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Research article

# Climate effects on honey bees can be mitigated by beekeeping management in Kenya

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ABSTRACT

In recent decades, worldwide concerns about the health of honey bees motivated the development of surveys to monitor the colony losses, of which Sub-Saharan Africa has had limited representation. In the context of climate change, understanding how climate affects colony losses has become fundamental, yet literature on this subject is scarce. For the first time, we conducted a survey to estimate the livestock decrease of honey bee colonies in Kenya for the year 2021–2022 to explore the effects of environmental conditions, such as temperature and precipitation, on livestock decrease. We define "livestock decrease" from the beekeeper's perspective, including dead colonies but also, in the specific context of the tropics, the colonies that absconded from the apiary. A total of 589 beekeepers from a variety of areas participated in the survey. Kenyan beekeepers had an average of 36.6% livestock decrease in 2021–2022, with higher decreases during the dry and hot (31.9%) than during the wet and cold season (20.2%). We found that livestock decreases were more important with temperature for both dry and hot and wet and cold seasons. Interestingly, we found that precipitation mitigated temperature effects on livestock decrease for both seasons. Finally, we found that beekeepers practicing water supplementation had up to 10% less livestock decrease during the dry and hot season than those that did not, suggesting it to be a relevant adaptive strategy to mitigate livestock decrease. It is worth noting that beekeepers can renew their stock by trapping swarms, yet this represents a cost in time and baiting materials. Based on climate change projections, we predicted that annual and seasonal livestock decrease would remain in the same range at horizon 2050 and horizon 2100. These results pinpoint difficulties in maintaining livestock for beekeepers in Kenya and provide clues for strategies to pursue in the context of climate change.

## 1. Introduction

The Western honey bee (*Apis mellifera* L.) is a key managed pollinator species for agriculture worldwide (Garibaldi et al., 2017). Honey bees have an economic and cultural importance beyond their pollination services. The products of the hive, mainly honey but also pollen, royal jelly, beeswax and propolis are commercialized, and together with the bees themselves, constitute cultural and economic values for many communities (Potts et al., 2016). Nonetheless, in recent decades, beekeepers have suffered high honey bee colony mortality rates (Neumann and Carreck, 2010).

Monitoring programs were developed in response to worldwide concerns about the health of managed honey bees. These programs have implemented national and international colony loss surveys, particularly in North America and Europe. In the United States the program is coordinated by the Bee Informed Partnership (BIP) (vanEngelsdorp et al., 2008), in Canada by the Canadian Association of Professional Apiculturists (Currie et al., 2010; 'CAPA – Canadian Association of Professional Apiculturists'), and in Europe by the Prevention of honey bee Colony LOSSes association (COLOSS) (van der Zee et al., 2013). Moreover, there are programs in Asia (Tang et al., 2023), in Oceania (Brown et al., 2018) and in Latin America, this last being coordinated by the Latin American Society for Bee Research consortium (SOLATINA) (Requier et al., 2018, 2024). Data on managed honey bee colony losses

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in Africa are more scarce (Osterman et al., 2021). In the North African region, COLOSS has published data from Algeria since 2015 (Brodschneider et al., 2016, 2018; Gray et al., 2019, 2020, 2023) and more recently from Egypt in 2019 (Gray et al., 2023). Moreover, two studies on colony loss have been published for all Sub-Saharan Africa (SSA), based on a survey conducted in some regions of South Africa between 2009 and 2011 (Pirk et al., 2014) and the most recent one from Oromia and Tigray regions in Ethiopia between 2022 and 2023 (Hailu et al., 2024). In many African countries, beekeeping is still a traditional practice used mainly as a supplementary income activity (Dietemann et al., 2009; Frazier et al., 2024). Nevertheless, this practice represents an important livelihood diversification, contributing to poverty alleviation and food security (Carroll and Kinsella, 2013; Potts et al., 2016).

These monitoring programs, along with field studies, identified groups of risk factors affecting honey bee survival, such as beekeeping management and climate (Potts et al., 2010; Switanek et al., 2017; Kuchling et al., 2018; Steinhauer et al., 2018, 2021; Requier, 2019; De Jong and Lester, 2023). Even though climate has been identified as a risk factor, studies focusing on climatic effects on honey bee colony losses are scarce and limited to temperate regions (Zapata-Hernández et al., 2024). For example, studies from Austria and the Netherlands found a correlation between honey bee mortality and warmer and drier conditions in the previous year (Switanek et al., 2017; Yasrebi-de Kom et al., 2019). Other studies from northeastern United States found a negative followed by positive effect (unimodal relationship) of both precipitation and temperature on colony loss, meaning highest honey bee survival corresponded to intermediate values (Calovi et al., 2021). Unfortunately, the climate effects on honey bee mortality in the tropics are lacking, although climate is known to influence the survival of many species. For example, in SSA high ambient temperatures are associated with higher mortality of African wild dogs (Rabaiotti et al., 2021), and drought drives cattle population dynamics (Oba, 2001). Besides, the SSA region provides a wide diversity of climates to study, from semi-arid areas, characterized by their dryness and high ambient temperatures to more humid and cooler conditions in tropical areas.

In the context of global climate change, assessing the impact of temperature and precipitation on honey bees in tropical regions has become critical. The climate variability hypothesis suggests that increasing temperatures may disproportionately influence insects in these areas due to their potentially narrower thermal tolerance and closer proximity to optimal temperature ranges (Bozinovic et al., 2011; Deutsch et al., 2008). Consequently, it is assumed that warming trends in tropical regions could have more severe consequences for insects compared to temperate regions. Honey bees are found nearly globally, yet studies have found differences in heat tolerance between subspecies (Abou-Shaara et al., 2012). In this sense, the climate variability hypothesis could affect honey bees according to the genetic diversity and plasticity of each subspecies. As for precipitations, depending on the context some studies have found either positive or negative effects on honey bee survival, yet these studies have focused on weather rather than climate (Zapata-Hernández et al., 2024). Furthermore, projections of climate change indicate that tropical regions will experience the surge of novel climates while others will disappear (i.e. in tropical montane regions), endangering biodiversity hotspots and possibly affecting plant-pollinator interactions in which the honey bees have an important role (Williams et al., 2007; Settele et al., 2016; Cruz et al., 2022).

Several studies from tropical countries have focused on beekeepers' opinions of climate change effects on honey productivity. Among the strategies used to mitigate climate change effects, beekeepers may relocate their apiaries, plant trees to increase shade and provide supplementary feeding (Ukamaka and Eberechukwu, 2018; Degu et al., 2022; Landaverde et al., 2023). In SSA, beekeeping management tends to be passive (Frazier et al., 2024), yet one of the few active practices is to provide an artificial source of water.

Here, we carried out a survey to estimate annual and seasonal honey bee livestock decrease for the year 2021–2022 in Kenya and to explore the climate effects on honey bee survival in SSA. This country is the third largest honey producer in the East African region (Sagwa, 2021) and includes the diversity of landscapes and climates from the SSA region. Kenya has a bimodal rainfall regime, with a "short" rainy season between October and November, and a "long" one from the end of March to the end of May (Ayugi et al., 2016). The warmest period is around February and the coolest around August (Lawrence et al., 2023). To simplify the representation of seasonality, we divided the year into two seasons: hot and dry, and cold and wet. We first investigated the relationship between temperature, precipitation, and water supplementation to define the characterization of seasons and test climatic dependency to the water supplementation practice. Then, we examined if honey bee livestock decrease was influenced by temperature and precipitation. We defined "livestock decrease" from the beekeeper's perspective in the African context, including dead and absconded colonies, since both cases represent a decrease of a colony from the apiary, but not necessarily from the ecosystem. Absconding refers to a phenomenon in which a whole colony abandons its nest/hive upon short-term disturbance and relocates to a different site, this movement being possible for short or long distances (Seeley, 1985). Moreover, migration refers to a seasonally predictable phenomenon of absconding, not directly associated with reproduction, where colonies move to a new location looking for more favorable conditions (Hepburn and Radloff, 1998). We hypothesize higher livestock decrease with temperature and a decrease with precipitation. Moreover, we explored the interacting effects of temperature and precipitation to represent the climatic diversity (tropical humid to semi-arid areas) on honey bee livestock decrease. We also considered climate change projections to predict future trends in honey bee livestock decrease in the region related with global warming scenarios to horizon 2050 and horizon 2100. Finally, we explored whether water supplementation could reduce livestock decrease by mitigating the climatic pressures (i.e. lack of precipitation or heat stress).

## 2. Materials and methods

### 2.1. Survey of honey bee livestock decrease

We established a survey using a standardized questionnaire which follows those used by BIP and COLOSS and adapted it to specificities of Kenyan conditions and practices. The questionnaire was divided into two seasons: from October 1st, 2021 to March 31st, 2022 and from April 1st, 2022 to September 30th, 2022. The first season, from October to March represents a dry and hot season, while the second one from April to September represents a wet and cold season. The number of livestock decrease was not directly asked to the beekeepers to avoid bias. Each participant was invited to respond on the number of colonies: owned at the beginning of the season, owned at the end of the season, added within the season (purchased, obtained from trapping, obtained from splitting), and subtracted within the season (sold or given away as gifts). We also asked each participant for their home address and the mean distance between their home and their apiary (x distance) from a list of four categories ("Less than 1 km" ($\leq$1 km), "Between 1 and 5 km" ($1 < x \leq 5$), "Between 5 and 10 km" ($5 < x \leq 10$) and "More", this last option was open for them to indicate the distance). With this information, we computed a GPS location for each participant, as the mean distance between their home and apiary was within 10 km for 94% of participants. Finally, we directly asked them for each season whether they provided a supplementary water source (Yes/No answer type). The questionnaire was written in English with a Swahili translation underneath.

### 2.2. Survey dissemination and data collection

We obtained a research permit (NACOSTI/P/22/16,641) from the National Commission for Science, Technology & Innovation (NASCOTI) to conduct the survey. The first season (dry and hot) of the survey was conducted using a network-based participatory approach, leveraging local contacts and International Centre of Insect Physiology and Ecology (*icipe*) technicians who were familiar with the beekeeping community. These local coordinators, facilitated introductions and arranged visits to beekeepers' homes. This approach was chosen due to the absence of accessible beekeeper registries in Kenya. Additionally, beekeeping events such as International World Bee Day provided opportunities to involve more participants in the survey and encouraged those from associations to become local coordinators. Finally, beekeeping courses organized by the *icipe* in several Kenyan regions also provided facilities to interview more beekeepers. Face-to-face interviews were conducted using a paper version of the questionnaire from the end of April 2022 to August 2022. For the follow-up survey, which included the wet and cold season information, we contacted the participants from the dry and hot season via phone calls to interview them between the end of October 2022 up to the end of March 2023. Before each interview, participants were reminded that participation was voluntary (right of withdrawal at any time), that the information would be processed anonymously, and that data would be published in a database for strictly scientific use. We transcribed all data into a digital form. Some beekeepers did not participate in the wet and cold season survey, leading to different sample sizes between seasons.

### 2.3. Assessing honey bee livestock decrease

We used Steinhauer's technique (Steinhauer et al., 2014) to calculate the number of present and absent colonies for each season (dry and hot season: from October 1st to March 31st, wet and cold season from April 1st to September 30th, and annually). Responses with abnormal livestock decrease ($<0$ or $>100\%$) were not considered in our analysis, representing 4% and 1.7% of the collected data for the dry and hot and wet and cold season respectively. It is important to note that a "livestock decrease" includes the dead colonies like it is considered by BIP in the United States (vanEngelsdorp et al., 2008), COLOSS in Europe (van der Zee et al., 2013) and SOLATINA in Latin America (Requier et al., 2024), but also the absconded ones, which is more specific to tropical honey bees (Seeley, 1985). This absconding can be caused by direct disturbance or for migration (Hepburn and Radloff, 1998). From the perspective of a beekeeper, an absconded colony from the apiary represents a livestock decrease, which is why we included this case in our estimations.

### 2.4. Climatic variables

For our analysis, we focused on examining a climatic gradient at a biogeographic level. To achieve this, we used WorldClim version 2.1, a resource providing comprehensive climate data covering a 30-year period from 1970 to 2000, with a monthly value basis and a 2.5-min spatial resolution (about 4.5 km at the equator) (Fick and Hijmans, 2017). Using the GPS coordinates for each participant, we extracted two climatic variables: the monthly values of maximum temperature (in °C) and monthly values of precipitation (in mm). In the tropical context of Kenya, maximum temperatures could lead to heat stress in honey bees, thus are more likely to reflect climatic pressures than mean temperatures. We computed an average value for the maximum temperature (in °C) and a sum to obtain accumulated precipitation (in mm) for each season and annually. For the dry and hot season, we used the values from October to March, and for the wet and cold season the values from April to September. For simplification, we called our computed variables "temperature" and "precipitation" from now on.

### 2.5. Climate change projections

In order to explore future trends in climate-related livestock decrease in the face of climate change in Kenya, we extracted information of future climate projections from IPCC interactive atlas (Gutiérrez et al., 2021). We considered the second Shared Socio-economic Pathways (SSP2-4.5) scenario, which considers intermediate greenhouse gas emissions and current $CO_2$ emissions to keep stable until 2050 and selected the East African Region (considering both northern and southern East African sub-regions). The atlas provides climatic information in terms of change from a selected period, so we chose the most recent one available (from 1995 to 2014). We extracted the mean annual and seasonal (from October to March and from April to September) values of maximum temperature change (in °C) and total precipitation change (in %) for a medium term (2041–2060, called "horizon 2050") and long term (2081–2100, called "horizon 2100"). We used the extracted information of change to obtain projected values for temperature and precipitation in Kenya for both horizon 2050 and horizon 2100 (Table S1).

### 2.6. Statistical analysis

All analyses were performed using the following packages: "stats", "ggeffects" (Lüdecke, 2018), "broom" (Robinson et al., 2023), "spdep" (Bivand and Wong, 2018), and "geosphere"(Hijmans, 2022) in the statistical program R version 4.3.2 (R Core Team, 2023).

*Climatic gradient and water supplementation practice:* We used a linear model (LM) to test for the link between the response variable temperature and the fixed factors precipitation and water supplementation, plus their interaction. Separate models were built for each period: dry and hot season, wet and cold season and annually (as response variables).

*Honey bee livestock decrease:* We used a Generalized Linear Model (GLM) with quasibinomial distributed error to assess the effects of temperature and precipitation as fixed factors on livestock decrease (computed as a binomial response by comparing the number of present and absent colonies per beekeeper). We considered the interaction between temperature and precipitation. The single effect of water supplementation could be affected by the presence of natural water sources; as we did not have data on water sources nearby, we could not test this hypothesis. Thus, we focused on the triple interacting effect between temperature, precipitation, and water supplementation. Three separate models were built to represent livestock decrease for each season and annually. Residuals of the models were tested for spatial autocorrelation using Moran I test (for more details see Section S1). We estimated global seasonal and annual average livestock decrease by averaging the predicted values and their associated confidence intervals based on the outputs of the GLM model. Livestock decrease and its confidence interval were predicted using sequences of the minimum and maximum values for each variable included in the model.

*Projected livestock decrease in the context of climate change:* We used the GLM predictions of seasonal and annual livestock decrease (see above) to predict future trends in livestock decrease for horizon 2050 and horizon 2100 based on climate change projections (i.e. temperature and precipitation, Table S1) for the region (i.e. Kenya).

In our statistical analysis, each data point was treated as spatially independent, given that less than 1% (5 out of 589 total observations) of our data points shared a foraging area defined by a 4.5 km distance between two points. This threshold was chosen based on the average foraging distance of honey bees, which is approximately 1.5 km (Steffan-Dewenter and Kuhn, 2003), and to align with the spatial resolution of the climatic variables extracted. Additionally, we adjusted the p-values in all our models using the Benjamini & Hochberg method (Benjamini and Hochberg, 1995) to control the false discovery rate (FDR) as we tested multiple hypothesis on each model.

## 3. Results

### 3.1. Characterizing climate conditions and water supplementation distribution

On the objective to analyze the climatic gradient of our data and the potential climatic dependency of water supplementation practice, we found that our climatic gradient ranged from tropical (more humid and cooler areas) to semi-arid (drier and warmer areas). We also found no link between temperature and precipitation for any period considered (dry and hot, wet and cold season, and annually) (Table S2). By visually comparing the distribution of climatic conditions between seasons, we can validate our October to March season as dry and hot, while the one from April to September as wet and cold (Fig. 1A and B). We found no link between seasonal nor annual climatic variables (interaction between temperature and precipitation) and supplementing water (Table S2). However, water supplementation was positively associated with temperature for both seasons (FDR adjusted p-value = 0.029 and 0.008, respectively), which means that more beekeepers use this practice in warmer places (Fig. 1A and B).

### 3.2. Annual and seasonal livestock decrease

We obtained a total of 569 responses for the dry and hot season (corresponding from October 2021 to March 2022), 511 responses for the wet and cold season (from April to September 2022) and 495 responses with annual information. The beekeepers collectively managed a total of 10,707 colonies, with an average of 22 colonies per beekeeper, with a standard deviation of 43 colonies. Due to inaccessibility, Eastern and North Eastern regions were out of reach for data collection. The collected data include beekeepers from different regions of the country, encompassing different climatic zones (Fig. 1C). Beekeepers had on average a livestock decrease of 36.6% (95% CI: 29.5–44.6%) of their colonies between the beginning of October 2021 and the end of September 2022 (annually). During the dry and hot season, their livestock decreased by an average 31.9% (25–39.5%) of the colonies they managed during that period, while during the wet and cold season, their livestock decreased by an average 20.2% (14.2–28%).

### 3.3. Climate influences seasonal livestock decrease

We found similar climatic effects on livestock decrease in both seasons (Table S3). Livestock decrease increased with temperature (FDR adjusted p-value = 0.009 for the dry and hot season, and FDR adjusted p-value <0.001 for the wet and cold one), yet an interaction effect was found with precipitation (FDR adjusted p-value <0.001 for the dry and hot season, and FDR adjusted p-value = 0.002 for the wet and cold one), mitigating temperature effects on livestock decrease. In dry areas, where precipitation was minimal (196 mm for the dry and hot season, 113 mm for the wet and cold season), there is an increase in livestock decrease with temperature from 20.6% (12.7–31.4%) to 35.4% (28.03–43.5%) for the dry and hot (Fig. 2A) and from 5.6% (2.7–11.1%) to 38.7% (27.1–51.8%) for the wet and cold season (Fig. 2B). On the contrary, the previous trend was reversed for humid areas, where precipitation was maximum (1096 mm for the dry and hot season, 1280 mm for the wet and cold season). Livestock decrease in humid areas decreased with temperature from 76.3% (53.3–90.2%) to 8.11% (3.5–17.6%) for the dry and hot season (Fig. 2A) and went from 46.5% (19.4–86.7%) to 9.5% (3.7–22.6%) for the wet and cold season (Fig. 2B). For locations with intermediate precipitation (mean value for each season, 437 mm for the hot and dry season and 511 mm for the cold and wet season), we found a decrease in livestock decrease along temperature for the dry and hot season (from 33.8% (26.2–42.3) to 25% (20.5–30.1%) Fig. 2A), and an increase for the wet and cold season (from 12.9% (8.2–19.6%) to 25.5% (19.3–32.9%), Fig. 2B).

### 3.4. Water supplementation reduces climate impact on livestock decrease

Interestingly, our triple interaction between climatic variables and water supplementation was significant for the dry and hot season (Table S3). The patterns found for the triple interaction are very similar to those described above (Fig. 3). Overall, beekeepers who practice water supplementation had less livestock decrease than those who did not perform this practice for all climatic conditions (Fig. 3A–E). The impact of water supplementation on seasonal livestock decrease became more pronounced as precipitation levels increased. In areas with low precipitation (Fig. 3A and B), the difference in livestock decrease between beekeepers who supplemented water and those who did not was

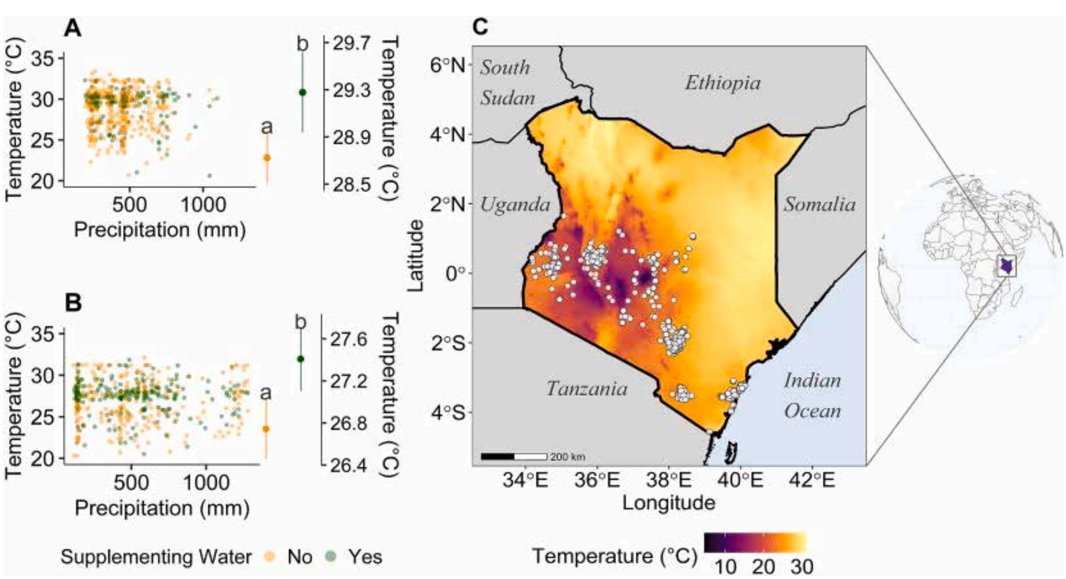


**Fig. 1.** Seasonal climate gradients of precipitation along temperature are presented for the dry and hot (A) and the wet and cold season (B). The colors in (A) and (B) distinguish the participants doing water supplementation (in green) from those who do not (orange). The predicted mean temperature for participants supplementing water (in green) or not (in orange) is shown on the right side of (A) and (B); lines represent the standard error and different lower-case letters indicate significant differences from the models. This shows more participants supplementing water in hotter areas (FDR adjusted p-value = 0.029 and 0.008, respectively). Spatial distribution of the data collection in Kenya is shown in (C). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

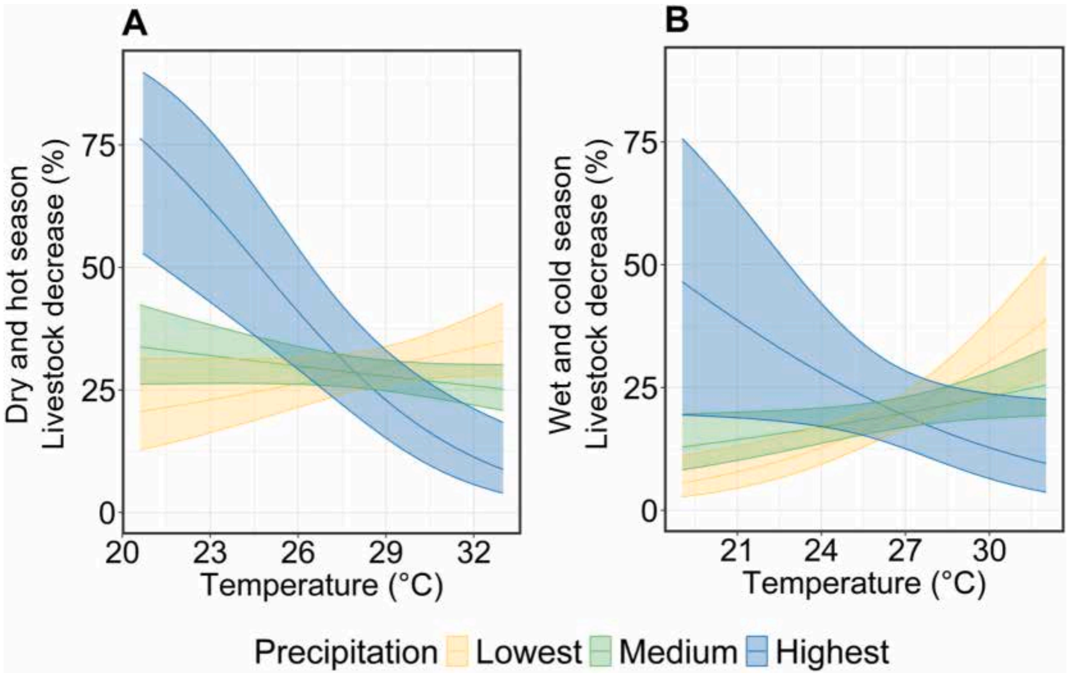


**Fig. 2.** Interacting effect between temperature and precipitation on livestock decrease for (A) the dry and hot season (n = 569, FDR adjusted p-value <0.001) and (B) the wet and cold season (n = 511, FDR adjusted p-value = 0.002). "Lowest" precipitation corresponds to 196 mm for the dry and hot season, 113 mm for the wet and cold season, "Medium" corresponds to 437 mm for the hot and dry season and 511 mm for the cold and wet season, and "Highest" corresponds to 1096 mm for the dry and hot season, 1280 mm for the wet and cold season. Thick lines show the model predictions with shaded areas indicating the 95% CI.

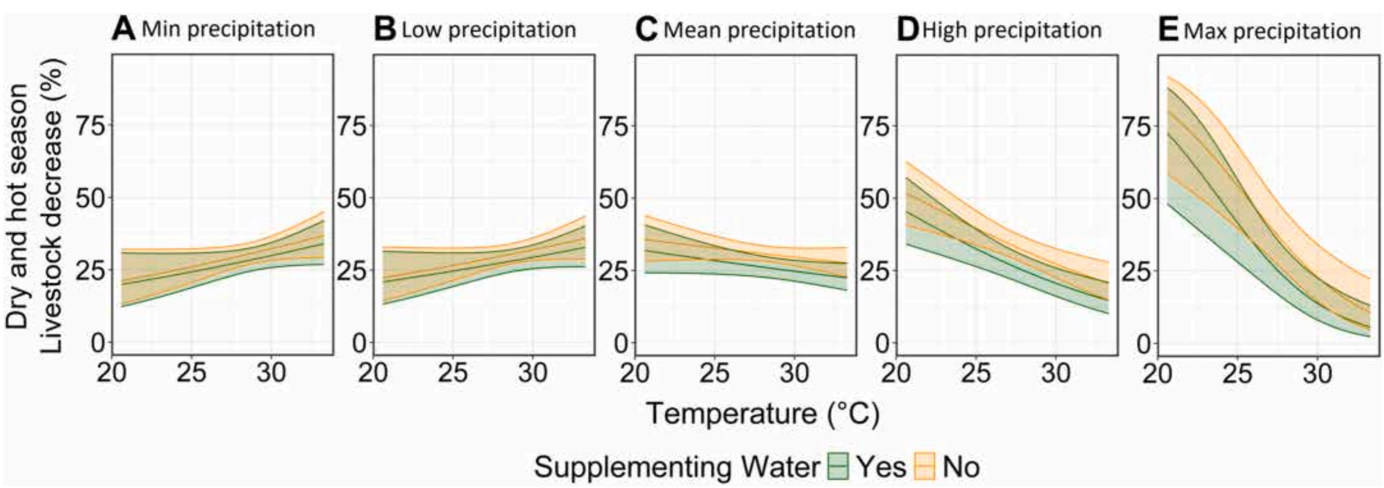


**Fig. 3.** Triple interaction effect between temperature, precipitation, and water supplementation on dry and hot season livestock decrease (n = 569, FDR adjusted p-value = 0.035). For illustration purposes, five arbitrary levels were used to represent the precipitation gradient. We used the "minimum" precipitation value within our dataset, "low" represents half of the average value, "mean" is the average value, "high" represents one and a half times the average value and finally the "maximum" value. Panels show livestock decrease predictions for the five precipitation levels (from the lowest to the highest) as follows: (A) minimum (196 mm), (B) low (218.5 mm), (C) mean (436.7 mm), (D) high (655.05 mm), and (E) maximum (1096 mm). Thick lines show the model predictions with shaded areas indicating the 95% CI.

around 2%. In regions with higher precipitation (Fig. 3C–E), this difference reached up to 10%.

### 3.5. Future projections related to climate change

According to climate change projections of temperature and precipitation for horizon 2050 and horizon 2100, we predicted that annual and seasonal livestock decrease in Kenya will stay overall within the 95% confidence interval of the current estimates. However, we estimated slight temporal trends. Livestock decrease for the dry and hot season is expected to decrease to 26.4% (23–30.1%) for horizon 2050 then to 25.4% (21.7–29.5%) for horizon 2100 (Table 1). As for the wet and cold season, livestock decrease will remain stable around 20% for horizon 2050 (21% [17.7–24.6%]) and horizon 2100 (21.7% [18–25.9%]) (Table 1). Finally, annual livestock decrease is expected to increase about 2% for horizon 2050 (38.3% [34.1–42.7%]) and stay stable for horizon 2100 (38.3% [33.6–43.3%]) (Table 1).

## 4. Discussion

In this study we estimated for the first time seasonal and annual livestock decrease of honey bees in Kenya and found important

**Table 1**
Predicted annual and seasonal livestock decrease related with climate change projections for horizon 2050 and horizon 2100 and compared with the current livestock decrease estimates. Estimates and confidence intervals are based on the outputs of the previously used models (Table S3) by using the projected temperature and precipitation data as input (Table S1).

| Period of colony loss | Current (2021–2022) | Horizon 2050 | Horizon 2100 |
|---|---|---|---|
| Dry and hot season (n = 569) | 31.9% (25–39.5%) | 26.4% (23–30.1%) | 25.4% (21.7–29.5%) |
| Wet and cold season (n = 511) | 20.2% (14.2–28%) | 21% (17.7–24.6%) | 21.7% (18–25.9%) |
| Annual (n = 495) | 36.6% (29.5–44.6%) | 38.3% (34.1–42.7%) | 38.3% (33.6–43.3%) |

decreases suggesting difficulties for Kenyan beekeepers in their practice. We found variability in livestock decrease rates, ranging from low to high, partially depending on temperature. As hypothesized, livestock decrease increased with temperature. This result is in accordance with findings in laboratory conditions where temperature had negative effects on the survival of worker bees (Abou-Shaara et al., 2012). Moreover, we found precipitation to mitigate temperature effects on livestock decrease. Previous studies have found reduced colony losses with wetter conditions (Switanek et al., 2017; Yasrebi-de Kom et al., 2019). Precipitation can be used as a proxy indicator of dryness and thus water availability, which is critical for colony survival. To avoid overheating their bodies, honey bees regurgitate water to lower their temperature (Kovac et al., 2007). To decrease the internal temperature of the hive and increase the internal relative humidity, foragers collect water (Bordier et al., 2017) and proceed with a process called evaporative cooling (Cooper et al., 1985; Mardan and Kevan, 2002; Stabentheiner et al., 2010). Thermoregulation inside the hive is essential to maintain survival of the brood, as high temperature decrease hatching rates and causes alterations of the body size and morphology of the resulting bees (Seeley, 1985; Abou-Shaara et al., 2017; Poot-Báez et al., 2020; Minaud et al., 2024).

Beekeeping in Kenya is mainly a traditional practice, with little intervention in the colonies. One of the few beekeeping practices consists of supplementing water. This practice was independent of precipitation but correlated with seasonal temperature. Participants beekeeping in warmer environments are more likely to supply water to their colonies. The interaction between water supplementation, temperature and precipitation was significant for the dry and hot season livestock decrease, where beekeepers supplementing with water had lower livestock decreases than those who did not. Our results confirm the importance of water availability during the dry season pointed out by other studies (Le Conte and Navajas, 2008), and are consistent with the water requirements of honey bees during warmer months to thermoregulate their body and the hive (Winston et al., 1983; Mardan and Kevan, 2002; Kovac et al., 2007; Stabentheiner et al., 2010). A study reported Kenyan beekeepers pointing out challenges on water availability for their colonies, and have related water scarcity to absconding during drought periods (Newman et al., 2021). During the wet and cold season, heat stress is reduced, and water availability is improved due to the seasonal conditions, explaining why there was no significant effect of the triple interaction between temperature, precipitation, and water supplementation on livestock decrease for this season. As it is recommended in other regions (Poot-Báez et al., 2020), we can advise Kenyan beekeepers to supplement their colonies with water in the dry and hot season, from October to March, to help reduce their livestock decrease. For future studies, it would be interesting to investigate whether practicing water supplementation is related to a specific beekeeping education or experience, as this practice could potentially reflect a certain level of education or experience.

We found seasonal variability in livestock decrease rates, with higher livestock decreases during the hot and dry season than during the wet and cold one. Both annual and seasonal livestock decreases (ranging between 20 and 40%) fall within the range of colony losses reported within the last decade in other regions like North America (vanEngelsdorp et al., 2008; Currie et al., 2010; Steinhauer et al., 2014; Lee et al., 2015; Seitz et al., 2015; Kulhanek et al., 2017; Aurell et al., 2023; Bruckner et al., 2023) and Europe (Brodschneider et al., 2016, 2018; Gray et al., 2019, 2020, 2023). Kenya having large semi-arid areas, our results are in accordance with findings from similar climatic regions, where colony losses mainly occur during the hottest months (Alattal and Alghamdi, 2015). Interestingly, the highest livestock decrease in both seasons was reached in cold and humid areas (minimum seasonal temperature and maximum precipitation values). These high rates could be linked to an elevated infestation of some pests triggered by wetter conditions, as found for small hive beetle in Nigeria (Akinwande and Neumann, 2018). Moreover, colder and wetter conditions could have a detrimental effect on honey bee activity by reducing both their foraging activity and pollen release from flowers as suggested by Joshi and Joshi (2010). This way, the overall colony's health could be reduced, limiting the chances of survival. Notably, Cheruiyot et al. (2020) observed decreased pollen storage levels to be related to absconding of African honey bees during the wet and cold season (specifically in July), supporting our results. Moreover, a causal link hypothesis may be that colder and wetter areas could reduce floral resources available during the hot and dry season, while the need in food reserve is higher in such areas to overcome the cold and wet season. The lowest livestock decrease during the dry and hot season was observed in hot and humid areas (maximum seasonal temperature and maximum precipitation values). This can be attributed to the role of water during the dry months. Conversely, during the wet and cold season, the lowest livestock decrease was observed in cold and dry areas (minimum seasonal temperature and minimum precipitation values). Foraging activity and pollen availability in dry areas are likely not significantly affected by seasonal precipitations.

African honey bees have different behavior compared to European subspecies, absconding being one of them. African honey bees tend to abscond and migrate in response to environmental pressures such as dry periods, insufficient floral resources, and nest disruptions (Hepburn and Radloff, 1998; Seeley, 1985; Frazier et al., 2024). That being noted, annual absconding rates for African honey bees range from 15 to 30% (Winston et al., 1983), corroborating our livestock decrease estimations. Migration has been defined as a seasonally predictable phenomenon of absconding, with reports of colonies moving to forests during the dry season and returning to open savannahs six months later in Kenya (Hepburn and Radloff, 1998). However, these movements are reported to be facultative, and colonies do not migrate every year (Hepburn and Radloff, 1998). We explored the hypothesis that our results on the increased livestock decrease during the dry and hot season could be attributed to migration, however, migration only cannot explain our estimations (for more details see Section S2). Thus, our findings suggest that the livestock decrease estimates we found are related to absconding (related to disturbances) and to mortality, as suggested by (Hepburn and Radloff, 1998). Assessing the relative contribution of absconding versus mortality could provide more insights to beekeepers on how to reduce livestock decrease, but would need specific field monitoring. Following the absconding, migration, and swarming periods, beekeepers can renew their livestock decrease within or between seasons by either multiplying the remaining colonies or by trapping swarms, which is the most common practice in the region (Dietemann et al., 2009). In Africa, wild honey bee colony density is much higher than in Europe (Requier et al., 2019), providing a high probability for the beekeepers to be able to renew their stock. Nonetheless, renewing livestock decrease represents a cost in time and baiting materials that poses a danger to the sustainability of the beekeeping sector.

Furthermore, a key difference in conducting a participatory questionnaire between developing and developed countries lies in the challenges associated with data collection. In developing countries, face-to-face interviews are essential due to difficulties like limited internet access, in contrast to the practicality of using web-based surveys in more developed countries (Requier et al., 2020). Our efforts with face-to-face interviews resulted in 569 and 511 responses for each season respectively. Our responses go from the coast, going through semi-arid areas and up to the tropical forest, including lowlands and highlands, providing a good representation of climates and landscapes used by beekeepers in Kenya. Within the African region, colony loss surveys have reached 48 participants in South Africa (Pirk et al., 2014), 106 participants in Egypt (Gray et al., 2023), and a maximum of 197 participants in Algeria (Gray et al., 2023) per year. This means that our study represents the largest data set on managed honey bees in the African region.

In the East African region, including Kenya, climate change projections indicate an increase in average temperatures and frequency and intensity of extreme heat events. Predictions also suggest an overall increase in precipitations, with a surge on heavy precipitation and pluvial flood events. The projected changes in temperature and precipitation are expected to result in drying trends in western portions of the East African region, while eastern regions are likely to become wetter (Intergovernmental Panel On Climate Change, 2023). These projections will have direct and indirect impacts on honey bees and their management practices. Beekeepers are already adapting their practices in different parts of the world (Malisa and Yanda, 2016; Degu et al., 2022; Landaverde et al., 2023). Our predictions indicate that current annual and seasonal livestock decrease rates are likely to persist through both 2050 and 2100 horizon, pointing to continuing challenges for Kenyan beekeepers in maintaining their managed colonies in the future. It would also be important to incorporate other factors such as land use (Archer et al., 2014; Newman et al., 2021; Ochungo et al., 2022) and pest and diseases (Pirk et al., 2015) in future models, as they are all related and affected by these climatic changes. Studies have predicted higher habitat suitability of pests like small hive beetles and great wax moths, potentiating their spread along the country (Cornelissen et al., 2019; Hosni et al., 2022), revealing again the importance of considering these variables. Understanding factors involved in honey bee livestock decrease in the tropics can help improve bee health and move forward sustainable beekeeping for the livelihood of beekeeping-dependent communities.

## 5. Conclusions

The findings of our study suggest that honey bee livestock decreases in Kenya are influenced by climatic factors, with precipitation mitigating the temperature-induced livestock decreases. Moreover, we found that providing supplementary water during the dry and hot season could reduce livestock decrease. Finally, our predictions of livestock decrease, both present and projected in the context of climate change, pinpoint difficulties for Kenyan beekeepers to maintain their colonies. This study highlights the need for further research on bee health in Africa.

## CRediT authorship contribution statement

**Malena Sibaja Leyton:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **H. Michael G. Lattorff:** Writing – review & editing, Supervision, Methodology. **Nkoba Kiatoko:** Writing – review & editing, Supervision, Resources. **Fabrice Requier:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

## Disclosure statement

The authors reported no potential conflict of interest.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123879.

## Data availability

The data presented in this manuscript are openly available in the *figshare* repository at: https://doi.org/10.6084/m9.figshare.25633866.v1 (Sibaja Leyton et al., 2024).

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