monthly raw NDVI and anomaly NDVI values for each focal USACHPPM installation. Finally, we plotted monthly 2003–2005 raw NDVI and anomaly NDVI values with monthly population densities of the focal mos-

quito species for each installation and qualitatively assessed associations of NDVI values with changes in mosquito populations.

RESULTS

Selected plots of 2003–2005 USACHPPM mosquito surveillance data and NDVI data at the focal installations are given in Figure 1. Overall, we observed several instances of mosquito populations appearing to be influenced by variations in climate, as measured with the NDVI. These instances can be placed into the following groups: case 1, unusually dry periods coinciding with the appearance of a mosquito species not collected at any other time in the sample period (Fig. 1A); case 2, unusually dry periods coinciding with populations reaching unusually high densities (Fig. 1B); case 3, unusually wet periods, especially over late winter/early spring months,

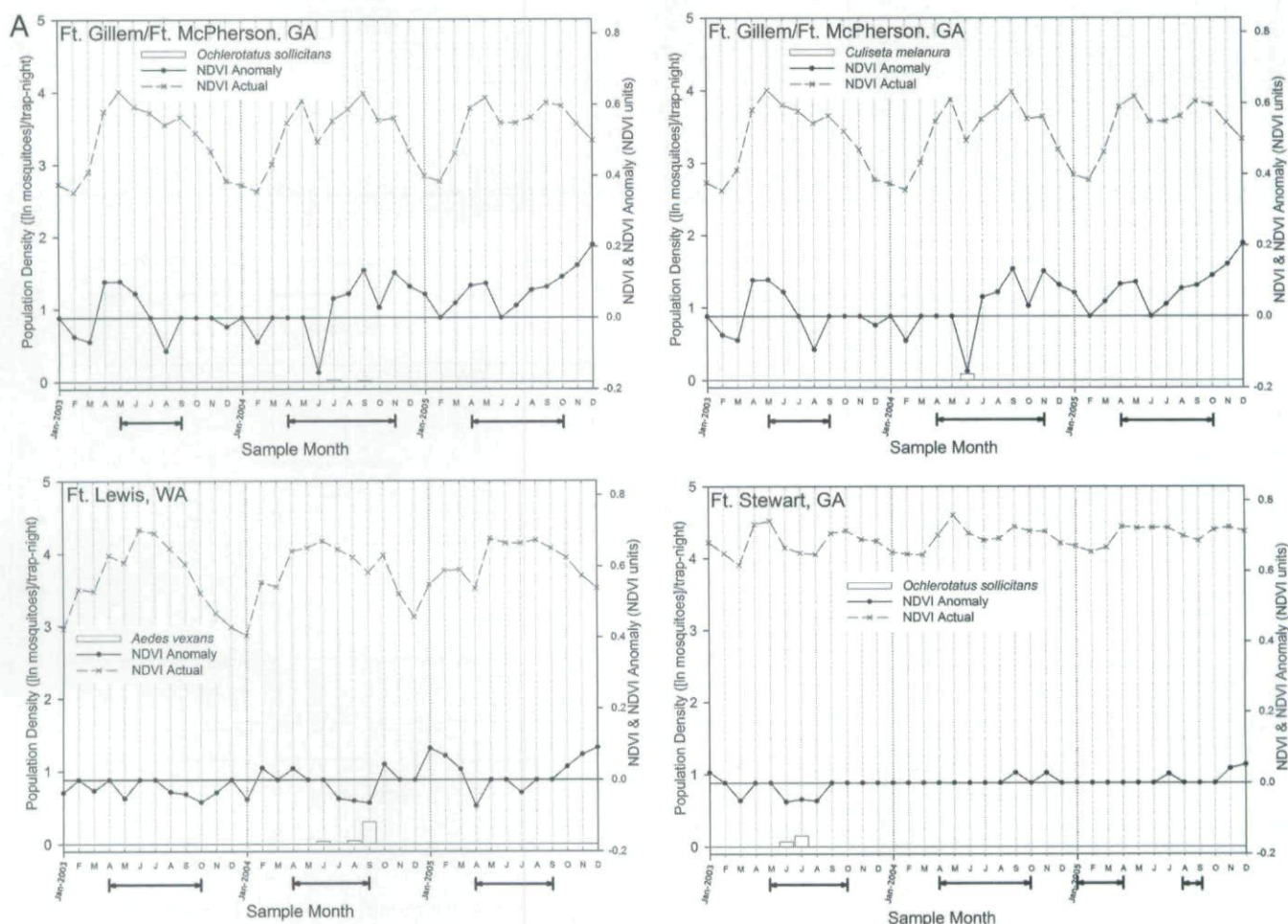


FIGURE 1. Representative 2003–2005 mosquito population data (bars) superimposed on curves of raw NDVI (dashed lines) and anomaly NDVI (solid lines) data for seven focal USACHPPM installations. Yearly and monthly breaks are shown with vertical dotted lines, and the NDVI zero-line provides quick reference to monthly anomalies above or below the 25-year average greenness for that location. Thick horizontal lines below the x-axis indicate the range of months sampled at that installation in a given year. It should be noted that, at most installations, peaks and troughs in raw NDVI values generally corresponded to summer (wet and warm) and winter (cool and dry) months, respectively. For Yuma Proving Ground, the NDVI curve typically was flat, reflecting year-round dry conditions. At all installations, anomaly NDVI values revealed fine-scale, month-to-month, climate effects that were hidden in the broad seasonal patterns of raw NDVI data. A, Case 1. B, Case 2. C, Case 3. D, Case 4.

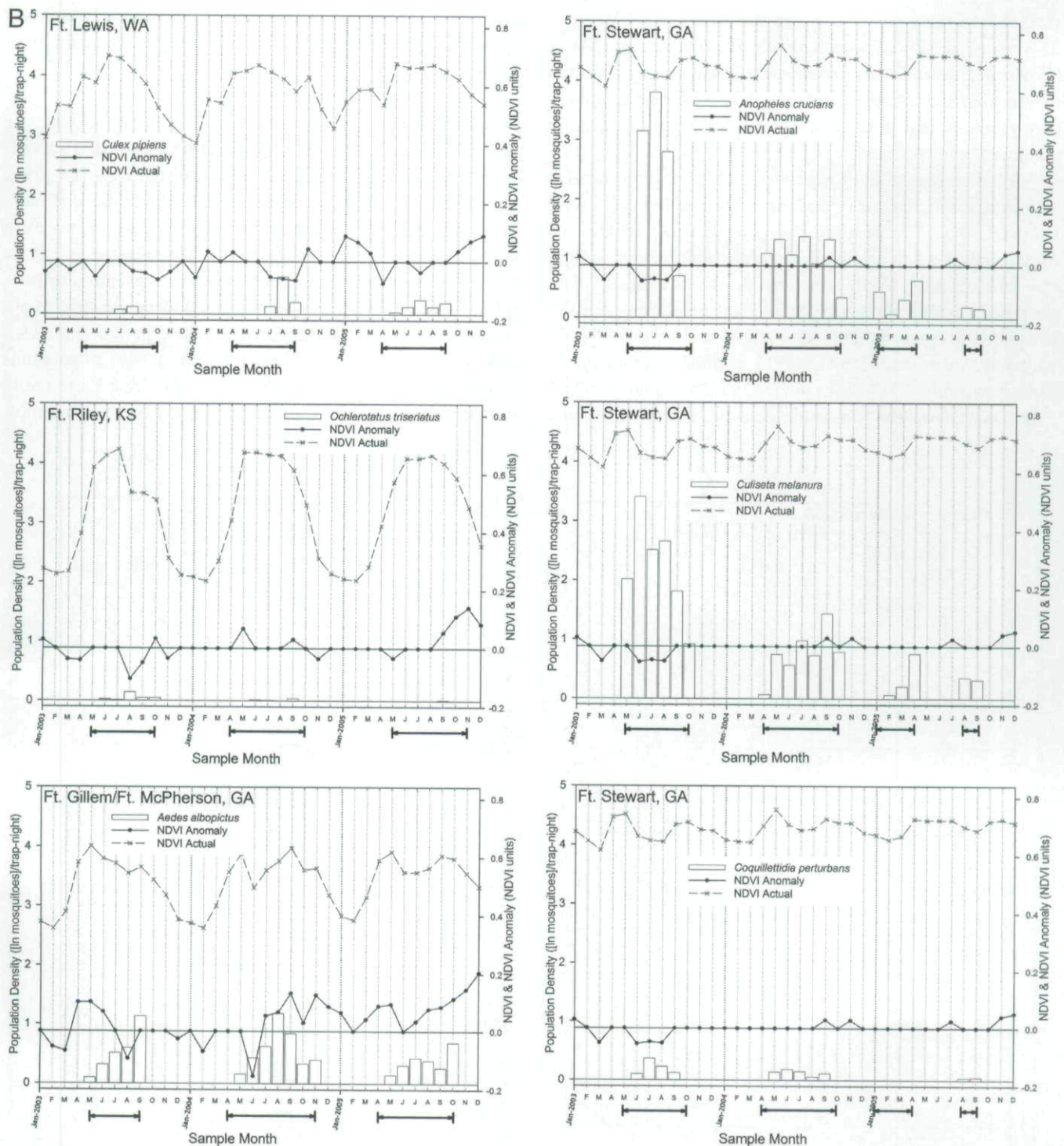


FIGURE 1. (Continued).

coinciding with populations reaching unusually high densities (Fig. 1C); case 4, populations appearing to rise and to fall synchronously with alternating wet and dry periods (Fig. 1D). There are variations in climate-population relationships in each of these cases. For instance, in case 1, a dry month may coincide with the month in which the rare species is observed, as with *Culiseta melanura* at Fort Gillem/Fort McPherson

(Fig. 1A), or the dry month may precede months in which the species is first detected, as with *Ochlerotatus sollicitans* at the same location (Fig. 1A). The anomalously dry periods at Fort Lewis and Fort Stewart both consisted of sustained dryness over three NDVI months (Fig. 1A), and the appearance of the rare species was sustained for more than one of those dry months.

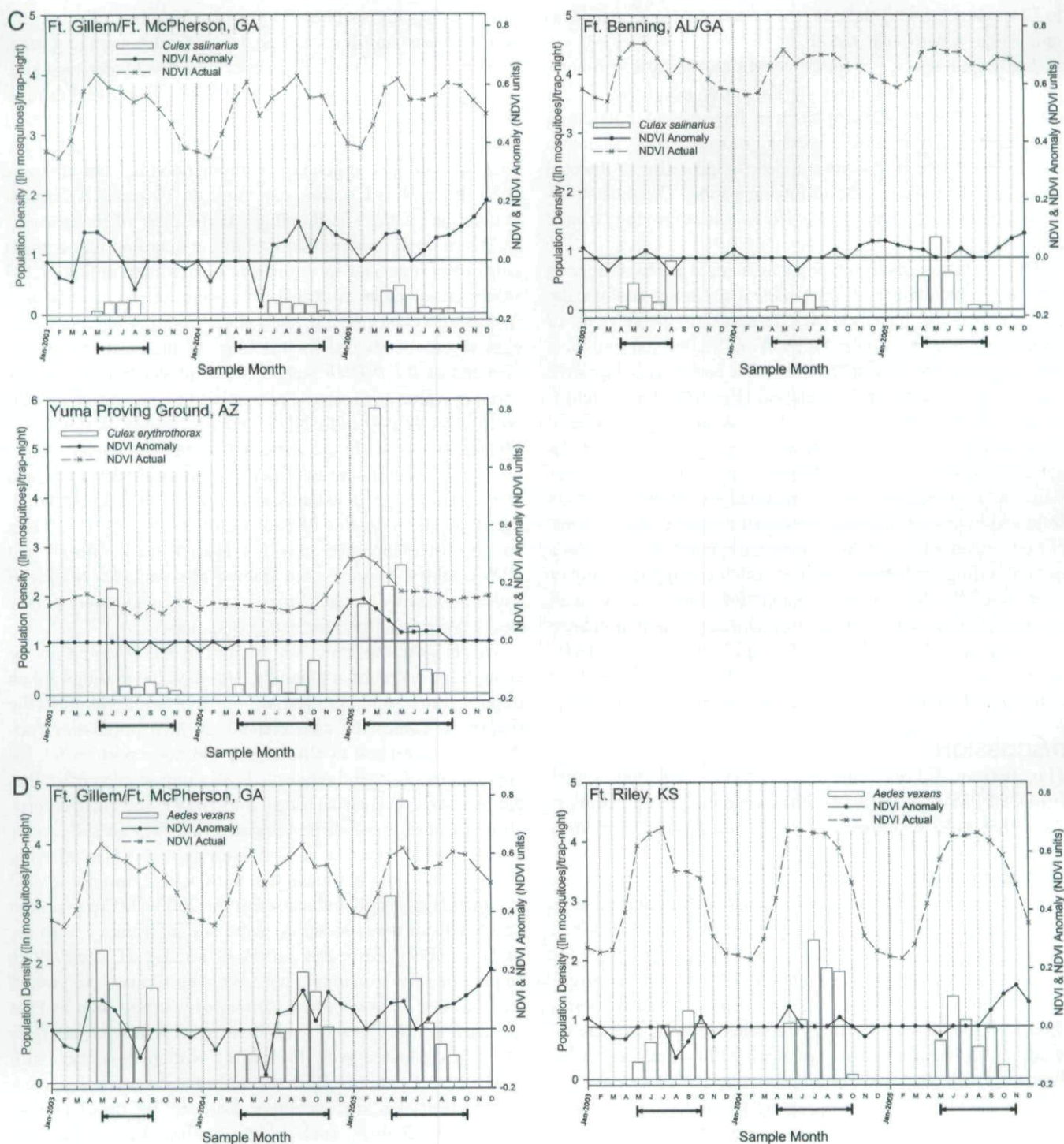


FIGURE 1. (Continued).

Case 2 is similar to case 1 except that the species appears at some density in the same season in at least one other year. As with case 1, there are variations in the patterns for case 2. The majority of instances of case 2 involve either rare or abundant species that at least double in density during short or sustained anomalously dry periods (Fig. 1B). These instances include *Culex pipiens* at Fort Lewis, *Ochlerotatus*

triseriatus at Fort Riley, and *Anopheles crucians*, *C. melanura*, and *Coquillettidia perturbans* at Fort Stewart. One instance of case 2, that of *Aedes albopictus* at Fort Gillem/Fort McPherson, shows a relationship in which populations of moderate abundance increased to unusually high peaks in the wet months immediately following large downswings in moisture. For this species at this location, the peaks appeared

to be associated with the patterns of moisture and greenness rather than a particular month.

For certain species in certain locations, the case 3 climate-population relationship may be the most worthy of further exploration for the development of forecasts of population abundances. In particular, excessive moisture and vegetation development late in the year appear to give rise to unusual population abundances the following spring. The most striking example is *Culex erythrothorax* at Yuma Proving Ground (Fig. 1C).

Case 4 demonstrates that populations of at least one species may respond to climate in comparable ways in two ecologically different regions. Increases and decreases in populations of *Aedes vexans* at both Fort Gillem/Fort McPherson and Fort Riley appeared to be synchronized with positive and negative changes in moisture and vegetation (Fig. 10). The synchronization is easily recognized for *Aedes vexans* at Fort Gillem/Fort McPherson where population changes closely track anomaly NDVI variations. However, the pattern is less obvious at Fort Riley. Here, a relatively wet May in 2004 followed by normal and above-normal moisture into September coincided with very high population numbers, whereas a normal spring and early summer followed by late summer dryness in 2003 led to smaller populations. Importantly, in all of these ecologically diverse installations, a sudden change from dry to wet corresponds to rapid increases in *Aedes vexans* trap counts, as observed June-July 2004 at Fort Gillem/Fort McPherson and May-June 2005 at Fort Riley.

DISCUSSION

This first qualitative analysis of NDVI and 2003–2005 USACHPPM mosquito surveillance data yields observations that hold promise for future climate-based models developed to forecast population dynamics of medically important mosquitoes. All mosquito species included in this study either are known to be associated with important U.S. arboviruses such as WNV, Eastern equine encephalitis virus, or St. Louis encephalitis virus¹⁴ or are strong candidates for transmitting emerging threats such as RVF^{15–17} or chikungunya² (Table I). Therefore, any ability to predict relative abundances of populations of these species in coming seasons would be an important tool in allocating limited resources for disease surveillance and control.

For future research, it is important to emphasize that these NDVI data are monthly summaries and data from finer temporal scales (i.e., 10-day and 15-day summaries) are also available. Although a dry month may coincide with the appearance of a rare species (case 1), the NDVI signal may actually be visible late in the previous month or early in the current month and so be useful operationally as a warning regarding potential mosquito-borne disease activity. Future studies should also consider mosquito bionomics, as outlined in Table I. Populations of peridomestic container breeders such as *A. albopictus* can theoretically peak during dry or wet periods, reflecting the human activity of irrigation in dry

times (especially sustained dry times) but also reflecting the fact that rain can fill containers left around houses and other buildings.²⁷ In contrast, *A. vexans* is a floodwater mosquito with population densities expected to be closely tied to rainfall, especially repeated flooding, and thus positive NDVI anomalies. Depending on its timing and intensity, rainfall can lead to increased vegetation without flooding, but in some years high NDVI values can indicate elevated *A. vexans* populations if there is flooding. At the peak of the growing season, rainfall patterns can lead to frequent flooding without concurrent increases in vegetation, which may unlink NDVI values and population changes. For some *Aedes* species, too-frequent flooding may prevent habitat from drying enough for eggs to be conditioned for hatching. In these situations, the element of the NDVI that is most informative is not the anomaly value as much as the number of consecutive months with anomalously high NDVI values. Many of the *Culex* species in this study are expected to emerge at some point after rainfall and flooding of new or previously dry areas, and they could emerge constantly in warm seasons without flooding if ponds or bodies of foul water do not dry out. Their patterns of emergence may not always track rainfall and NDVI values, because their habitat also includes bodies of water flooded by human activity, such as containment ponds, storm drains, and peridomestic containers.

On its own, the basic analysis in this study would not be enough for operational planning, although the findings are an important first step. For instance, our analyses highlighted the species in Table I because changes in their populations appeared to be related to climate; we did not report results for populations of several other medically important species that did not have such associations with NDVI, such as *Ochlerotatus canadensis* at Fort Benning and Fort Stewart and *Ochlerotatus taeniorhynchus* at Fort Stewart and Yuma Proving Ground. This does not mean that those species are not related to climate but simply indicates that the 2003–2005 population samples from those locations were not informative with respect to NDVI. Also, this survey of a range of installations helped identify locations with promising climate-population relationships for a maximal number of species, such as Fort Gillem/Fort McPherson with five species across all case patterns, compared with Fort Riley with two species with only two case patterns. With this information, we will narrow future efforts to key locations that can be developed as sentinel installations, such as one of the bases in Georgia, especially because of the geographic and cultural properties outlined above.

Mosquito surveillance at military installations should be continued or even augmented, to improve our ability to forecast mosquito population changes and to build an automated sentinel system for conditions favorable for mosquito-borne diseases.²⁸ When integrated into routine, mosquito-borne disease surveillance and control plans, these satellite climate-based population forecasts could contribute to strategic preparation of military installations if exotic mosquito-

borne pathogens such as RVF virus are detected in the United States. Because mosquito surveillance catalogs all sampled mosquito species, these analyses and derivative products could inform strategies against potential vectors for an array of emerging or established mosquito-borne pathogens.

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