Life-Table Analysis of *Anopheles arabiensis* in Western Kenya Highlands: Effects of Land Covers on Larval and Adult Survivorship

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**Abstract.** In high-elevation areas in western Kenya, the abundance of *Anopheles arabiensis* is either very low or absent. The western Kenya highlands (an area with an elevation ≥ 1,500 m above sea level) have also been experiencing extensive deforestation, and deforestation has been suggested as one of the important factors that facilitate malaria transmission in the highlands. This study investigated whether climate conditions in the western Kenya highlands (Kakamega, elevation 1,500 m above sea level) were permissive to the development and survival of *An. arabiensis* and whether deforestation promoted *An. arabiensis* survivorship of immature and adult stages, using life-table analysis. We found that in larval habitats located in forested areas, only 4–9% of first-instar larvae developed into adults and the development length exceeded 20 days. Mean water temperature of aquatic habitats in the deforested area was 4.8–6.1°C higher than that in the forested area, larval-to-adult survivorship was increased to 65–82%, and larval-to-adult development time was shortened by 8–9 days. The average indoor temperature in houses in the deforested area was 1.7–1.8°C higher than in the forested area, and the relative humidity was 22–25% lower. The median survival time of adult mosquitoes in the deforested area was 49–55% higher than those in the forested area. The net reproductive rate of female mosquitoes in the deforested area was 1.7- to 2.6-fold higher than that in the forested area. Compared with previously published data on *An. gambiae*, the net reproductive rate of *An. arabiensis* was only 0.8–1.3% of *Anopheles gambiae* in the forested area and 2.3–2.6% in the deforested area. Therefore, the current ambient climate condition is less permissive to *An. arabiensis* than to *An. gambiae* in western Kenya highlands. However, environmental changes such as deforestation and global warming may facilitate the establishment of *An. arabiensis* populations in the highlands.

**INTRODUCTION**

The African highlands (areas with an elevation ≥ 1,500 m above sea level) are experiencing dramatic environmental and climate changes.1–3 A recent study, using temperature data from 1950 to 2002 in 4 high-altitude sites in East Africa, found a significant warming trend at all sites and predicted that an increase in temperature of 0.5°C may translate into a 30–100% increase in mosquito abundance.4 Climate variability, defined as short-term fluctuations around the mean climate state, also increased on a larger regional scale in East African highlands in the past decade.2 Furthermore, land-use and land-cover changes such as deforestation have been occurring rapidly in western Kenya highlands. For example, Mau forest, a tropical rain forest in Kakamega district, has shrunk from 150 km² in 1965 to 86 km² in 1997.5 In the East African highlands, 2.9 million hectares of forest were cleared between 1981 and 1990, representing an 8% reduction in forest cover in 1 decade.6 Land use and land-cover changes may modify the temperature and relative humidity of malaria vector habitats in the highlands. It was demonstrated that in the southwestern highlands of Uganda, maximum and minimum temperatures were significantly higher in communities bordering cultivated swamps than in those near natural swamps.7 These changes in regional climate and microclimatic conditions of mosquito habitats cause abundance changes of the existing mosquito species8 and may make the highlands susceptible to the proliferation of new species. For instance, deforestation caused the introduction of *Anopheles gambiae* into a habitat that was previously predominated by *Anopheles moucheti* in Cameroon.7 In northern Brazil, *Anopheles marajoara*, a species previously of minor importance, has become the principal malaria vector following changes in land use.8 *An. gambiae* and *Anopheles arabiensis* are the most important vectors of human malaria in Africa. *An. arabiensis* is either absent or shows a very low abundance in high-elevation areas where temperature is low and relative humidity and the amount of rainfall are high, but it is abundant in dry areas.9–12 For example, indoor spray collection in Kakamega, western Kenya highlands, did not observe any *An. arabiensis* adults; however, *An. arabiensis* is abundant in the surrounding lowland areas and is the only human malaria vector within *An. gambiae* species complex in the Great Rift Valley.10 If the present rate of deforestation in the western Kenya highlands as well as global warming and climate variability continue, there is a possibility that *An. arabiensis* may colonize, proliferate, and establish its populations in the western Kenya highlands. A recent study by Chen and others11 in Mount Kenya highlands reported new records of *An. arabiensis* in areas with elevations of 1,720–1,921 m above sea level where human malaria vectors were previously not observed.

The aim of this study was to determine whether the climate conditions in the high-elevation area in western Kenya are permissive to the development and survival of *An. arabiensis*, and whether land-use changes enhance the survivorship of immature and adult stages of *An. arabiensis*. Our hypothesis is that the ambient climate conditions in the highlands have not been suitable to *An. arabiensis* development and survival at either larval or adult stages; however, land-use changes, specifically deforestation in the highlands, may significantly alter the microclimatic conditions of mosquito habitats either at larval or adult stages. This in turn may enhance the survivorship and reproduction of *An. arabiensis* in the highlands. Deforestation is a dramatic land-use change that leads to a
reduction of forest canopy and an increased exposure to sunlight, which could substantially affect the survivorship and development time of larval and adult mosquitoes. Life tables may be used to study inherent differences in the survivorship and reproductive strategies of populations under different ecological regimes. Age-specific life tables provide a concise summary of mortality and reproductive schedules and can help explain why certain species proliferate in particular environments. For example, Maharaj used life tables to show how both immature and adult An. arabiensis, the most important vector of human malaria in South Africa and many parts of southern Africa, could survive in different simulated seasons of winter, autumn, spring, and summer conditions in laboratory experiments. Diop and colleagues used life tables to show how An. arabiensis could be bred in insectary conditions in Dakar, Senegal. Life-table analyses were conducted in other malaria vector species under controlled environmental conditions or seminatural conditions. In this study, we also used life tables to show how with ongoing deforestation, An. arabiensis, which currently is absent or in small numbers, could become established in the western Kenya highlands.

MATERIALS AND METHODS

Study sites. The study was conducted in a 4 × 4 km² area in the village of Iguhu (34°45'E and 0°10'N; 1,480–1,580 meters above sea level), Kakamega district, and at a lowland site (Kisian village; 34°75'E and 0°10'S; elevation 1,190 meters above sea level), Kisumu district, western Kenya. The average minimum and maximum temperatures during 1970–2000 were 13.8 and 28.0°C in Kakamega and 15.0 and 28.4°C in Kisian, with the hottest season in January–February and the coolest season in July–August. The average annual rainfall for the same period was ≈1,950 mm in Iguhu and 1,400 mm in Kisian. Mosquito breeding sites in the highland mostly occurred in cultivated swamps in the valley along the Yala River, which transects the area, and also at the edges of the several streams. The study was conducted in the forested and deforested areas in the highland. Forested area is defined as the area with a tree canopy cover > 60%, whereas a deforested area is a previously forested area that has been recently cleared and has < 10% canopy coverage. The lowland site at Kisian is flat land on the shores of Lake Victoria. The land-cover type in Kisian is primarily farmland, with little tree canopy present, and thus it is classified as deforested.

Life tables for immature An. arabiensis. Thirty newly hatched 2-hour-old An. arabiensis larvae were placed into basins (30 cm diameter and 14 cm deep). Each basin contained 2 kg of soil collected from the cultivated swamp area in Iguhu and 8 L of stream water. Five basins were placed in the forested area of the study site where canopy cover was > 80%, and another 5 were placed in the deforested area near drainage ditches where there was no canopy cover. Another five basins were placed in the deforested areas in the lowland site of Kisian. All basins were screened with white, insect-proof, nylon netting to prevent colonization by other mosquitoes and predators. Each day the number of larvae alive and their stage of development were counted and recorded. Adult mosquitoes that emerged were counted daily, and the sexes were recorded. The 3 experiments in the highland deforested and forested sites as well as in the lowland site were done simultaneously.

Water temperature was measured hourly using the HOBO data loggers placed in the basins. These data were offloaded using a Hobo Shuttle Data Transporter (Shuttle, Onset Computer Corporation, Bourne, MA) and then downloaded to a computer using BoxCar Pro 4.0 (Onset Computer Corporation). Three data loggers were used in each land-cover type.

Life tables for adult An. arabiensis. One hundred newly emerged female and male An. arabiensis were placed in a 30 cm × 30 cm × 30 cm metal-framed cage covered with nylon netting. The mosquitoes were F₁ individuals that originated from a lowland area on the Kano plains of western Kenya and that were reared in an insectary in the Center for Vector Biology and Control Research of Kenya Medical Research Institute in Kisian, western Kenya. The cages were suspended from the ceiling in the bedrooms of selected houses, 2 m above the ground with twine smeared with grease to prevent ants from interfering with the experiment. Houses selected had iron sheet roofs, and cooking activities and the use of mosquito coils or spray did not occur in the bedrooms during the experimental period. Human blood was provided to the mosquitoes for about 20 minutes every morning through feeding of a human arm (YAA). An oviposition substrate consisting of a Petri dish lined with a filter paper disk on top of cotton wool was provided in each cage. Cotton wool soaked in 10% sucrose solution was supplied to the mosquitoes daily. The number of eggs laid on the oviposition substrate was counted under a dissecting microscope and recorded daily to determine fecundity. Dead mosquitoes were recorded and removed from the cage daily. The experiment was done in the dry season, January–March 2005, and repeated during the rainy season, July–September 2005, in both the highland and lowland sites. There were 4 replicates in each site during each season.

HOBO data loggers were placed inside the selected houses to record indoor temperature and relative humidity hourly at all 3 study sites for the entire duration of the experiment. The data loggers were suspended from the roof, 2 m above the ground. Outdoor temperature was recorded with HOBO data loggers by placing them 2 m above the ground in standard meteorological boxes. Three houses in each site were equipped with a HOBO data logger for both outdoor and indoor microclimate measurements.

Data analysis. Daily average, minimum, and maximum temperatures and relative indoor and outdoor humidity were calculated from the hourly record. Analysis of variance (ANOVA) with repeated measures was conducted to determine the effects of land cover and season on outdoor and indoor temperature and relative humidity in the experimental houses. Tukey honestly significant difference (HSD) post hoc tests were used to determine the statistical significance of mean temperature and relative humidity at different landcover areas for each season. Water temperature in larval habitats was analyzed in the same manner.

Survivorship of An. arabiensis larvae was calculated as the proportion of first-instar larvae survived to adults. Mean larval development time was defined as the average duration of first-instar larvae to develop into adults. Because male and female mosquitoes have different development time, the mean larval development time was computed separately for each sex. The t-test and Tukey HSD test were used to com-
pare the effects of land cover on larval survivorship and development time. Kaplan–Meier survival analysis was conducted to determine the effect of land cover on adult mosquito survivorship. The age-specific survivorship was calculated for all houses at each area and season. The effect of land cover on the survivorship of female mosquitoes was analyzed using the non-parametric Friedman χ² test. Fecundity was calculated as the number of eggs laid per female per day. The net reproductive rate, R₀, was calculated for each land-use type in both dry and rainy seasons based on the daily survivorship and fecundity schedule. R₀ is defined as the average number of offspring a female individual produces in her lifetime and is calculated as $R_0 = \sum (l_i m_i)$, where $l_i$ is the age-specific survivorship, and $m_i$ is the age-specific fecundity. Per-capita intrinsic growth rate $r$, defined as the number of progeny born to each female mosquito per unit of time, was calculated as $r = \ln(R_0)/G$, where $G = \sum l_i m_i x / \sum l_i m_i$, and $x$ is mosquito age. The non-parametric Wilcoxon test was used to compare differences in fecundity, net reproductive rate, and intrinsic growth rate between forested and deforested areas and between highland and lowland sites. Only female mosquito life-history traits were considered in this analysis, even though male mosquitoes were also present in the cages. In the case where multiple comparisons were conducted, the significance level was adjusted using the Bonferroni method. The analysis was conducted using JMP statistical software.

RESULTS

Aquatic habitat water temperatures. Water temperatures in basins used for the immature life-table analyses differed significantly between basins placed in forested and deforested areas. During the dry season, average daily temperature in basins in the deforested site was 4.8°C higher than those in the forested site (Tukey HSD test, $P < 0.05$; Table 1). Basins in the lowland site exhibited a significantly higher water temperature than those in the deforested highland site (Table 1). Similar results were found in the rainy season. For example, the average daily temperature in basins placed in the deforested area was 5.6°C higher than those in the forested area in the highlands (Table 1).

Survivorship and development time of immature An. arabiensis. In both dry and rainy seasons, larval-to-adult survival rate of An. arabiensis larvae in basins placed in the deforested area was significantly higher than those placed in the forested area in the highlands (0.82 versus 0.04 in dry season, $t = 18.29$, df = 8, $P < 0.0001$; 0.60 versus 0.09 in the rainy season, $t = 11.72$, df = 8, $P < 0.0001$; Table 1). Larval survival rate between the highland deforested area and lowland deforested area was not different ($P > 0.05$). Overall, larval survivorship was significantly higher during the dry season than during the rainy season (ANOVA, $F = 6.39$, df = 1, 21, $P < 0.05$).

Larval-to-adult development time of males and females was ~8–10 days shorter in the deforested area than in the forested area in both dry and rainy seasons in the highlands (Tukey HSD test, $P < 0.05$, Table 1). The larvae in the lowland area showed the shortest development times (Table 1).

Microclimate of houses in the deforested and forested areas. Houses in the deforested area had a significantly higher indoor temperature than those in the forested area in the highlands (Table 2). During the dry season, mean maximum and minimum indoor temperatures of the houses in the deforested site were 3.4°C ($P < 0.0001$) and 0.6°C ($P < 0.05$) higher than in houses in the forested area, respectively (Figure 1), and the mean average daily temperature was 1.7°C higher ($P < 0.0001$; Table 2). During the rainy season, the mean maximum and minimum indoor temperatures in the deforested area were 2.3°C ($P < 0.0001$) and 1.9°C ($P < 0.0001$) higher than those in the forested area, respectively (Figure 1), and the mean average daily temperature was 1.8°C higher ($P < 0.0001$). The average temperatures of houses in the lowland deforested area were 0.9 and 2.2°C higher than those in the highland deforested area ($P < 0.0001$) in the dry and rainy seasons, respectively.

During the dry season, the average indoor relative humidity in the highland deforested area was 25.3% lower than that in the forested area (Tukey HSD test, $P < 0.05$; Table 2). Similarly, houses in the highland deforested area showed a 21.9% higher average relative humidity than those in the forested area in the rainy season ($P < 0.05$; Table 2). The indoor average relative humidity in lowland deforested area was 6.5–14.9% higher than that for houses in the highland deforested area in the rainy and dry seasons ($P < 0.05$; Table 2).

Survivorship of adult An. arabiensis. In the highland, female mosquitoes placed in houses in the deforested area lived significantly longer than those in the forested area in both dry season (χ² = 93.2, df = 1, $P < 0.0001$; Figure 2) and rainy season (χ² = 46.8, df = 1, $P < 0.0001$). The median survival length was 17.5 days in the deforested area and 11.0 days in the forested area in the dry season. In the rainy season, the median survival length was 15.6 days in the deforested area and 10.5 days in the forested area. There was no significant variation in mosquito survivorship between the dry and rainy seasons in both deforested area (χ² = 2.3, df = 2, $P > 0.05$; Figure 2) and forested area (χ² = 2.2, df = 2, $P > 0.05$).

Female mosquitoes in the lowland deforested area showed

### Table 1

Survivorship and development time of immature *An. arabiensis* larvae in different land-cover types in western Kenya highland and lowland sites

<table>
<thead>
<tr>
<th>Season</th>
<th>Area</th>
<th>Land-cover type</th>
<th>Average water temperature (°C)</th>
<th>Mean development time of males (days)†</th>
<th>Mean development time of females (days)†</th>
<th>Proportion of first-instar larvae developed to adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>Highland</td>
<td>Forested</td>
<td>19.8 ± 0.8a</td>
<td>21.9 ± 6.2a</td>
<td>20.0 ± 0.0a</td>
<td>0.04 ± 0.04a</td>
</tr>
<tr>
<td></td>
<td>Lowland</td>
<td>Deforested</td>
<td>24.6 ± 1.7b</td>
<td>12.1 ± 0.2b</td>
<td>11.8 ± 0.2b</td>
<td>0.82 ± 0.07b</td>
</tr>
<tr>
<td>Rainy</td>
<td>Highland</td>
<td>Forested</td>
<td>27.5 ± 1.5c</td>
<td>10.9 ± 0.3b</td>
<td>10.6 ± 0.3c</td>
<td>0.87 ± 0.08b</td>
</tr>
<tr>
<td></td>
<td>Lowland</td>
<td>Deforested</td>
<td>18.5 ± 0.5a</td>
<td>20.8 ± 1.2a</td>
<td>20.7 ± 0.6a</td>
<td>0.09 ± 0.06a</td>
</tr>
</tbody>
</table>

† Mean male and female development time is the number of days taken for the first-instar larvae to develop into adults.
Indoor climate condition, survivorship, and reproductive fitness of *An. arabiensis* adults in different land-cover types in western Kenya highland and lowland sites

<table>
<thead>
<tr>
<th>Season</th>
<th>Area</th>
<th>Land-cover type</th>
<th>Mean indoor relative humidity (%)</th>
<th>Mean indoor temperature (°C)</th>
<th>Mean survival time (days)</th>
<th>Fecundity</th>
<th>$R_0$</th>
<th>$r_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>Highland</td>
<td>Forested</td>
<td>66.4 ± 10.0a</td>
<td>22.9 ± 0.8a</td>
<td>11.0 ± 0.3a</td>
<td>1.0 ± 0.2a</td>
<td>4.70 ± 0.41a</td>
<td>0.100 ± 0.001a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deforested</td>
<td>41.1 ± 10.6b</td>
<td>24.6 ± 1.8b</td>
<td>17.5 ± 0.5b</td>
<td>1.7 ± 0.3a</td>
<td>16.78 ± 2.83b</td>
<td>0.144 ± 0.004b</td>
</tr>
<tr>
<td>Rainy</td>
<td>Lowland</td>
<td>Forested</td>
<td>56.0 ± 13.1c</td>
<td>25.5 ± 1.1c</td>
<td>26.5 ± 0.7c</td>
<td>6.0 ± 3.0b</td>
<td>70.13 ± 5.44c</td>
<td>0.169 ± 0.005c</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deforested</td>
<td>79.6 ± 2.5a</td>
<td>19.4 ± 0.6a</td>
<td>10.5 ± 0.4a</td>
<td>0.8 ± 0.3a</td>
<td>4.11 ± 2.12a</td>
<td>0.088 ± 0.011a</td>
</tr>
<tr>
<td></td>
<td>Lowland</td>
<td>Forested</td>
<td>57.7 ± 3.4b</td>
<td>21.2 ± 0.6b</td>
<td>15.6 ± 0.5b</td>
<td>1.1 ± 0.2b</td>
<td>11.28 ± 1.39b</td>
<td>0.132 ± 0.002b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deforested</td>
<td>64.2 ± 6.5c</td>
<td>23.4 ± 0.7c</td>
<td>24.6 ± 0.7c</td>
<td>4.0 ± 0.8c</td>
<td>54.29 ± 3.79c</td>
<td>0.156 ± 0.007c</td>
</tr>
</tbody>
</table>

* Values are means ± standard deviations. Letters following the numerical values indicate the results of multiple comparison tests, and values with the same letter were not statistically significant at $P = 0.05$ within a season.
† Fecundity refers to the number of eggs produced per female per day.
‡ $R_0$ is the net replacement rate (number of offspring per female per generation).
§ $r$ is the intrinsic per-capita growth rate (number of offspring per female per day).

The highest median survival times: 26.5 days in the dry season and 24.6 days in the rainy season (Figure 2). This was significantly higher than that in the highland deforested area ($\chi^2 = 221.6$, df = 1, $P < 0.0001$ in the dry season; and $\chi^2 = 285.9$, df = 1, $P < 0.0001$ in the rainy season).

**Fecundity, net reproductive rate, and the intrinsic growth rate of adult *An. arabiensis***. During the dry season in the highland, average fecundity of mosquitoes in the deforested area was significantly higher than the forested area (1.7 versus 1.0 egg per female per day; $\chi^2 = 5.3$, df = 1, $P < 0.05$; Table 2). During the rainy season, fecundity was higher in the deforested site compared with the forested site, but the difference was not significant (1.1 egg per female per day in the deforested site versus 0.8 egg per female per day in the forested area; $\chi^2 = 2.55$, df = 1, $P > 0.05$; Table 2). Mosquito fecundity in the lowland deforested area was substantially higher than the highland deforested area in the dry season ($\chi^2 = 5.3$, df = 1, $P < 0.05$) and the rainy season ($\chi^2 = 5.4$, df = 1, $P < 0.05$). Fecundity did not vary significantly between dry and rainy seasons in both highland ($\chi^2 = 2.8$, df = 1, $P > 0.05$) and lowland ($\chi^2 = 3.0$, df = 1, $P > 0.05$).

The net reproductive rates in the highland forested areas were 257% and 174% higher than in the forested area during the dry ($\chi^2 = 5.4$, df = 1, $P < 0.05$; Table 2) and rainy seasons ($\chi^2 = 5.3$, df = 1, $P < 0.05$), respectively. Mosquitoes in the lowland deforested area exhibited a 3.2- to 3.8-fold increase in $R_0$ over the highland deforested area in the dry and rainy seasons ($P < 0.0001$; Table 2). The high $R_0$ values in the lowland indicate a large potential for mosquito reproduction when larval habitats are available. The net reproductive rates did not vary significantly between the dry and rainy seasons. Similarly, the intrinsic growth rate was the highest in the lowland deforested area, followed by the highland deforested area, and the highland forested area showed the lowest $r$ value for both dry and rainy seasons (Table 2). Mosquito intrinsic growth rate was not significantly different between the dry and rainy seasons ($\chi^2 = 1.5$, df = 1, $P > 0.05$).

**DISCUSSION**

In this study, we investigated the effects of deforestation in western Kenya highlands on microclimate of mosquito habitats and mosquito survivorship in both immature and adult stages. Canopy clearing leads to exposure of aquatic habitats to sunlight, resulting in increased water temperature and increased algal contents. Higher water temperatures and nutritional conditions in aquatic habitats in the deforested area enhance the survivorship of *An. arabiensis* larvae and shorten the larval-to-adult development time. Similarly, vegetation changes may affect the radiation budget and energy balance of the land surface and thus may modify local climate. We found that average indoor ambient temperature in houses located in the deforested area was increased by 1.7–1.8°C compared with the houses in the forested area. Our finding is consistent with the study in the Amazon forest of South America, where extensive deforestation was found to cause a 2.5°C increase in mean surface temperature and a 30% decrease in the annual evapotranspiration. We also found that deforestation causes a reduction of indoor relative humidity by 22–25%.

The altered landscape in the western Kenya highlands may result from rapid human population increases in the region. It was estimated that the net human population increase rate was 2.8%, and the population size was doubled within 20–25 years. Major ongoing land-use changes in western Kenya highlands include deforestation and swamp reclamation. Here we showed that deforestation alters the microclimate of mosquito habitats and that subtle local climate changes led to increased adult *An. arabiensis* survivorship and higher reproductive fitness. Such changes in habitat microclimate and nutritional conditions may permit proliferation of new vector species. *An. arabiensis* generally prefers areas with low humidity and high temperature. The decreased humidity as well as the increased temperatures as a result of deforestation creates a more suitable environment for adult *An. arabiensis* to survive. In addition, higher indoor temperature may cause adult mosquitoes to digest blood faster and reduce the duration of the gonotrophic cycle, as demonstrated in *An. gambiae*. These factors contribute to increased mosquito vectorial capacity.

The larval-to-adult survival rate of *An. arabiensis* in the highlands found in this study was comparable to that of *An. gambiae*. Using the same site, Tuno and others and Munga and others reported that only 2–6% *An. gambiae* larvae developed into adult stages in the forested area while > 49–65% larvae survived to adult stage in the deforested area. The higher larval survivorship in aquatic habitats in the deforested area likely results from increased water temperature and perhaps better food conditions. Interestingly, we found that the adult survivorship of *An. arabiensis* was significantly increased when they were placed in houses in the deforested areas (17.5 days in the deforested area and 11.0 days in the
forested area during the dry season, and 15.6 days in the deforested area and 10.5 days in the forested area during the rainy season). This is in sharp contrast to An. gambiae adults, which were found to exhibit reduced life span under deforested environments in the same study site (44.1 days in the forested area and 39.0 days in the deforested area during the dry season, and 30.6 days in the forested area and 21.8 days in the deforested area in the rainy season).

Previous studies have demonstrated that An. gambiae is better adapted to humid environments while An. arabiensis is more suited to dry environments. The higher survivorship of adult An. arabiensis in the deforested site compared with the forested site is likely caused by lower indoor relative humidity and perhaps temperature differences. Consistent with the finding of Koenraadt and others in Nandi Hills of western Kenya, we also observed a much reduced adult survivorship of An. arabiensis in comparison to that of An. gambiae in the highland. Further, daily fecundity of An. arabiensis was much lower than An. gambiae. Consequently, the net reproductive rate of An. arabiensis was only 0.8–1.3% that of An. gambiae in the for-

**Figure 1.** Average hourly temperature of daily maximum, mean, and minimum indoor temperatures in forested and deforested areas in western Kenya highland (Kakamega) and deforested lowland (Kisian). Dry season refers to January–March 2005, and the rainy season refers to July–September 2005.
Establishment of new malaria vector species in the highland increases malaria transmission risks and renders malaria control more difficult.

In summary, this study demonstrated that the current ambient climatic condition is less permissive to the development and survival of An. arabiensis than to An. gambiae in western Kenya highland. However, deforestation changed the microclimate of mosquito larval and adult habitats and enhanced the survivorship and reproduction of An. arabiensis in the highland region. Increased survivorship and reproduction of An. arabiensis due to deforestation-induced microclimate change or global climate warming have the potential of allowing An. arabiensis to establish its population in western Kenya highlands, thus adding new malaria vector species to the suite of the existing vector species, An. gambiae and Anopheles funestus, in the highlands. In addition, increased survivorship and fecundity of An. arabiensis would lead to increased vectorial capacity and thus, malaria transmission.

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