The effect of irrigation on malaria vector bionomics and transmission intensity in western Ethiopia

Werissaw Haileselassie1†, Endalew Zemene2†*, Ming-Chieh Lee3, Daibin Zhong3, Guofa Zhou3, Behailu Taye4, Alemayehu Dagne4, Wakgari Deressa1, James W. Kazura5, Guiyun Yan3 and Delenasaw Yewhalaw2,6

Abstract
Background: Irrigation schemes may result in subsequent changes in malaria disease dynamics. Understanding the mechanisms and effects of irrigation on malaria vector bionomics and transmission intensity is essential to develop new or alternative surveillance and control strategies to reduce or control malaria risk. This study was designed to assess the effect of rice irrigation on malaria vector bionomics and transmission intensity in the Gambella Region, Ethiopia.

Methods: Comparative cross-sectional study was conducted in Abobo District of the Gambella Region, Ethiopia. Accordingly, clusters (kebeles) were classified into nearby and faraway clusters depending on their proximity to the irrigation scheme. Adult mosquito survey was conducted in February, August and November 2018 from three nearby and three faraway clusters using Centers for Disease Control and Prevention (CDC) light traps (LTs). During the November survey, human landing catch (HLC) and pyrethrum spray catch (PSC) were also conducted. The collected mosquitoes were morphologically identified to species and tested for Plasmodium infection using circumsporozoite protein enzyme-linked immunosorbent assay (CSP-ELISA). Furthermore, species-specific polymerase chain reaction (PCR) was performed to identify member species of the Anopheles gambiae complex. Chi-square and t-tests were used to analyze the data using the SPSS version 20 software package.

Results: A total of 4319 female anopheline mosquitoes comprising An. gambiae sensu lato, An. funestus group, An. pharoensis, An. coustani complex and An. squamosus were collected. Overall, 84.5% and 15.5% of the anopheline mosquitoes were collected from the nearby and faraway clusters, respectively. Anopheles gambiae s.l. was the predominant (56.2%) anopheline species in the area followed by An. pharoensis (15.7%). The density of anopheline mosquitoes was significantly higher in the nearby clusters in both HLCs \( t_{(3)} = 5.14, P = 0.0143 \) and CDC LT catches \( t_{(271.97)} = 7.446, P < 0.0001 \). The overall sporozoite rate of anopheline species from the nearby clusters was 10-fold higher compared to the faraway clusters.

Conclusions: Significantly higher mosquito population density was observed in areas close to the irrigation sites. Sporozoite infection rate in the mosquito population was also markedly higher from the nearby clusters. Therefore, the irrigation scheme could increase the risk of malaria in the area.

© The Author(s) 2021. Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/. The Creative Commons Public Domain Dedication waiver (http://creativecommons.org/publicdomain/zero/1.0/) applies to the data made available in this article, unless otherwise stated in a credit line to the data.
Keywords: Mosquito vectors, Malaria, Transmission intensity, Irrigation, Ethiopia

Background

Understanding bionomics of malaria vectors is pillar to develop and implement effective vector control interventions. Malaria transmission in Ethiopia varies spatio-temporally, mainly depending on microclimate and altitude [1]. In most parts of the country the transmission is seasonal and unstable. In the seasonal transmission areas, malaria cases usually peak following the major rainy season that extends from June to September. In these unstable transmission areas, there might also be a minor malaria transmission period that extends from April to June following minor rains in February and March. In the western lowlands, including Gambella Region, the transmission is generally high and year-round. While there is spatial variation in the distribution of the different species of anopheline mosquitoes in Ethiopia, Anopheles arabiensis is generally widely distributed and is the primary vector of malaria [2]. Anopheles pharoensis, An. funestus and An. nili are secondary vectors, while An. coustani is a suspected vector with limited distribution.

The dynamics of malaria transmission are affected by several factors including microclimate variation associated with altitude and ecological factors related to land-use changes. Ecological changes resulting from water resource development projects (WRDPs), including construction of hydroelectric dams and irrigation schemes, markedly affect the epidemiology of malaria [3, 4]. Irrigated rice cultivation in particular may provide favorable mosquito breeding habitats, resulting in higher vector density [5] and enhanced malaria transmission [6]. Rice irrigation schemes may create suitable larval ecology for An. arabiensis, which prefers open sunlit aquatic habitats [7]. However, higher vector mosquito density in rice irrigation areas may not always be translated to higher malaria transmission [5, 8]. Rice irrigation could also extend the duration of malaria transmission as a result of the presence of flooded fields suitable for mosquito breeding during the dry seasons [4]. Deforestation which may precede large-scale rice cultivation could also contribute to enhanced malaria transmission [9, 10], although the link between deforestation and malaria transmission is not always straightforward [11].

In Ethiopia, construction of irrigation projects and hydroelectric dams has been enhanced in recent years. It is obvious that such WRDPs are crucial to ensure food security and generate power, hence alleviating poverty [12, 13]. However, the possible ecological changes and the resulting impact on vector-borne diseases in general and malaria in particular is not adequately addressed in some of the WRDPs. Irrigated farming has the potential to create additional breeding sites enhancing malaria transmission [3, 14, 15]. Some studies have also documented increased malaria risk due to rice irrigation, mainly demonstrating its impact using entomological parameters [6, 16]. Rice irrigation may also alter the transmission dynamics of malaria from seasonal to perennial [17], likely as a result of prolonged presence of aquatic habitats suitable for mosquito breeding.

The effect of irrigation on risk of malaria appears to be complex. Ecological setting of the irrigation is one of the major factors affecting the epidemiology of malaria, with irrigation schemes undertaken in lowland areas remarkably favoring malaria transmission compared to those taking place in the highlands [18]. Moreover, the economic return from the irrigation scheme to the local community is another important factor affecting the net effect of irrigation on the risk of malaria. In some areas, reduced risk of malaria in irrigated areas has been reported [19, 20]. These factors dictate area-specific evaluation of impact of irrigation schemes on the risk of malaria transmission. Because of food insecurity issues, major investments in water resources are taking place in Ethiopia. One of the WRDPs is taking place in Gambella, where there is extensive rice cultivation through irrigation. As the rice farming in the area relies on flooded paddies, favorable mosquito breeding sites may be created, which has implications for the local community. In light of the aforementioned and anticipated expansion of WRDPs in Ethiopia in the years to come, understanding the effects of rice irrigation on malaria transmission dynamics in the area is crucial to effectively deploy malaria prevention. However, the potential effect of the land-use change due to irrigation on malaria transmission in the Gambella Region has not yet been studied. Therefore, the current study was designed to assess the effect of rice irrigation schemes on malaria vector bionomics and transmission intensity in the Gambella Region, Ethiopia.

Methods

Study setting

The study was conducted in Abobo District of Gambella Regional State, western Ethiopia. The district is located 811 km west of the capital, Addis Ababa. It is one of the districts in Anuak Zone of Gambella Regional State. The projected total population size of the district in 2019 was estimated to be 26,080 [21]. The total number of households in the district is 5670. The district is located at 7°51’0” N, 34°33’0” E, with altitude ranging from 500 to...
700 m above sea level, and covers an area of 3116 km². The area is characterized by savanna grassland, wetlands, and some portion covered by forest. The weather condition is hot (mean annual temperature range 28–37 °C) and humid with seasonal rainfall (annual rainfall range 900–1200 mm). The mean annual relative humidity of the district ranges from 74.1 to 88.3%. The hot and humid conditions, coupled with seasonal rainfall, create a favorable environment for mosquito breeding. The main socioeconomic activities of the community are farming and fishing. Cotton, maize, sorghum and fruits (mango, papaya and banana) are mainly grown by the local community. Fishing takes place in Alwero Dam, which is also used for large-scale irrigation of rice (owned by Saudi Star Agricultural Development PLC, a privately owned company). The canal extends 25 km from Alwero Dam, which is the major water body in the district, covering a total of 2700 hectares. The irrigation project was established in 2012 and has about 2000 workers. The current rice irrigation area is 3000 hectares, with planned expansion to 10,000 hectares. There has been extensive deforestation prior to rice cultivation. The irrigation scheme uses surface irrigation method. There is no crop rotation in the rice irrigation to avoid mixing of varieties, as there is a seed bank. While the irrigation farm workers live mainly in the Ghulam Rasool Company (GRC) and Bravo camps of the company, most of the residents in the district live in traditional houses constructed of wood and mud walls, with thatched roofs, and some live in houses with corrugated iron sheets.

The study site was classified into different clusters. Each cluster was georeferenced to its geographic centroid. Spatial coordinates were used to map the clusters with important landmarks to facilitate identification of clusters by the research team. The clusters were grouped into nearby and faraway mainly depending on their proximity to the rice irrigation scheme (Fig. 1). Clusters within 3 km radius from the irrigation scheme were classified as nearby clusters, while those located 6–10 km from the irrigation site were grouped as faraway clusters (considering flight range of the local mosquito vector population). Of the total 21 clusters identified in the district, six clusters (three from nearby and three from faraway clusters) were purposively selected for the study. A cluster is an area with radius ranging from 250 to 500 m and with 100–250 households. Malaria vector control interventions were implemented in the district using indoor residual spraying and insecticide-treated nets, similar to other malaria endemic areas in Ethiopia. The vector control interventions being implemented were similar in each cluster.

**Entomological study**

Adult mosquitoes were collected from all the selected clusters in three rounds in 2018. Centers for Disease Control and Prevention (CDC) light traps (LTs) (John W. Hock Ltd., Gainesville, FL, USA) were used to collect adult mosquitoes during the three survey rounds (February, August and November 2018) from all six clusters. Moreover, during the November survey, mosquitoes were also collected using human landing catches (HLCs) and pyrethrum spray catches (PSCs) from one nearby cluster (Bravo) and one faraway cluster (Mender 13) besides the CDC LT collections.

The CDC LTs were set both indoors (inside bed room on roof support or ceiling) and outdoors (5–8 m from the house where the CDC LT was set indoors) in seven selected houses in each cluster. Mosquitoes were collected from 18:00 to 06:00 from each house for two consecutive nights in the seven selected houses per cluster. The CDC LTs were hung indoors near an occupied bed or mattress protected by bed net, approximately 1.5 m from the ground. The collection bags attached to each of the CDC LTs were labeled. The research team removed the bags from each trap early in the morning from 6:00 to 6:30 am. The CDC LT collection bags were transported to the field entomology lab to sort and identify mosquitoes.

HLC was conducted for two nights in two houses from each of the two clusters in November 2018. Thus, mosquito collection was conducted for a total of eight person-nights (four person-nights in each of the two clusters). Four experienced volunteers (two teams of two people) were involved in mosquito collection using HLC each night switching between indoors and outdoors each hour. The collection was carried out from 18:00 to 06:00 with the mosquitoes captured each hour being kept in separate labeled paper cups. The mosquitoes were collected using aspirator and torch. Volunteers were provided with prophylaxis (mefloquine) as per the national malaria treatment guidelines [1].

Indoor resting anopheline mosquitoes were collected using PSC from 20 houses each in the Bravo (nearby) and Mender 13 (faraway) clusters. Prior to conducting the PSC, human occupants and animals (where present) were evacuated, and food items were removed from each house. White sheets were spread to fully cover the floor. After closing doors and windows, one of the collectors sprayed aerosol insecticide (Baygon, SC Johnson & Son Inc., Racine, WI, USA) in the room. Fifteen minutes after spraying, the sheets were carefully removed from the house and taken outside to look for knocked-down mosquitoes. Mosquitoes were then transferred to petri dishes using forceps for morphological identification. The PSC was conducted earlier in the morning from 06:00 to 08:00.
The collected anopheline mosquitoes were morphologically identified to species level using standard taxonomic keys [22]. The identified mosquitoes were preserved individually in labeled Eppendorf tubes over silica gel for further processing (information on the label included morphological ID and site, date and method of collection).

**Sporozoite ELISA**

Sporozoite infection of the female anopheline mosquitoes was tested using circumsporozoite protein (CSP) enzyme-linked immunosorbent assay (ELISA) following an established method [23]. In brief, the head and thorax of the dried anopheline mosquitoes were cut from the abdomen transversely. A pool of 10 anopheline mosquitoes (the head and thorax portion) were ground in a 1.5 ml Eppendorf tube using a pestle and mortar, and thoroughly homogenized in 50 µl grinding buffer. The pestle was rinsed with grinding buffer, making a total volume of 250 µl homogenate of each pool. It was immediately tested for *Plasmodium falciparum*, *P. vivax*-247 and *P. vivax*-210 CSPs as follows: labeled 96-well plates were coated with the respective monoclonal antibodies (mAbs). After incubation for 30 min at room temperature, the solution was removed and blocking buffer added to each well. Following 1 h of incubation, the contents of the wells were discarded in a sink by rapidly turning the plates upside down, and 50 µl negative control, positive control and samples was loaded into the respective wells. The plates were covered and incubated for 2 h. The plates were washed using Tween-20, and peroxidase-labeled conjugate solutions were added and incubated for 1 h. After washing the plates, ABTS (2,2'-azinobis [3-ethylbenzothiazoline-6-sulfonic acid]-diammonium salt) substrate was added to each well and incubated for 30 min. The plates were read using an ELISA reader at 405 nm. Similar anopheline mosquito species collected by a similar method from the same cluster were pooled and analyzed.

**Molecular identification of the An. gambiae complex**

Sub-samples (n = 120) of *An. gambiae* s.l. were randomly selected and analyzed using species-specific polymerase chain reaction (PCR) following the method reported by Scott et al. [24]. The specimens were sampled from each cluster including both the nearby and faraway clusters and for each trapping method. Genomic DNA was extracted from the legs and wings of specimens using the Qiagen DNA extraction kit. A cocktail of three primers specific for *An. arabiensis* (AR: 5′AAGTGTCCCTTCT
The monthly EIR of HLC and CDC LT-collected anopheles observed proportion of positive pools and using area and difference in pooled indoor and outdoor catches between indoor and outdoor sampling in the same risk days per month [27]. Differences in anopheline catches away clusters were compared using Chi-square tests.

Differences in biting rates between indoors and outdoors dently associated with anopheline mosquito density. Regression analysis was utilized to determine factors indepen - dently associated with anopheline mosquito density. The EIR from the CDC LT collected from the nearby and faraway clusters, respectively. The anopheline species collected using HLC and CDC LTs are shown in Fig. 2.

Of the 120 subsamples of An. gambiae s.l. tested using PCR, 86.7% (104/120) were successfully amplified and all belonged to An. arabiensis. The number of each anophe- line species and their proportion by risk level is shown in Table 1.

Results

Phylotype analysis

A total of 4319 female anopheline mosquitoes were collected from the six clusters. Anopheles gambiae s.l., An. pharoensis, An. coustani group, An. funestus group, and An. squamosus comprised 56.5%, 15.7%, 14.4%, 11.7% and 1.6% of the total collections, respectively. Overall, 84.5% and 15.5% of the anopheline mosquitoes were collected from the nearby and faraway clusters, respectively.

Anopheline mosquito density

The density of anopheline mosquitoes collected using HLC and CDC LTs in the nearby and faraway clusters is presented in Fig. 3. The density of mosquitoes collected by HLC was significantly higher in the nearby clusters (84.6 ± 14.9 mosquitoes/person/night) than in the faraway clusters (6.3 ± 1.3 mosquitoes/person/night) [t(68) = 6.5, P = 0.001]. Similarly, the density of anopheline mosquitoes collected using CDC LTs in the nearby clusters (11.7 ± 1.2 mosquitoes/trap/night) was significantly higher than those collected in the faraway clusters (2.41 ± 0.25 mosquitoes/trap/night) [t(271.97) = 7.446, P < 0.0001]. The density of mosquitoes collected in November using HLC (45.4 mosquitoes/person/night) was markedly higher than those collected using CDC LTs (2.4 mosquitoes/trap/night). The density of anopheline mosquitoes collected from each cluster using the different collection methods is shown in Additional file 1: Table S1.

The difference in the density of indoor-collected anopheline mosquitoes in the nearby clusters (12.4 ± 1.9 mosquitoes/trap/night) was significantly higher than that of the indoor collections from the faraway clusters (2.44 ± 0.4 mosquitoes/trap/night) (P < 0.0001). Likewise, the difference in the density of outdoor-collected anopheline mosquitoes in the nearby clusters (11.03 ± 1.5 mosquitoes/trap/night) was significantly higher than those collected from the faraway clusters (2.37 ± 0.4 mosquitoes/trap/night) (P < 0.0001). After controlling for the effects of venue of collection and date, season of collection (P < 0.0001) and risk level (P < 0.0001) were found to have significant effects on the density of anopheline mosquitoes collected using CDC LTs.

Results of mosquito analysis by species showed significantly higher density of An. gambiae s.l. [t(261.144) = 6.568, P < 0.0001], An. coustani group [F(357.072)]
4.136, \( P < 0.0001 \), \( An. \) pharoensis \([t_{(254.647)} = 7.636, \ P < 0.0001]\), \( An. \) funestus group \([t_{(432.036)} = 2.519, \ P = 0.012]\) and \( An. \) squamosus \([t_{(352.98)} = 2.535, \ P = 0.012]\) collected from nearby clusters compared to faraway clusters. However, there was no significant difference in the overall anopheline density between indoor and outdoor CDC LT catches \([t_{(502)} = 0.546, \ P = 0.586]\). The density of \( An. \) gambiae s.l. collected using outdoor CDC LTs was significantly higher than that in the indoor catches in both the nearby and faraway clusters \( (P < 0.05) \). Moreover, the density of \( An. \) coustani collected using outdoor CDC LTs in the faraway clusters was significantly higher than the density in the indoor collections \( (P < 0.05) \).

The highest density of anopheline mosquitoes was observed in August CDC LT collections \( [16.4 \text{ mosquitoes/trap/night}, \ F_{(2.2517)} = 116.453, \ P < 0.0001] \). Pair-wise comparisons of the mosquito density showed that the anopheline density in August \( (16.4 \text{ mosquitoes/trap/night}) \) was significantly higher than the density in November and February \( (2.4 \text{ mosquitoes/trap/night each}) \) \( (P < 0.0001) \).

**Table 1** Abundance of *Anopheles* mosquito species by location of collection and cluster in Gambella, Ethiopia, 2018

| Cluster     | Collection method | Environment | Anophele species |
|-------------|-------------------|-------------|------------------|
|             |                   |             | *An. gambiae s.l.* | *An. funestus* | *An. pharoensis* | *An. coustani* | *An. squamosus* |
| Nearby      | CDC light trap    | Indoor      | 1147 (31.4)      | 67 (1.8)       | 207 (5.7)       | 116 (3.2)      | 25 (0.7)        |
|             |                   | Outdoor     | 675 (18.5)       | 185 (5.1)      | 221 (6.1)       | 282 (7.7)      | 27 (0.7)        |
|             |                   | HLC         | 106 (2.9)        | 18 (0.5)       | 91 (2.5)        | 21 (0.6)       | 0 (0.0)         |
|             |                   | Indoor      | 229 (6.3)        | 48 (1.3)       | 135 (3.7)       | 31 (0.8)       | 0 (0.0)         |
|             |                   | Outdoor     | 4 (0.1)          | 14 (0.4)       | 0 (0.0)         | 0 (0.0)        | 0 (0.0)         |
|             |                   | Subtotal    | 2161 (59.2)      | 332 (9.1)      | 654 (17.9)      | 450 (12.3)     | 52 (1.4)        |
| Faraway     | CDC light trap    | Indoor      | 160 (23.9)       | 99 (14.8)      | 8 (1.2)         | 39 (5.8)       | 2 (0.3)         |
|             |                   | Outdoor     | 87 (13.0)        | 64 (9.6)       | 10 (1.5)        | 121 (18.1)     | 17 (2.5)        |
|             |                   | HLC         | 7 (1.0)          | 1 (0.1)        | 3 (0.4)         | 4 (0.6)        | 0 (0.0)         |
|             |                   | Outdoor     | 12 (1.8)         | 6 (0.9)        | 5 (0.7)         | 10 (1.5)       | 0 (0.0)         |
|             |                   | PSC         | 12 (1.8)         | 3 (0.4)        | 0 (0.0)         | 0 (0.0)        | 0 (0.0)         |
|             |                   | Subtotal    | 278 (41.5)       | 173 (25.8)     | 26 (3.9)        | 174 (26.0)     | 19 (2.8)        |

Numbers in brackets indicate percent calculated out of total number of anopheline mosquitoes in each risk level.

HLC human landing catch; PSC pyrethrum spray catch.
Anopheline mosquito biting activity

In the faraway clusters, biting occurred mainly between 6:00 pm and 2:00 am, with peak activity between 7:00 and 9:00 pm (Fig. 4a), and biting activity was similar between indoors and outdoors ($\chi^2 = 2.82, df = 7, P = 0.9015$). In contrast, in the nearby clusters, mosquito biting activity occurred throughout the night from 6:00 pm to 6:00 am, although there was a slightly higher biting period between 8:00 pm and 2:00 am (Fig. 4b), and biting patterns were similar between indoors and outdoors ($\chi^2 = 8.39, df = 11, P = 0.6781$). The biting patterns were different between the nearby and faraway clusters ($\chi^2 = 41.18, df = 11, P < 0.0001$).

Indoor and outdoor biting activity of *An. gambiae* s.l. and *An. Pharoensis* was markedly more pronounced in the nearby than faraway clusters. Biting activity occurred throughout the night for both *An. gambiae* s.l. and *An. pharoensis* in the nearby clusters (Fig. 5). Noticeably higher outdoor biting activity was recorded in *An. Funestus* in the nearby clusters compared to the faraway clusters.

Entomological inoculation rate

Four of the five anopheline species from the nearby clusters were positive for CSP, while a single specimen of *An. coustani* was positive for CSP from the faraway clusters. The overall SR of the different anopheline species collected from the nearby clusters was 10-fold higher than that of the faraway clusters. The overall monthly *P. falciparum* and *P. vivax* EIR of the anopheline species collected using the different methods from the nearby clusters was 7.6 and 23.5 infective bites/person/month, respectively. In contrast, the corresponding monthly *P. falciparum* and *P. vivax* EIR of the anopheline mosquitoes collected from the faraway clusters was zero and 0.2 infective bites/person/month, respectively (Table 2).

Discussion

The overarching objective of the study was to assess the effect of rice irrigation on the risk of malaria transmission in Gambella, Ethiopia. Accordingly, more than 10-fold higher SR of the anopheline mosquitoes was obtained from the nearby clusters compared to the faraway clusters. Monthly *P. vivax* EIR of *An. coustani* collected from the nearby
clusters was nearly 25-fold higher compared to the faraway clusters. None of the other anopheline species collected from the faraway clusters were CSP-positive. These indicate the impact of the irrigation scheme on malaria transmission intensity in the area. The findings show that the risk of malaria transmission was remarkably higher in the irrigation sites compared to the non-irrigation sites. Several other similar studies also documented the effects of irrigation in enhancing malaria transmission [3, 15]. The lower SR in the faraway clusters could also be related to the low density of mosquitoes collected from these clusters. The overall SR of the anopheline mosquitoes collected using HLC was fourfold higher than the SR obtained using CDC LT collections in the nearby clusters. The lower SR from CDC LT collections could be attributed to higher proportion of nulliparous female mosquitoes collected by CDC LTs [28].

Adult anopheline density was significantly higher in the nearby clusters compared to the faraway clusters. This could be attributable to favorable microhabitats formed by the agro-ecosystem, allowing proliferation of a range of anopheline mosquitoes. The higher density of anopheline species observed in the irrigation clusters could also be due to the odor of the rice. Rice odor surrounding rice fields elicits attraction and oviposition in gravid female An. arabiensis [29], the dominant anopheline species in the area. Moreover, there could be differences in survivorship of adult An. arabiensis in the nearby and faraway clusters [30]. Alterations in the microclimatic environment in the rice irrigated areas resulting from deforestation might also have contributed to the observed higher mosquito density in the irrigated clusters [31]. Immature stages of An. arabiensis typically prefer sunlit pools [7], which may be created as a result of deforestation for rice cultivation. This allows the presence of abundant sunlit aquatic habitats to be created, increasing the water temperature, making the habitat conducive for larval development. Increased temperature and relative humidity resulting from deforestation in irrigation areas may also affect the extrinsic incubation period of the malaria parasites in mosquito guts [32], ultimately enhancing transmission.

Outdoor biting by malaria vectors is a huge challenge for malaria control and elimination efforts, and may contribute a substantial number of additional malaria cases after deployment of the indoor-based interventions [33]. In this study, two-thirds of the anophelines collected using HLC were captured outdoors. The density of outdoor host-seeking anopheline mosquitoes was significantly higher in the nearby clusters compared to the faraway clusters. This shows higher risk of outdoor transmission of malaria, which may sustain residual transmission near rice irrigation areas. Moreover, biting activity throughout the night near irrigation areas poses particular risk to individuals involved in nighttime activities and those who may sleep outdoors. The tendency to bite predominantly outdoors earlier in the evening in the faraway clusters may also contribute to residual transmission of malaria in these areas.

Anthropogenic manipulation of water resources, including development of irrigation schemes and hydroelectric dams, is being intensified in Ethiopia and other developing countries to provide food and energy to satisfy the fast-growing population [12, 13]. Although irrigation activities do not necessarily lead to increased malaria transmission
surveillance of vector-borne disease in general and malaria in particular is critically required. The observed higher vector density near the rice irrigation scheme could be attributed to favorable breeding habitats created by the rice paddies. As Alwero Dam supplies water to the main irrigation canals, the rice field obtains continuous supply of water, which enables prolonged flooding of the rice fields during dry season.

In Ethiopia, malaria is principally transmitted by An. arabiensis, with An. pharoensis playing a secondary role and An. coustani being a suspected vector. Due to its limited geographical distribution, An. funestus also plays a secondary role in malaria transmission in some areas in Ethiopia [1, 2]. This study revealed that four of the five mosquito species collected (with An. squamosus being the exception) were CSP-positive, indicating that malaria is likely transmitted by multiple vector species in this area. An. pharoensis had the highest EIR, which is not the case in other areas of Ethiopia [34, 35]. Historical data also showed that An. pharoensis was found to be parasite-infected in the Gambella area [36]. A recent mosquito infection study using membrane feeding assay documented that An. pharoensis was as susceptible as An. gambiae s.l. to P. vivax infections [37]. Infectivity of An. pharoensis in this area is likely due to increase in its longevity associated with microclimate change (increase in relative humidity) in irrigation areas [38]. Repeated gonotrophic cycles are likely in the long-surviving adult vectors, possibly perpetuating malaria transmission. Higher survivorship in other anopheline species in lower altitudes (hotter areas) was documented elsewhere as well [39]. However, it should also be noted that the highest EIR obtained in An. pharoensis specimens could also be due to the low number of An. pharoensis collected and analyzed.

### Table 2 Sporozoite rates and entomological inoculation rates of Anopheles mosquito species from nearby and faraway clusters in Gambella, Ethiopia, 2018

| Cluster         | Method of collection | Species          | Total tested | No. of pools positive (SR) | SR Pf | SR Pv-210 | SR Pv-247 | EIR Pf | EIR Pv |
|-----------------|----------------------|------------------|--------------|-----------------------------|-------|-----------|-----------|--------|--------|
| Nearby          | CDC light trap       | An. coustani     | 398 (43)     | 4 (0.97)                     | 0     | 0.48      | 0.48      | 0      | 0.7    |
|                 |                      | An. funestus group | 252 (31)   | 1 (0.33)                     | 0.33  | 0        | 0        | 0      | 0.2    |
|                 |                      | An. gambiae s.l. | 1822 (189)  | 2 (0.11)                     | 0.05  | 0.05     | 0.05     | 0      | 0.4    |
|                 |                      | An. pharoensis    | 428 (47)    | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. squamosus     | 52 (6)      | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | Subtotal          | 2952 (316)  | 7 (0.22)                     | 0.03  | 0.1       | 0.1       | 0      | 0.2    |
|                 | HLC                  | An. coustani     | 52 (6)      | 1 (1.81)                     | 1.81  | 0        | 0        | 0      | 3.5    |
|                 |                      | An. funestus group | 66 (7)    | 1 (1.53)                     | 1.53  | 0        | 0        | 3.8    | 0      |
|                 |                      | An. gambiae s.l. | 335 (34)    | 2 (0.60)                     | 0.3   | 0        | 0.3       | 3.8    | 3.8    |
|                 |                      | An. pharoensis    | 226 (23)    | 4 (1.89)                     | 0.9   | 0.9       | 0         | 16.0   | 0      |
|                 |                      | Subtotal          | 679 (70)    | 8 (1.21)                     | 0.29  | 0.44      | 0.44      | 7.4    | 22.4   |
|                 | PSC                  | An. gambiae s.l. | 4 (1)        | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. funestus group | 14 (2)    | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | Subtotal          | 18 (3)      | 0                            | 0     | 0        | 0        | 0      | 0      |
| Faraway         | CDC light trap       | An. coustani     | 160 (19)    | 1 (0.54)                     | 0.54  | 0        | 0        | 0      | 0.2    |
|                 |                      | An. funestus group | 163 (19)  | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. gambiae s.l. | 247 (28)    | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. pharoensis    | 18 (3)      | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. squamosus     | 19 (2)      | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | Subtotal          | 607 (71)    | 1 (0.14)                     | 0.14  | 0        | 0        | 0      | 0.2    |
|                 | HLC                  | An. coustani     | 14 (2)      | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. funestus group | 7 (1)     | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. gambiae s.l. | 19 (2)      | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. pharoensis    | 8 (1)       | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | Subtotal          | 48 (6)      | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 | PSC                  | An. gambiae s.l. | 12 (2)      | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | An. funestus group | 3 (1)     | 0                            | 0     | 0        | 0        | 0      | 0      |
|                 |                      | Subtotal          | 15 (3)      | 0                            | 0     | 0        | 0        | 0      | 0      |

EIR entomological inoculation rate per month; HLC human landing catch; PSC pyrethrum spray catch; SR corrected sporozoite rate
The effect of WRDPs on the bionomics of anopheline mosquitoes is complex. Limited studies done earlier in Ethiopia documented increased malaria transmission associated with irrigation, focusing on sugar cane and crops other than rice [15, 40]. The impact of rice irrigation on the risk of malaria in Ethiopia has not been explored. Flooded paddy fields may create conducive breeding habitats for a wide range of anopheline mosquitoes, ultimately enhancing malaria transmission intensity in the locality. Contrary to the findings of this study, other investigations have found no impact of rice irrigation on the risk of malaria, and reduced risk in rice irrigated areas has even been reported [5, 8]. Therefore, it appears that the ultimate impact of irrigation schemes on the epidemiology of malaria is not straightforward. The impact of such projects on the risk of malaria partly depends on the level of endemicity of malaria, the type of principal malaria vectors in the area, the ecological setting of the irrigation scheme (whether located in lowland or highland area), the status of vector management, and the economic return obtained by the local community from the irrigation scheme [5, 8, 18]. It should be noted that in this study, mosquitoes were sampled using HLC from one village each from the nearby and faraway clusters during one sampling season. This limited the number of mosquitoes processed from the faraway clusters.

Conclusions
In conclusion, higher anopheline density was recorded in the irrigation areas compared to the non-irrigation areas. The EIRs of the anopheline mosquitoes were also higher in clusters near the irrigation scheme. Multiple anopheline mosquito species including secondary and suspected malaria vector species were found sporozoite-positive in the irrigation sites compared to non-irrigation sites. Hence, the irrigation scheme in the study area could increase the risk of malaria transmission in communities residing in proximity to the irrigation sites. WRDPs including irrigation schemes should be critically monitored for their potential effect on transmission of vector-borne diseases in general and malaria in particular. Further studies are required to better understand the epidemiology of malaria in the area.

Abbreviations
CDC LT: Centers for Disease Control and Prevention light trap; CSP: Circumsporozoite protein; ER: Entomological inoculation rate; ELISA: Enzyme-linked immunosorbent assay; HLC: Human landing catch; PCR: Polymerase chain reaction; PSC: Pyrethrum spray catch; SR: Sporozoite rate; WRDP: Water resource development project.

Supplementary Information
The online version contains supplementary material available at https://doi.org/10.1186/s13071-021-04993-y.

Acknowledgements
We would like to thank Gambella Region Health Bureau, Abobo District Health Office, kebele administration of the clusters, and Saudi Star Agricultural Development PLC for their support and facilitating the data collection. We are grateful to the households where mosquitoes were collected. We would also like to thank the entomology technicians involved in the fieldwork, and lab technicians of TIDRC for their technical support.

Authors’ contributions
WH, EZ, ML, WD, JW, GY, and DY conceived and designed the study. WH, EZ, ML, DW, and GZ were involved in the fieldwork, data collection, and analysis. WH and EZ drafted the manuscript. BT and AD were involved in the fieldwork and contributed to the write-up. DY, WD, JW, and GY critically reviewed the manuscript. All authors were involved in the interpretation and discussion of the results and provided comments. All authors read and approved the final version of the manuscript.

Funding
This study was supported by grants from the National Institutes of Health (U19 AI129326 and D43 TW001505). The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Availability of data and materials
The data supporting the results reported in this article are included within the article and its supplementary file.

Declarations
Ethics approval and consent to participate
Ethical approval was obtained from the National Ethical Review Committee of the Ministry of Science and Higher Education of Ethiopia (Ref No. MoSHE/ RD/14.1/691/19) and the Institutional Review Board of the University of California, Irvine (HS#2017–3512). Written informed consent was obtained from heads of households where mosquitoes were collected. Experienced male adult entomology technicians over 18 years of age were involved in mosquito collection using HLC. Written consent was sought from the technicians before involving them in the human landing collections. They were provided with malaria prophylaxis and supervised for any development of fever following HLC. This study did not involve vertebrate animals.

Consent for publication
Not applicable.

Competing interests
We declare that we have no competing interests.

Author details
1School of Public Health, College of Health Sciences, Addis Ababa University, Addis Ababa, Ethiopia. 2School of Medical Laboratory Sciences, Institute of Health, Jimma University, Jimma, Ethiopia. 3Program in Public Health, College of Health Sciences, University of California at Irvine, Irvine, CA 92697, USA. 4Department of Biology, Faculty of Natural and Computational Science, Mettu University, Mettu, Ethiopia. 5Center for Global Health and Disease, Case Western Reserve University, Cleveland, OH 44106, USA. 6Tropical and Infectious Diseases Research Centre, Jimma University, Jimma, Ethiopia.

Received: 6 January 2021   Accepted: 8 September 2021
Published online: 07 October 2021

References
1. FMOH. National malaria guidelines. Ethiopia: Federal Democratic Republic of Ethiopia, Ministry of Health, 2018.
2. PMI. Ethiopia malaria operational plan FY 2019. Ethiopia: President’s Malaria Initiative, 2019.

3. Lautze J, McCartney M, Kinshen P, Olana D, Jayasinghe G, Spielman A. Effect of a large dam on malaria risk: the Koka reservoir in Ethiopia. Trop Med Int Health. 2007;12:982–9.

4. Dolo G, Briet OJ, Dao A, Traceé SF, Bouare M, Sogoba N, et al. Malaria transmission in relation to rice cultivation in the irrigated Sahel of Mali. Acta Trop. 2004;89:147–59.

5. Muturi EJ, Murisi S, Shillu J, Mwanganji J, Jacob BG, Mboogo C, et al. Effect of rice cultivation on malaria transmission in central Kenya. Am J Trop Med Hyg. 2008;78:270–5.

6. Koudou BG, Tano Y, Doumbia M, Nsanzabana C, Cissé G, Girardin O, et al. Malaria transmission dynamics in central Côte d’Ivoire: the influence of changes in the characterized breeding habitat of the principal malaria vector, Anopheles darlingi. Am J Trop Med Hyg. 2009;81:15.

7. Chirebvu E, Chimbari MJ. Characteristics of Anopheles arabiensis larval habitats in Tsho village. Botswana J Vector Ecol. 2015;40:129–38.

8. Ijumba J, Mosha F, Lindsay S. Malaria transmission risk variations derived from different agricultural practices in an irrigated area of northern Tanzania. Med Vet Entomol. 2002;16:26–38.

9. Olson SH, Gangnon R, Silveira GA, Patz JA. Deforestation and malaria in Mancio Lima County, Brazil: Emerg Infect Dis. 2010;16:1108.

10. Vittor AY, Pan W, Gilman RH, Tielsch J, Glass G, Shields T, et al. Linking deforestation to malaria in the Amazon: characterization of the breeding habitat of the principal malaria vector, Anopheles darlingi. Am J Trop Med Hyg. 2009;81:15.

11. Bahuoff S, Busch J. Does deforestation increase malaria prevalence? Evidence from satellite data and health surveys. Working paper 480. Washington: Center for Global Development; 2018.

12. Burney JA, Naylor RL. Smallholder irrigation as a poverty alleviation tool in sub-Saharan Africa. World Dev. 2012;40:110–23.

13. Bacha D, Namara R, Bogale A, Tesfaye A. Impact of small-scale irrigation on household poverty: empirical evidence from the Ambo district in Ethiopia. Irrig Drain. 2011;60:1–10.

14. Ghebreyesus TA, Haile M, Witten KH, Getachew A, Yohannes AM, Yohannes M, et al. Incidence of malaria among children living near dams in northern Ethiopia: community-based incidence survey. BMJ. 1999;319:663–6.

15. Olsson SH, Hangnon R, Silvera GA, Patz JA. Deforestation and malaria in Mancio Lima County, Brazil: Emerg Infect Dis. 2010;16:1108.

16. Vittor AY, Pan W, Gilman RH, Tielsch J, Glass G, Shields T, et al. Linking deforestation to malaria in the Amazon: characterization of the breeding habitat of the principal malaria vector, Anopheles darlingi. Am J Trop Med Hyg. 2009;81:15.

17. Koudou BG, Tano Y, Doumbia M, Nsanzabana C, Cissé G, Girardin O, et al. Malaria transmission dynamics in central Côte d’Ivoire: the influence of changes in the characterized breeding habitat of the principal malaria vector, Anopheles darlingi. Am J Trop Med Hyg. 2009;81:15.

18. Kibret S, Wilson GG, Ryder D, Tekie H, Petros B. Malaria impact of large dams for malaria vector control. Malar J. 2014;13:360.

19. Sharma SK, Tyagi PK, Upadhyay AK, Haque MA, Adak T, Dash AP. Building small dams can decrease malaria: a comparative study from Sundargarh District, Orissa. India Acta Trop. 2008;107:174–8.

20. Gillies M, Coetzee M. A supplement to the Anophelinae of Africa South of the Sahara. Publ S Afr Inst Med Res. 1987;55:1–143.

21. Beier JC, Perkins PV, Wirtz RA, Whitmire RE, Mugambi M, Hockmeyer WT. Field evaluation of an enzyme-linked immunosorbent assay (ELISA) for Plasmodium falciparum sporozoite detection in anopheline mosquitoes from Kenya. Am J Trop Med Hyg. 1987;36:459–68.

22. Scott JA, Brogdon WG, Collins FH. Identification of single specimens of the Anopheles gambiae complex by the polymerase chain reaction. Am J Trop Med Hyg. 1993;49:520–9.

23. Chirebvu E, Chimbari MJ. Characteristics of Anopheles arabiensis larval habitats in Tsho village. Botswana J Vector Ecol. 2015;40:129–38.

24. Scott JA, Brogdon WG, Collins FH. Identification of single specimens of the Anopheles gambiae complex by the polymerase chain reaction. Am J Trop Med Hyg. 1993;49:520–9.

25. Warrell DA, Gilles HM. Essential malariology. 4th ed. London: Taylor & Francis; 2002.

26. Lines J, Curtis C, Wilkes T, Njunwa K. Monitoring human-biting mosquitoes (Diptera: Culicidae) in Tanzania with light-traps hung beside mosquito nets. Bull Entomol Res. 1991;81(1):77–84.

27. McDermott EG, Mulkins BA. The dark side of light traps. J Med Entomol. 2005;42:974–80.

28. Dongre MR, Adak T, Dash AP. Building small dams can decrease malaria: a comparative study from Sundargarh District, Orissa. India Acta Trop. 2008;107:174–8.

29. Graafbergen A, Bouman AM, Graafbergen JR, Schuitemaker C. Similar trends of susceptibility in Anopheles gambiae for Plasmodium falciparum. Theob. Z Angew Entomol. 1971;67:88–94.

30. Brown S, Chitnis N, Das M, Dhillon P, Moris P, Patel S, et al. Microclimatic conditions change due to land use and cover changes in the Ambo district in Ethiopia: a longitudinal study. Malar J. 2013;12:1–1.

31. Lines J, Curtis C, Wilkes T, Njunwa K. Monitoring human-biting mosquitoes (Diptera: Culicidae) in Tanzania with light-traps hung beside mosquito nets. Bull Entomol Res. 1991;81(1):77–84.

32. McDermott EG, Mulkins BA. The dark side of light traps. J Med Entomol. 2005;42:974–80.

33. Sherrard-Smith E, Skapp JE, Beale AD, Fardel C, Norris LC, Moore SJ, et al. Malaria incidence and assessment of entomological indices among resettled communities in Ethiopia: a longitudinal study. Malar J. 2015;14:24.

34. Negatu W, Petros B, Lulu M, Adugna N, Wirtz R, Tilahun D, et al. Some aspects of malaria prevention, vector infectivity and DDT resistance studies in Gambella Region, Southwest Ethiopia. EHD. 1994;81.

35. Afriane YA, Lawson BW, Githeko AK, Yan G. Effects of microclimatic changes caused by land use and land cover on duration of gonotrophic cycles of Anopheles gambiae (Diptera: Culicidae) in Western Kenya Highlands. J Med Entomol. 2005;42:974–80.

36. Afriane YA, Little TJ, Lawson BW, Githeko AK, Yan G. Deforestation and vectorial capacity of Anopheles gambiae Giles mosquitoes in malaria transmission, Kenya. EID. 2008;14:1533.

37. Abduselam N, Zeynudin A, Berens-Riha N, Seyoum D, Pritsch M, Tibebe H, et al. Similar trends of susceptibility in Anopheles arabiensis and Anopheles pharoensis to Plasmodium vivax infection in Ethiopia. Parasit Vectors. 2016;9:552.

38. Gaaboub I, El-Sawaf S, El-Latif M. Effect of different relative humidities and temperatures on egg production and longevity of adults of Anopheles (Myzomyia) pharoensis. Theob. Z Angew Entomol. 1971;67:88–94.

39. Zhong D, Wang X, Xu T, Zhou G, Wang Y, Lee MC, et al. Effects of microclimate condition changes due to land use and cover changes in the Ambo district in Ethiopia: a longitudinal study. Malar J. 2013;12:1–1.

40. Jaleta KT, Hill SR, Seyoum E, Balkew M, Gebre-Michael T, Ignell R, Tekie H. Agro-ecosystems impact malaria prevalence: large-scale irrigation drives vector population in western Ethiopia. Malar J. 2013;12:1–1.

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.