NEW EVIDENCE OF THE EFFECTS OF AGRO-ECOLOGIC CHANGE ON MALARIA TRANSMISSION

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Abstract. Although maize pollen is known to provide nutrition for larval anopheline mosquitoes, the epidemiologic relationship between maize agriculture and malaria transmission has never been defined. To determine whether recent changes in malaria transmission in Ethiopia might be linked to the spread of maize as a commercial crop, we compared malaria transmission and maize cultivation intensity in 21 villages in the Bure District of northwestern Ethiopia where maize cultivation has recently expanded. The cumulative incidence in high maize cultivation areas was 9.5 times higher than in areas with less maize. A chi-square goodness-of-fit test results showed that malaria cases were not distributed evenly among categories of maize cultivation intensity, ($\chi^2 = 1.578$, $P < 0.001$). A Poisson regression suggested that the intensity of maize cultivation, controlled for differences in elevation between sites, was positively and significantly correlated with malaria incidence. Thus, the intensity of maize cultivation was associated with exacerbated human risk of malaria in Bure.

INTRODUCTION

This research seeks to evaluate the epidemiologic implications of several recent studies1,2 that suggested that the presence of maize pollen as a larval food source enhances the production of Anopheles arabiensis, the dominant mosquito vector of malaria in Ethiopia.3 It may be that such relationships may have facilitated the spread of malaria to previously unaffected zones of Ethiopia,4 such as the Bure District, where concurrent agro-ecologic changes have recently occurred. The key link lies between the expanding cultivation of maize (Zea mays) on small farms and increasing malaria infection rates.

Prior to 1998, the Bure District of northwestern Ethiopia was not affected by the malaria epidemics that periodically affected (1953, 1958, 1964/1965, 1973/1974, 1980/1981, 1987/1988, and 1994/1995) wide areas of the country, including the nearby Lake Tana region.4,7 The recent expansion of malaria transmission into the Bure District is coincident with the replacement of more traditional crops, such as teff, with maize in many rural villages or “kebeles.” The relationship between maize and malaria vector mosquitoes may have contributed to the increasing malaria case rate. Previous studies have found that 1) the proximity of maize pollen-breeding sites to maize pollen sources (i.e., within 10 meters) enhanced development of larval An. arabiensis,1,2 and 2) adult mosquitoes that fed on maize pollen as larvae are larger (larger mosquitoes may live longer, thus increasing the force of malaria transmission).8 These observations suggest that the presence of maize pollen near breeding sites may exacerbate malaria transmission in areas of high maize cultivation. The objective of this study was to explore the epidemiologic relationship between increased malaria transmission and agro-ecologic changes related to intensified maize cultivation.

MATERIALS AND METHODS

The study was conducted in the Bure District of northwestern Ethiopia, an area consisting of 21 rural villages according...
In the Bure District, to scratch plow that does not create furrows and has The farming system has Eragrostis Kafa 12 and eleusine or finger millet, cereals derived from Ethiopia. teff taken its historical form within a bi-modal seasonal rainfall observed at the site and recorded historically uses the single-ferred early maturing local flint maize types known as mostly as a garden vegetable. For this purpose, farmers pre-

Malaria incidence density ratios (IDRs) were calculated from the total number of cases occurring over a period of three contiguous years for the total population of the villages aggregated among each maize production category. Standard errors were calculated for these IDRs, assuming that the incidence of malaria cases conformed to a Poisson distribution. A chi-square goodness-of-fit test compared the number of observed cases within each maize production category against the number of cases that would have been expected in each if cases were distributed evenly among them. The IDRs were calculated and chi-square analysis was conducted on a subset of 17 villages that conformed to an altitude range of 2,000–2,200 meters to ensure that only villages of similar elevation were compared in this manner. On that basis, two of the villages (Agni Ferede and Jib Gedel) were excluded as too high and two (Gedam Lejamor and Boko Tabo) as too low. A multivariate Poisson regression analysis was then performed on the entire set of villages using cumulative malaria incidence as the outcome variable, and including average altitude (in meters) and maize cultivation intensity (categorized as high, medium or low) as covariates. We did not correct for spatial correlation in the observations.

RESULTS

Bure District is historically a sub-set of the classic Ethiopian highland ox-plow agro-ecology set on small farms of less than two hectares (five acres). The farming system has taken its historical form within a bi-modal seasonal rainfall regimen and annual cropping of endemic cereals (Eragrostis teff and eleusine or finger millet), cereals derived from Ethiopia’s role as one of Vavilov’s centers of secondary diffusion (wheat and barley), pulses (chickpeas, horsebeans, field peas), and oil seeds (nug, safflower). Until the 1980s, maize was a minor field crop in Gojjam and appeared on farms mostly as a garden vegetable. For this purpose, farmers preferred early maturing local flint maize types known as Mareysa, Hauer, and Kafa. The vast majority of cultivation observed at the site and recorded historically uses the single-tine “ard” scratch plow that does not create furrows and has little effect on potential mosquito habitat. There is virtually no irrigated agriculture in this region, now or historically.

In the early 1980s, political changes initiated a transformation in Ethiopia’s agrarian economy. Under the socialist government known as the Derg, grain marketing policy, forced labor, insecurity over land holdings, and government food security programs brought political disaffection but also changes in Ethiopia’s national cropping patterns. Ethiopia’s socialist government saw maize as a high yielding field crop to replace labor-intensive teff and poor yielding sorghum. Unbeknown to most observers, by the mid-1980s maize had surpassed teff, barley, and sorghum as the major crop produced in Ethiopia. The agricultural development programs that evolved during the 1980s used primarily open-pollinated maize that farmers could replant with seeds from their own fields rather than higher yielding hybrids that required new seed to be purchased every year.

In 1995, after the 1991 fall of the military government, the Ministry of Agriculture and the international organization Sasakawa/ Global 2000 began a demonstration package program for small Ethiopian farms to expand use of inorganic fertilizers, improved maize seeds, and agronomic techniques such as row planting and intense early weeding in high potential areas to improve national food production. While the program proved controversial in many areas, farmers in Gojjam and in other regions accepted the program readily because it offered preferred access to credit, fit their new market orientation, and seemed to deliver substantially improved yields over traditional crops. By 1998, nationally maize had reached 32.6% of the country’s cereals production, higher than all other grains. Between 1993 and 1998, the area of maize cultivation increased by 79%. In the Bure District, the results were on a similar scale (Table 1).

In the Bure district, the shift to maize included predominant use of a late-pollinating, high yield variety of hybrid maize. The botanical vehicle for this transformation was the BH660 hybrid maize variety (Gebre T, unpublished data). Released in 1993 and introduced into the Bure area beginning in 1995, BH660 by 1998 had replaced virtually all other improved varieties in the Gojjam area. It is a late-maturing (165–180 days) and high yield (6–8 tons/hectare) type that needs substantially different care than earlier local types. It requires early planting (i.e., late April/early May), high amounts of nitrogen, and earlier and more intensive labor for weeding than local varieties. Above all, it is the prodigious yield of BH660 that prompted farmers to sow it in every available space, even in school yards, household garden space, and in the fenced compounds of health centers.

As late as the 1970s, malaria did not affect the mid and high altitude zones in Bure. Therefore, the 1998 malaria epidemic was unprecedented in the area and in the region. The 1998

<table>
<thead>
<tr>
<th>Year</th>
<th>Total area (hectares) planted with maize</th>
<th>Total cereal area planted, hectares (maize % of total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>11,331</td>
<td>63,795 (17.7)</td>
</tr>
<tr>
<td>1994</td>
<td>11,933</td>
<td>59,114 (20.1)</td>
</tr>
<tr>
<td>1995</td>
<td>12,882</td>
<td>61,012 (21.1)</td>
</tr>
<tr>
<td>1996</td>
<td>13,268</td>
<td>62,921 (21.0)</td>
</tr>
<tr>
<td>1997</td>
<td>13,727</td>
<td>66,217 (20.7)</td>
</tr>
<tr>
<td>1998</td>
<td>17,642</td>
<td>73,834 (23.8)</td>
</tr>
<tr>
<td>1999</td>
<td>19,460</td>
<td>77,078 (25.2)</td>
</tr>
<tr>
<td>2000</td>
<td>26,902</td>
<td>79,143 (33.9)</td>
</tr>
<tr>
<td>2001</td>
<td>26,758</td>
<td>78,140 (35.9)</td>
</tr>
<tr>
<td>2002</td>
<td>19,929</td>
<td>74,505 (26.7)*</td>
</tr>
</tbody>
</table>

* 2002 had a major decrease in the main rains; farmers shifted from maize fields to short-season wheat and maize yields decreased by half.
outbreak in our study area of Bure (Figure 1) began in a few districts adjacent to the disease-endemic areas in May and June, but then expanded into higher altitude zones in September−October 1998, and exploded into previously malaria-free zones in October and November when the powerful wave of malaria washed onto further new ground. The outbreaks finally subsided into a more endemic level of transmission by January 1999.

Table 2 shows the cumulative incidence rate of the 21 villages in Bure. The cumulative incidence rate of malaria for the three contiguous years (1997–1999) in the 21 villages ranged from 3 to 3,223 cases per 10,000 person years (mean = 292 cases/10,000 person-years).

Table 3 shows comparison of the cumulative incidence of malaria between high, medium, and low maize cultivating areas after excluding two villages with high altitudes and two with low altitudes. The IDR between the high maize area relative and the low maize area was 9.54:1. For the intermediate maize cultivation category, this ratio was 3.67:1. Chi-square goodness of fit tests rejected the null model of an equal distribution of malaria cases among the maize cultivation categories ($\chi^2 = 1.578$, degrees of freedom = 2, $P < 0.01$). Maize cultivation and malaria incidence thus showed a strong association that appeared to be proportional. Since the results are not corrected for possible spatial correlation in the observations, significance may be somewhat weaker than presented.

Poisson regression results are presented in Table 4. Maize cultivation intensity was found to significantly ($P < 0.001$) account for a large proportion of the variation in malaria cases between kebeles. Elevation was also a significant factor, but accounted for much less of the total variation in this data set. Thus, the presence of maize cultivation in moderate to high levels led to almost twice as many malaria cases according to this model, which did not exclude any outliers.

DISCUSSION

This study is the first to show an epidemiologic link between intensification of maize cultivation and an increase in malaria incidence. The sequence of events narrated above and correlated in our data strongly suggests a relationship between a newly evident agro-ecology and malaria in which the newly intensified cultivation of maize has helped create the conditions for malaria transmission in Bure that had not existed previously. Previous studies of the relationship between maize and An. arabiensis showed the effect of maize pollen on vector development and abundance, but had not determined whether actual vector ecologies on the farm and in rural settings in interaction with maize may have markedly exacerbated malaria transmission. Our results show that malaria incidence is significantly greater in villages that are similar in all respects other than the intensity of maize as a crop, regardless of differences in elevation.

Maize cultivation, specifically, and intensified agricultural

<table>
<thead>
<tr>
<th>Villages</th>
<th>Maize yield</th>
<th>Mean elevation (meters)</th>
<th>Person-years*</th>
<th>Cumulative number of malaria cases*</th>
<th>Incidence rate/10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulim</td>
<td>High</td>
<td>2.050</td>
<td>23,458</td>
<td>683</td>
<td>291</td>
</tr>
<tr>
<td>Denbun</td>
<td>High</td>
<td>2.050</td>
<td>20,630</td>
<td>88</td>
<td>43</td>
</tr>
<tr>
<td>Wadra</td>
<td>High</td>
<td>2.050</td>
<td>12,805</td>
<td>170</td>
<td>133</td>
</tr>
<tr>
<td>Zalimashebekuma</td>
<td>High</td>
<td>2.050</td>
<td>16,857</td>
<td>370</td>
<td>219</td>
</tr>
<tr>
<td>Adel Agata</td>
<td>High</td>
<td>2.050</td>
<td>12,805</td>
<td>226</td>
<td>176</td>
</tr>
<tr>
<td>Fetamsantom</td>
<td>High</td>
<td>2.050</td>
<td>18,333</td>
<td>552</td>
<td>301</td>
</tr>
<tr>
<td>Zyeweshwun</td>
<td>High</td>
<td>2.050</td>
<td>18,384</td>
<td>857</td>
<td>466</td>
</tr>
<tr>
<td>Feszeltentekez</td>
<td>High</td>
<td>2.050</td>
<td>16,063</td>
<td>395</td>
<td>246</td>
</tr>
<tr>
<td>Woinnaambaye</td>
<td>Medium</td>
<td>2.200</td>
<td>12,079</td>
<td>71</td>
<td>59</td>
</tr>
<tr>
<td>Wangedam</td>
<td>Medium</td>
<td>2.200</td>
<td>26,223</td>
<td>218</td>
<td>83</td>
</tr>
<tr>
<td>Taitia</td>
<td>Medium</td>
<td>2.200</td>
<td>10,960</td>
<td>180</td>
<td>164</td>
</tr>
<tr>
<td>Bagunakbesi</td>
<td>Medium</td>
<td>2.200</td>
<td>17,522</td>
<td>177</td>
<td>101</td>
</tr>
<tr>
<td>Alefaisi</td>
<td>Medium</td>
<td>2.050</td>
<td>13,344</td>
<td>94</td>
<td>70</td>
</tr>
<tr>
<td>Wehindurbete</td>
<td>Low</td>
<td>2.200</td>
<td>13,145</td>
<td>5</td>
<td>4</td>
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<tr>
<td>Arbsi</td>
<td>Low</td>
<td>2.200</td>
<td>12,639</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Wendgi</td>
<td>Low</td>
<td>2.200</td>
<td>19,646</td>
<td>79</td>
<td>40</td>
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<tr>
<td>Shakahe</td>
<td>Low</td>
<td>2.200</td>
<td>17,441</td>
<td>66</td>
<td>38</td>
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<tr>
<td>Agnifereca</td>
<td>Low</td>
<td>2.450</td>
<td>17,309</td>
<td>5</td>
<td>3</td>
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<tr>
<td>Jhgedel</td>
<td>Low</td>
<td>2.450</td>
<td>15,570</td>
<td>23</td>
<td>15</td>
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<tr>
<td>Bokotabo</td>
<td>Low</td>
<td>1.770</td>
<td>7,319</td>
<td>2,359</td>
<td>3,223</td>
</tr>
<tr>
<td>Gedam Lijamor</td>
<td>Low</td>
<td>1.850</td>
<td>8,836</td>
<td>398</td>
<td>450</td>
</tr>
</tbody>
</table>

* For a three-year period (1997−1999).
activity, in general, contribute to the production of vector mosquitoes in diverse ways. Nutritional input into breeding sites close to pollen sources and human housing may increase vectorial capacity by allowing more mosquitoes to survive to adulthood, and to develop more quickly into larger and longer-lived vectors.\textsuperscript{1,2,8} Maize pollen release tends to coincide with the period near the end of the rainy season when mosquito breeding sites are most stable and abundant, optimizing its effect on larvae. Because maize is grown so close to households in Bure, maize-enhanced mosquito populations can participate directly in cycles of human biting and malaria transmission.

The new agro-ecology of maize is related specifically to the agronomic characteristics of improved maize in that its high yield has encouraged the expansion of its planting within close proximity of dwellings and vector breeding habitats. Moreover, the tall stature of the hybrid plant increases the range of wind-borne pollen dispersal; the extension of tassel ing time to early September synchronizes anthesis with the peak larval development period. Thus, conditions on farms in Bure approximated the ideal conditions for mosquito propagation.

Northwestern Ethiopia, and our study area in particular, have historically enjoyed a climate marked by a high degree of consistency in annual amount and seasonal distribution of rainfall. The primary climatic anomalies occurring during our study period appear to have been a somewhat longer dry season between 1997 and 1998; and somewhat more rainfall than average during 1998. Analysis of the numbers of rainy days suggests that 1998 had more agriculturally suitable rainfall than in the previous year, although the rains began a few weeks later. The later onset of rains in 1998 may have prompted farmers to plant several weeks late in 1998, thus pushing tasseling into early September, when conditions for mosquito breeding would be ideal, i.e., warmer temperatures and less likelihood that pollen and mosquito larvae would be washed away by heavy downpours.

Most important for this study, the tasseling and pollen release of BH660 takes place later than in previous varieties, i.e., late August–September, at precisely the time when temperature and moisture are ideal for mosquito breeding, a consequence of the agro-ecologic calendar that evidence suggests has serious implications for malaria transmission. By appearing later in the rainy season, the improved pollen of maize is less likely to be washed away at the time when mosquito larvae are more likely to have stable breeding sites.

The expansion of maize within the farming systems of Ethiopia has constituted an agro-ecologic sea change in terms of labor requirements, links to national markets, and requirements for inputs, i.e., new seed, fertilizer, and storage. Secondary factors associated with these economic changes may have also contributed to increased malaria transmission in Bure. These include the 1988 opening of the new commercial road that brought increasing numbers of malaria-infected people from lowland disease-endemic areas into contact with Bure and other area of the Highlands, and the national agricultural policy of promoting new maize programs.

Trends of rising highland temperatures in Ethiopia (0.4°C increase per decade in daily minimum temperature)\textsuperscript{14} expand the territory and lengthen the daily period in which minimum temperatures remain above the 18°C threshold for \textit{Plasmodium falciparum} development in mosquitoes.\textsuperscript{15} This may also have contributed to the expansion or intensification of malaria transmission in the Highlands around Bure, but it was unlikely to have accounted for the differences in malaria transmission between the villages included in this study because of the uniformity of altitude and topography between them.

The transition of the Bure District from a mixed cereal crop agricultural system to one dominated by hybrid maize began in the post-revolutionary period of the 1980s with the establishment of two model state farms, a tractor mechanization facility, and establishment of several producer cooperatives for the production of improved maize using both mechanization and fertilizer. With the collapse of the military socialist government’s programs in the late 1980s and the ascension of the current government in 1991, a new phase emerged in which the Ministry of Agriculture and the Sasakawa/Global 2000 aggressively encouraged farmers to adopt an agricultural package that included inorganic fertilizer, improved maize varieties, and new techniques for cultivating long maturing, but high yield maize.

Formally launched in 1995 this national program took a strong hold in Bure, transforming the district from one renowned for small grains (i.e., teff and eleusine) to one increasingly dominated by the cultivation of improved maize grown as a field crop. Figures in Bure mirror national trends, and indicate maize’s domination of cereal production in the Bure District. The final figure for the 2001 crop year indicates

\begin{table}
\centering
\footnotesize
\caption{Comparison of malaria cases by status of maize cultivation}
\begin{tabular}{|l|l|l|l|l|}
\hline
Maize cultivation intensive category & Person-years\textsuperscript{*} & Cumulative no. of malaria cases\textsuperscript{*} & Incidence rate/10,000 person-years & Incidence density ratio SE \\
\hline
High & 139,335 & 3,341 & 239.8 & 9.54 & 1.72 \\
Medium & 80,128 & 740 & 92.4 & 3.68 & 1.15 \\
Low & 62,871 & 158 & 25.1 & 1.00 & \\
\hline
\end{tabular}
\textsuperscript{*}Cumulative number for a three-year period (1997–1999).
\end{table}

\begin{table}
\centering
\footnotesize
\caption{Poisson regression of average elevation and maize cultivation intensity score against malaria cases for 21 kebeles in Bure-Wemberma District of northwestern Ethiopia, the Bure district (corrected for differing population size)}
\begin{tabular}{|l|l|l|l|}
\hline
Variable & Coefficient & SE & 95\% confidence interval & \textit{P} \\
\hline
Elevation (Average) & -0.0104 & 0.0002 & -0.0107, -0.007 & 7.75 \times 10^{-9} \\
Maize (High-low) & 0.5703 & 0.0444 & 0.4832, 0.6573 & 1.76 \times 10^{-28} \\
Maize (Medium-low) & 0.6873 & 0.0640 & 0.5620, 0.8127 & 9.13 \times 10^{-23} \\
Constant & 25.8253 & 0.2951 & 25.2468, 26.4037 & 1.45 \times 10^{-10} \\
\hline
\end{tabular}
\end{table}
that in Bure itself maize accounts for well over one-third of all cereals. Moreover, for the purposes of this study, the key issue is the high concentration of maize in particular villages in 8 of the study area’s 21 rural villages, where maize’s share of total cereal planted reaches an estimated 85% of the total.4

Even national aggregate data do not reflect the full impact of intensified maize since the total includes some areas where altitude and soils favor teff, wheat, and eleusine. In 13 of the district’s 21 villages maize became a dominant crop; in 8 of those 13 it approaches monoculture. In the four villages that we visited, maize occupied 75–90% of the cropland. In particular, those areas that were surveyed where maize dominated cropping choice entirely new patterns of residence and cultivation were ubiquitous. With farmers’ concentration on hybrid maize has come the virtual abandonment of the fenced house garden (gwaro) that formerly surrounded the farm homestead and buffered field crops from the main dwelling. Instead, farmers’ houses in the maize districts have collected into villages, almost small towns, with early vestiges of urban services. In these nucleated settlements, the cultivated fields of maize often stood within one meter of the houses themselves. Virtually all houses were within 5–10 meters of a field cultivated maize field, and most were within 2 meters or less of a maize field.

The increasing role of maize in national and international agricultural policy suggests that at least one important factor in malaria transmission requires more attention. The evidence presented here shows that the spatial and temporal relations between increasing malaria and a shift in agroecology brought on by increasing maize production, along with other factors such as climate and new patterns of human settlement, resulted in the disease’s presence, its spatial distribution, and its intensity. Maize thus has served as an accelerant for vector density, mosquito longevity, and malaria infection.

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