Climate-smart apiary site selection in East Africa: GIS-based analysis of current and future climate projections

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Abstract

Purpose – This study aims to evaluate beekeeping as a sustainable strategy to enhance resilience in East African agriculture by improving food security, livelihoods and pollination services. Using GIS-based analysis, it identifies climate-smart apiary sites, assesses current suitability and forecasts future conditions to support sustainable practices and climate adaptation.

Design/methodology/approach – This study sought to improve the robustness and adaptability of apiary site selection in Yabelo, Ethiopia and Taita-Taveta County, Kenya by using fuzzy Multicriteria Decision-Making methods under current climate and future low emission (SSP1-2.6) and high emission (SSP1-2.6) Shared Socioeconomic Pathways. By integrating these future climate scenarios, the authors assessed the future suitability of the apiary area under changing climate conditions.

Findings – The results revealed that under current climate conditions, 40.2% of the Yabelo area is highly suitable for beekeeping, with 43.6% and 16.2% being moderately and less suitable areas, respectively. On the other hand, Taita-Taveta County had higher current suitability, with 54.9% classified as highly suitable, 34.0% as moderately suitable and 11.2% as less suitable. Under SSP1-2.6 and SSP5-8.5 scenarios, highly suitable areas had a decreasing trend in both sites, whereas moderately and less suitable areas exhibited an increasing trend, reflecting the impact of climate change on apiary site variability. Despite these trends, Taita-Taveta County exhibited higher overall suitability than Yabelo. By anticipating future climate conditions, this study emphasized the importance of integrating climate projection into suitability analysis to ensure the long-term variability and resilience of beekeeping operations in East Africa.

Practical implications – This study highlights the role of beekeeping as a climate-resilient strategy to enhance livelihoods and food security in East Africa. Integrating climate projections allows policymakers to prioritize beekeeping through adaptive agricultural policies, while refined site selection methods help identify climate-suitable apiary locations. Targeted support for moderately suitable areas, along with broader adaptation strategies, will help sustain productivity and resilience in climate-sensitive regions, promoting long-term rural sustainability.

Conflict of interest: To maintain the integrity and impartiality of the review process, the authors wish to disclose that a conflict of interest has arisen involving the editor assigned to this manuscript and the authorship team.

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Originality/value – The manuscript was prepared based on the primary data and hence, it provides fresh insights.

Keywords Beekeeping, Suitability, Fuzzy, Resilience, Scenarios, Adaptability

Paper type Research paper

1. Introduction

East Africa is vulnerable to climate change, as this region is highly dependent on agriculture, which is already affected by rising temperatures and fluctuating rainfall (IPCC, 2014; Leal Filho *et al.*, 2017; Natamba *et al.*, 2018; Souverijns *et al.*, 2016). This vulnerability is expected to increase as surface temperatures continue to rise. This will require not only mitigation measures but also adaptations to maintain food and nutrition security. Food achievement is not possible without access to income, and beekeeping is a recognized best practice for improving livelihoods among poor farming communities (Prodanović *et al.*, 2024).

Beekeeping is a valuable practice for the livelihood diversity of agro-pastoral communities, as it provides sustainable low-cost income to support traditional agro-pastoral activities and playing an important role in crop development via pollinators living in woody landscapes, which increase overall agricultural productivity (Prodanović *et al.*, 2024). Having apiaries requires less land and resources, which makes it more convenient even for smaller farms. Apiaries also promote environmental protection by encouraging the conservation of natural habitats, which are important for healthy bee populations (Hilmi *et al.*, 2011).

As demand for honey and other bee-related products continues to increase, sustainable and strategic site selection for apiaries is important (Sari *et al.*, 2020). Traditional apiary site selection relies on experiential knowledge of beekeepers, who consider factors such as presence of flowering plants, proximity to water sources and protection from harsh weather conditions. While this traditional approach is valuable, it can be limited by subjective biases and the inability to assess larger-scale environmental changes or the suitability of more distant locations (Komasilova *et al.*, 2020). In contrast, Geographic Information Systems (GIS) allow analysis of extensive spatial data, including vegetation cover, land use, climate patterns and topography for more objective apiary site selection (Fotso Kamga *et al.*, 2024; Tennakoon *et al.*, 2023; Zoccali *et al.*, 2017). GIS-based site selection can lead to more strategically located apiaries that maximize honey production and pollination efficiency while minimizing risks, thereby improving the sustainability and productivity of beekeeping operations. Fuzzy Multicriteria Decision-Making (MCDM) techniques provide a robust framework for integrating multiple criteria and accommodating uncertainty in decision-making (Tennakoon *et al.*, 2023).

Climate change introduces significant uncertainty, affecting the long-term suitability of apiary sites by altering the availability of floral resources, water sources and suitable habitats for bees (Gallardo-López *et al.*, 2021). Traditional methods of site selection often rely on local knowledge and static environmental assessments, which may not fully account for the dynamic and unpredictable nature of climate change. In contrast, modern approaches, such as GIS and fuzzy Multicriteria Decision-Making (MCDM), provide tools to incorporate complex data sets and future climate projections, bridging critical gaps in traditional methods.

The variability of temperature and precipitation due to climate change poses considerable challenges for beekeepers, who must adapt to evolving conditions that can impact honey production and colony health. Shared Socioeconomic Pathways (SSPs) offer a framework to analyze how various greenhouse gas emission trajectories influence future conditions. For instance, SSP1-2.6 represents a low-emission scenario where aggressive mitigation strategies limit global warming, leading to less severe ecosystem disruptions and more stable environmental conditions for apiaries. Conversely, SSP5-8.5 describes a high-emission scenario with minimal mitigation, resulting in significant temperature increases and extreme weather events that may drastically alter habitats and reduce the viability of traditional apiary sites (IPCC, 2021). Each scenario profoundly impacts key environmental variables critical to apiary site selection, such as forage plant availability, water resources and protection from extreme weather. This underscores the necessity of climate-informed planning and management in beekeeping activities to ensure long-term sustainability (Gebremedhn *et al.*, 2024).

Apiary site selection can offer a more comprehensive perspective when traditional knowledge is integrated with GIS and fuzzy MCDM methodologies. This combined approach is vital for advancing site selection processes, enhancing resilience, supporting ecosystem stability and fostering sustainable beekeeping practices in the face of climate change uncertainties. Given security risks, the primary focus of this study was the application of fuzzy MCDM techniques for apiary site selection under current climate conditions and future scenarios (SSP1-2.6 and SSP5-8.5) in Yabelo, Ethiopia and Taita-Taveta County, Kenya. The study also sought to identify key factors influencing apiary site selection, evaluate current site suitability in these regions and assess the potential impacts of climate change scenarios on apiary viability.

2. Material and methods

2.1 Study area

The study was conducted in Yabelo, the Borena Zone of the Oromia regional states, in southern Ethiopia and Taita-Taveta County (TTC), Kenya (Figure 1). Elevation in Yabelo

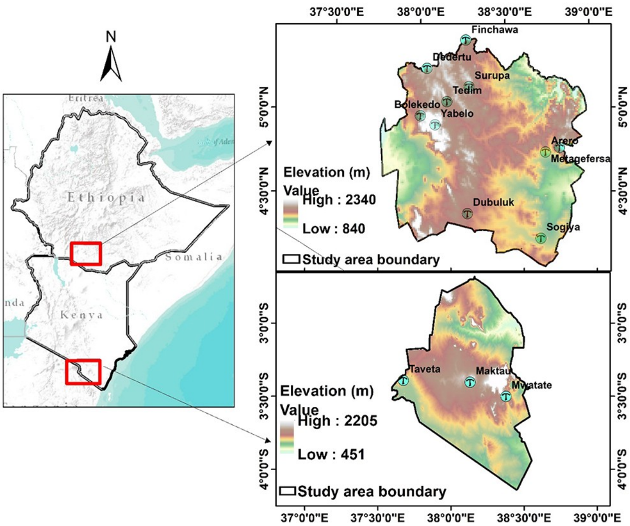

Figure 1. Location map of the study area
Note(s): (a) Yabelo and (b) Taita-Taveta County
Source: Authors' own creation

ranges from 840 to 2,340 m above sea level. The area exhibits a bimodal precipitation pattern, with long rains between March and May and short rains between September and November. Average temperature varies from 17°C to 25°C with mean annual rainfall from 410 to 820 mm. The Borana plateau is dominated by savannah vegetation, with both woody and herbaceous vegetation. Common tree species include *Acacia* spp., *Commiphora* spp., *Combretum* spp., *Cordia Africana*, *Terminalia* spp., *Aspilia* spp., *Albizia* spp., *Juniperus procera*, *Rhus* spp., *Boswellia* spp. and *Balanites aegyptica*. Grasses and leguminous plant species include *Andropogon gayanus*, *Hyparrhenia* spp., *Panicum* spp., *Crotalaria* spp., *Indigofera* spp., *Tephorsia* spp. and *Psoralea plicata*, which are used as animal forage and may also be used by honey bees (Addi *et al.*, 2014; Bareke and Addi, 2019b).

TTC is located in southern Kenya. We selected three subcounties within TTC, Wundanyi, Taveta and Mwatate, to provide a comprehensive analysis of apiary site suitability under current and future climate scenarios. The area has varied rainfall and topography, with lower elevation zones receiving an average 440 mm of rain annually and highland areas receiving up to 1,500 mm annually. The county ranges in altitude from 450 to 2,205 m above sea level, with Mt. Vuria being the highest point. The Taita Hills, situated within Kenya's Eastern Arc Mountains, are characterized by high population density, leading to widespread agricultural and agroforestry activities. These land use practices have driven extensive deforestation throughout, especially in the hills. Consequently, the once continuous forest cover has been significantly reduced, leaving behind only small, isolated patches of forest. These remaining fragments are predominantly found at higher elevations near the mountain tops (Pellikka *et al.*, 2013). The Taita Hills are home to a diverse array of native plant species, such as *Tabernaemontana stapfiana, Macaranga capensis, Oxyanthus speciosus* and *Phoenix reclinata* and *Celtis Africana.* Nonnative species, such as *Eucalyptus spp., Pinus patula, Cupressus lusitanica* and *Acacia mearnsii*, surround the montane forests (Amara *et al.*, 2023).

The Taita Hills lowlands are situated within the extensive Tsavo ecosystem. This ecosystem includes key conservation areas, such as the Taita Hills Wildlife Sanctuary (THWS) and the LUMO Community Wildlife Sanctuary, both of which are crucial for maintaining large populations of livestock and wildlife. THWS is also notable for riverine forests, which provide essential habitats and support diverse species. Conversely, the areas outside these protected zones are predominantly used for dryland agriculture, sisal plantations (Vuorinne *et al.*, 2021), livestock management (Wachiye *et al.*, 2020) or are covered by Acacia-Commiphora bushland and thickets (Abera *et al.*, 2023; Amara *et al.*, 2023).

The study sites in Yabelo, Ethiopia and Taita-Taveta County (TTC), Kenya, offer favorable conditions for beekeeping, which supports community livelihoods and resilience. Yabelo's savannah ecosystem, with diverse flora and moderate rainfall (410–820 mm annually), supports bee foraging and complements livestock livelihoods. Beekeeping diversifies income, mitigates climate impacts and promotes biodiversity. In TTC, varied rainfall (440–1,500 mm annually) and rich plant species provide ample forage, with diverse topography supporting local agriculture and conservation, making beekeeping a viable livelihood. Beekeeping boosts income diversification, food security through pollination and ecological resilience by supporting biodiversity. The involvement of local, refugee and pastoralist communities promotes social cohesion. By integrating GIS, fuzzy MCDM and traditional knowledge, this study identifies climate-smart apiary sites, ensuring the sustainability of beekeeping and enhancing community resilience to climate change.

2.2 Criteria and data sources for apiary site selection

Defining environmental, meteorological and topographic requirements is crucial for identifying landscapes suitable for apiaries. This phase involves consulting the expertise of bee specialists, experienced beekeepers and local knowledge to ensure that the chosen sites will support effective beekeeping activities and maximize productivity (Fotso Kamga *et al.*, 2024). Effective site selection relies on criteria and data based on proven beekeeping practices. We used nine specific criteria to analyze suitability, namely, forage sources, temperature, precipitation, distance from water sources, distance from roads, elevation, slope, aspect and wind speed. By considering these criteria, we wanted to identify the most conducive environments for sustainable and productive beekeeping operations. Data sources for different criteria are listed in Table 1 and visualized in Figures 2 and 3.

Food sources are important for bee health and productivity, as they provide pollen essential for honey production (Leponiemi *et al.*, 2023). Forage availability and quality directly affect bee colony fitness and survival. A varied and abundant diet ensures that bees can have a balanced diet, which is essential for immune system function and lifespan. Plants bloom at different times of the year, providing a constant supply of resources and reducing the risk of food shortages (Pande and GI, 2018; Ricigliano *et al.*, 2019; Parreño *et al.*, 2022). The bee forage significantly influences the quality, type and quantity of honey produced. Accordingly, certain forage criteria should be given more weight than others. For pollen and nectar sources, beekeepers prefer a variety of landscapes, like forests, bushlands and shrublands. Grasslands are important for certain wildflowers that bloom at different times, providing seasonal resources for bees. In addition, croplands with flowering crops provide essential foraging resources, such as nectar and pollen, which bees need to survive or to produce honey (Sari *et al.*, 2020).

Temperature is the most important predictor of bee behavior and overall health. Bees are ectothermic animals, whose body temperature and metabolic processes are greatly influenced by external temperatures. An optimal temperature range is essential for various bee activities, including foraging, brood rearing and hive maintenance (Clarke and Robert, 2018; Gebremedhn *et al.*, 2024; Mishra *et al.*, 2023; Simioni *et al.*, 2015). Increasing temperature affects the internal dynamics of the bee colony by decreasing the number of bees inside, thereby reducing the overall bee density. This decline in bee density can hinder the colony's ability to perform essential functions, which ultimately threatens the stability and sustainability of the bee population (Chabert *et al.*, 2021; Karbassioon *et al.*, 2023).

Table 1. Data sources for apiary suitability analysis

Criteria	Data type and resolution	Source
Elevation	Raster (30 m x 30 m)	SRTM-DEM
Aspect	Raster (30 m x 30 m)	SRTM-DEM
Slope	Raster (30 m x 30 m)	SRTM-DEM
Water source	Vector	Geoportal.rcmrd.org for river network and ministry of water and energy of Ethiopia for water points
Road	Vector	Geoportal.rcmrd.org
LULC	Raster (10 m x10 m)	Mengistu *et al.* (2024) (Yabelo) and Abera *et al.* (2023) (Taita-Taveta)
Precipitation	Raster (1 km x 1 km)	Worldclim.org (Fick and Hijmans, 2017)
Temperature	Raster (1 km x 1 km)	Worldclim.org (Fick and Hijmans, 2017)
Wind speed	Raster (1 km x 1 km)	Worldclim.org (Fick and Hijmans, 2017)

Source(s): Authors' own creation

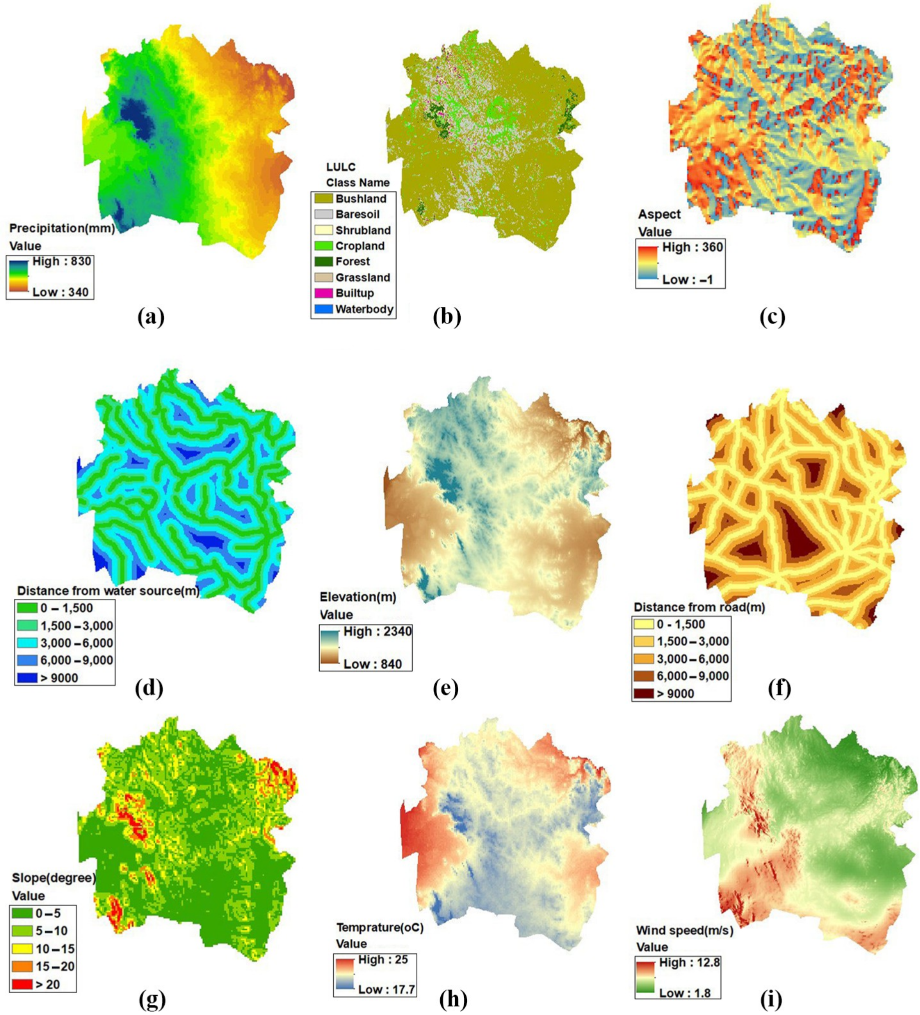

Figure 2. Criteria map of Yabelo

Note(s): (a) Precipitation; (b) forage source; (c) aspect; (d) distance from water resources; (e) elevation; (f) distance from roads; (g) slope; (h) temperature and (i) wind speed

Source: Authors' own creation

Precipitation plays an important role in determining the suitability of an area for beekeeping. Effective rainfall distribution is essential for growth of pollinators and pollinator food plants. Regular rainfall ensures a steady supply of floral resources, which is critical for sustaining bee populations and maintaining high honey production (Gebremedhn *et al.*, 2024; Mishra *et al.*, 2023). Excessive rainfall can reduce soil fertility and flowers, reducing nutrient availability (Kim *et al.*, 2024). It can also increase the wetness of marshland, causing

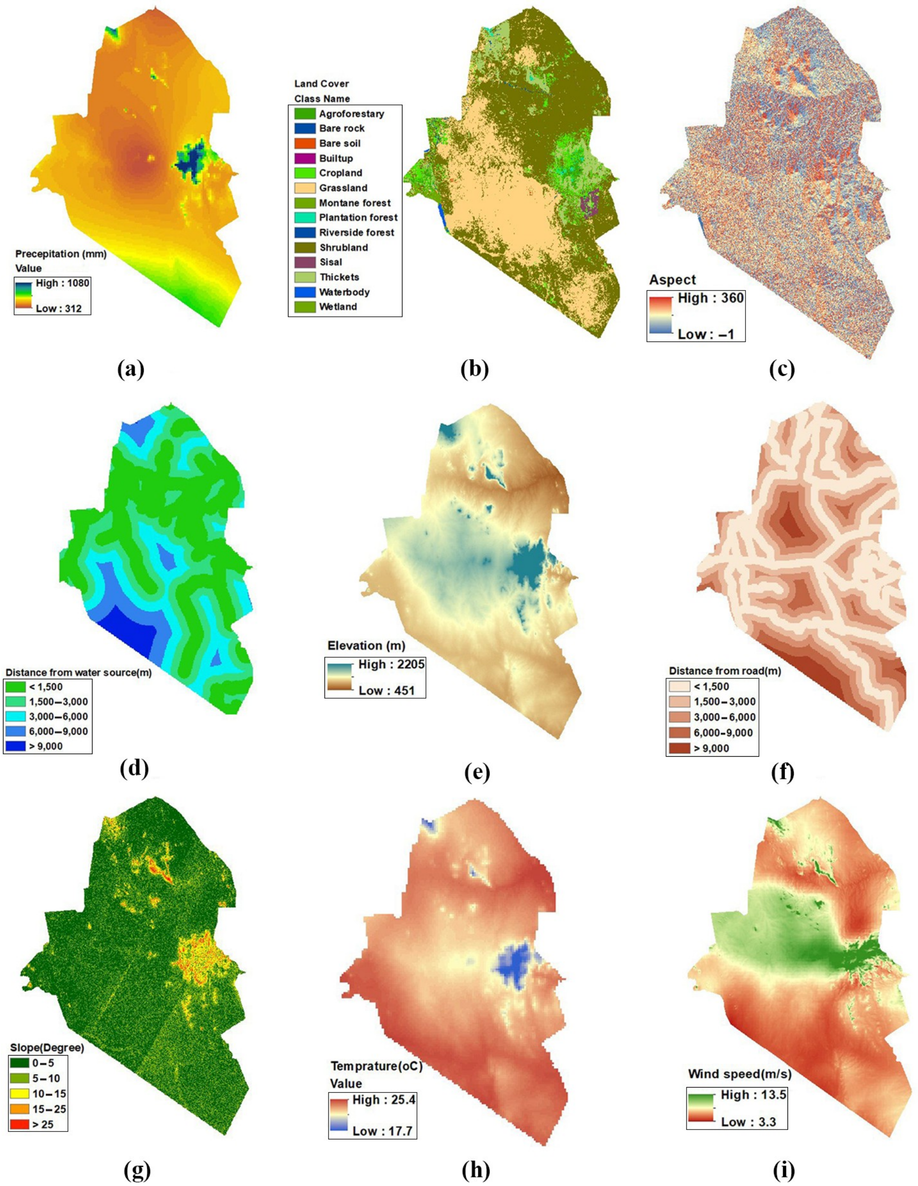

Figure 3. Criteria map of Taita-Taveta

Note(s): (a) Precipitation; (b) forage source; (c) aspect; (d) distance from water resources; (e) elevation; (f) distance from roads; (g) slope; (h) temperature and (i) wind speed

Source: Authors' own creation

favorable conditions for mold growth and spread of insect diseases (Mishra *et al.*, 2023). On the other hand, insufficient rainfall may lead to drought, reducing the number and diversity of food plants and disturbing honey bee colonies due to lack of resources (Frazier *et al.*, 2024).

Windspeed can significantly impact foraging behavior and efficiency. Strong wind makes flight more difficult for bees, increasing energy expenditure and reducing food intake efficiency. In strong wind, bees struggle to navigate and remain stable, which can prevent them from finding and collecting nectar and pollen (Hennessy *et al.*, 2020). Wind may present additional difficulties for bees, as they conduct numerous short flights between specific flowers or inflorescences, for example visiting between 250 and 1,446 flowers every trip. Foraging time can be increased exponentially even by a minor increase in the time required to travel between and to land on flowers due to wind-induced delays (Couvillon *et al.*, 2015).

Elevation above sea level and land surface play a crucial role in determining suitable locations for beehives. Temperature variations, microclimate conditions, forage availability, wind exposure, water sources and pest management factors associated with different elevations (Olliff-Yang and Ackerly, 2020; Tian, 2016; Zoccali *et al.*, 2017).

Slope and aspect also have significant implications for beehive location and management in beekeeping. Drainage, stability, sun exposure, wind protection, accessibility and erosion control factors associated with slope gradients (Marnasidis *et al.*, 2021; Doherty *et al.*, 2021).

The distance from the road to beehive locations is a critical factor in beekeeping operations, impacting hive disturbance, safety and accessibility (Dietzel *et al.*, 2023). Choose hive locations that strike a balance between road distance and accessibility, ensuring ease of transportation, equipment access and routine inspections while minimizing traffic-related disturbances (Bond *et al.*, 2021).

Proximity to water sources improves foraging efficiency and productivity, supporting healthy bee colonies and increasing honey yields. Streams, rivers and dams are considered water sources. An adequate supply of water is necessary for beekeeping so that bees can maintain suitable hive temperature and produce honey efficiently (Dietzel *et al.*, 2023).

2.3 Fuzzy analytic hierarchy process

Land suitability analyses frequently use multicriteria decision analysis (MCDA), which can handle several criteria and produce decisions based on human judgment. Many factors, such as the ecological demands of bees and the requirements for apiary management, must be considered (Tennakoon *et al.*, 2023; Fotso Kamga *et al.*, 2024; Gebremedhn *et al.*, 2024).

Fuzzy Analytic Hierarchy Process (AHP) methods are extensions of the traditional AHP technique that incorporate fuzzy logic to handle uncertainty and vagueness in decision-making (Alaqeel and Suryanarayanan, 2018; Liu *et al.*, 2020). Fuzzy AHP methods add another layer of flexibility by allowing decision-makers to express preferences in a more nuanced way. Similar to traditional AHP, the decision problem is structured hierarchically, with the main goal at the top, criteria in the middle and alternatives at the bottom (Sarkar *et al.*, 2022). However, in fuzzy AHP, the linguistic terms or fuzzy numbers are used to represent the judgments of decision-makers about the importance of criteria and the performance of alternatives (Liu *et al.*, 2020; Tennakoon *et al.*, 2023). This research uses fuzzy AHP that integrates fuzzy logic with basic AHP. The advantages of both AHP and fuzzy logic are combined in this integrated method, which can handle the imprecision associated with conventional AHP, particularly when decisions are made under uncertainty (Nuhu *et al.*, 2022; Tennakoon *et al.*, 2023).

The pairwise comparison matrix was prepared using linguistics developed by Tennakoon *et al.* (2023) (Table 2). Fuzzy AHP can translate linguistic terms into Triangular Fuzzy Numbers (TFN) (Chang, 1996; Zamani-Sabzi *et al.*, 2016; Sarkar *et al.*, 2022), which is

Table 2. Linguistic variable for pairwise comparison of each criterion

Linguistic variable	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equally strong	(1,1,1)	(1,1,1)
Moderately strong	(2,3,4)	(1/4,1/3,1/2)
Strong	(4,5,6)	(1/6,1/5,1/4)
Very strong	(6,7,8)	(1/8,1/7,1/6)
Extremely strong	(9,9,9)	(1/9,1/9,1/9)
Intermediate values	(1,2,3)	(1/3,1/2,1)
	(3,4,5)	(1/5,1/4,1/3)
	(5,6,7)	(1/7,1/6,1/5)
	(7,8,9)	(1/9,1/8,1/7)

Source(s): Adapted from Tennakoon *et al.* (2023)

known as fuzzification. TFN consists of three integers that includes the smallest possible value, the most probable value and the largest possible value [Equation (1)] (Sarkar *et al.*, 2022). The inverse of a TFN is used when the relative importance of criterion "j" over criterion "i" is expressed [Equation (2)] (Wang and Chen, 2008):

$$\text{A TFN A is denoted as } A = (l, m, u) \tag{1}$$

$$\text{The inverse of that TFN } (A)^{-1} = (l, m, u)^{-1} = (1/l, 1/m, 1/u) \tag{2}$$

In the present study, a geometric mean method introduced by Buckley (1985) was used to calculate the fuzzy weight of each criterion [Equation (3)].

The fuzzy geometric mean value r_i for each criterion n^{th} is computed as:

$$r_i = (l_1 * l_2 * \ldots l_n,\ m_1 * m_2 * \ldots m_n,\ u_1 * u_2 * \ldots u_n)^{1/n} \tag{3}$$

where l_n, m_n and u_n are the smallest possible value, the most probable value and the largest possible value of the n^{th} criterion (such as, forage source, distance from water source and precipitation), respectively, and n is the number of criteria.

The fuzzy weight w_i for each criterion i is calculated as:

$$w_i = r_i * (r_1 + r_2 + \ldots + r_n)^{-1} \tag{4}$$

where r_i is the fuzzy geometric mean value of the i^{th} criterion.

Once the pairwise comparisons are made, the fuzzy judgments are aggregated to derive the overall priority or ranking of criteria and alternatives. This often involves defuzzification, which is the process of converting fuzzy sets into crisp values. The most common method of defuzzification is the center of area (CoA) method [Equation (5)] (Buckley, 1985). The fuzzy weights $w_i = (l_i, m_i, u_i)$ are defuzzified by any defuzzification method; here we used the CoA method as follows:

$$\text{Weight of a criterion as a crisp numerical value} = \frac{li + mi + ni}{3} \tag{5}$$

The weight of every criterion is normalized by dividing each weight by the summation of weights.

The vector layers were converted into raster format and subsequently resampled to a uniform 30 x 30 m resolution, ensuring consistency across layers for effective overlay analysis using ArcGIS 10.8 software. The Fuzzy Analytic Hierarchy Process (Fuzzy AHP) calculations were performed using MS Excel.

The main criteria represent factors influencing honey bee habitat suitability, with assigned weights indicating their relative importance in the assessment process (Table 3). In addition to the main criteria, their corresponding weights, subcriteria and suitability values for evaluating honey bee habitat suitability, several subcriteria are listed, each with assigned suitability values (highly, moderately or less) indicating the suitability of the habitat based on that specific criterion.

2.4 Apiary site selection analysis under future climate change scenarios

Future land suitability assessment aims to evaluate land suitability for sustainable honey production in the future. Assuming consistent forest management over time, the focus is on evaluating the impact of future climate change on beekeeping. Various methods exist for projecting climate change impacts on honey bees, given the challenge of integrating local-scale

Table 3. Weights of main criteria and Subcriteria

Main criteria	Weight	Subcriteria	Suitability value
Forage source	28	Forest, bushland, thickets and shrubland	Highly
		Grassland	Moderately
		Cropland	Less
Distance from water source (m)	22	<1,000	Highly
		1,000–3,000	Moderately
		>3,000	Less
Distance from road (m)	4	<1,000	Highly
		1,000–3,000	Moderately
		>3,000	Less
Elevation (m)	9	898–1,400	Highly
		1,400–1,800	Moderately
		1,800–2,300	Less
Aspect	9	Flat, North, Northeast and East	Highly
		Southwest, West and Northwest	Moderately
		South	Less
Slope (°)	9	0–10	Highly
		10–20	Moderately
		20–35	Less
Precipitation (mm)	11	1,100–500	Highly
		500–300	Moderately
		300–100	Less
Temperature (°C)	4	15–21	Highly
		21–25	Moderately
		25–29	Less
Wind speed (m/s)	4	1–4	Highly
		4–8	Moderately
		8–13	Less

Source(s): Authors' own creation

models with coarse GCM projections. Most impact models require high-resolution climate data, especially temperature and precipitation (Navarro-Racines *et al.*, 2020).

We used climatic variables, such as rainfall and temperature, from the WorldClim database (www.worldclim.org), which provides historical and future data on rainfall, temperature and other climatic variables. These data are based on the Coupled Model Intercomparison Project Phase 6 (CMIP6) Shared Socioeconomic Pathways (SSPs) projections. The database offers high spatial resolutions, which allow for detailed and precise climate modeling. By using WorldClim version 2.1 with a 30-s spatial resolution, the analysis can capture small-scale climatic variations crucial for assessing habitat suitability for beekeeping.

The model was configured to cover two future prediction periods (2021–2040 and 2061–2080). The inclusion of two distinct periods allows for analysis of both short-term and long-term climate impacts on beekeeping suitability. For future projections, the study focused on two SSP scenarios: SSP1-2.6 and SSP5-8.5. SSP1-2.6 represents a low-emission scenario, aiming to keep global warming well below 2°C above pre-industrial levels, reflecting a world with strong climate policies and sustainable practices. In contrast, SSP5-8.5 is an extreme emission scenario, assuming continued high greenhouse gas emissions and resulting in significant global warming (IPCC, 2021). This dual approach allows for an analysis of how different emission trajectories might affect beekeeping suitability.

To ensure reliable projections, the study selected three general circulation models (GCMs) known for their performance in East Africa (CMCC-ESM2, HadGEM3-GC31-LL, MPI-ESM1-2-HR) (Table 4). These models were chosen based on their ability to accurately simulate climatic conditions in the region (Kogo *et al.*, 2019; Yebeyen *et al.*, 2022; Jimma *et al.*, 2024). By using multiple GCMs, the study incorporates a range of potential outcomes, enhancing the reliability of the predictions. This method provides a comprehensive understanding of how varying climatic conditions could influence beekeeping suitability in different future scenarios, enabling better planning and adaptation strategies for beekeepers in East Africa.

2.5 Model validation and evaluation

Data for model validation were obtained from the International Centre of Insect Physiology and Ecology (icipe) and field observations, providing detailed records of honey bee occurrences and managed apiary locations (see Appendix). This data served as a critical foundation for assessing the accuracy of the apiary site suitability model. By using this data set, we aimed to validate the model's predictions under current climate conditions.

Table 4. Climate model outputs used for future climate analysis

Climate model	Model prediction	Reference
HadGEM3-GC31-LL	Hadley Centre Global Environmental Model run in the Global Coupled configuration 3.1	(Roberts, 2017)
MPI-ESM1-2-HR	Max planck institute for meteorology, earth system model	(Schupfner *et al.*, 2019)
CMCC-ESM2	Centro Euro-Mediterraneo sui cambiamenti climatici, earth system model	(Peano *et al.*, 2020)

Source(s): Authors' own creation

The validation process involves analyzing the intersection of existing apiary locations with the predicted suitability classes under both current and future climate conditions. For the current suitability analysis, we mapped existing apiary locations onto the model's current suitability classifications (highly, moderately and less) to determine the alignment between observed beekeeping activities and model predictions. Future suitability analysis followed a similar procedure, evaluating how the distribution of existing apiary locations shifts across suitability classes under climate scenarios SSP1-2.6 and SSP5-8.5 for the periods 2021–2040 and 2061–2080.

Evaluation metrics were focused on the percentage distribution of apiary locations within each suitability class and the spatial intersection of these locations with suitability predictions. We calculate the percentage of existing apiary sites in highly, moderately and less suitable areas.

3. Results

3.1 Suitability of apiary sites under current climate

The modeled apiary suitability analysis for the study sites Yabelo and Taita-Taveta provides a comparative overview of their current potential for supporting honey bee colonies (Figure 4). For Yabelo, 40.2% of the area is classified as highly suitable for apiaries, indicating that nearly half of the region offers optimal conditions for beekeeping; 43.6% of the area is moderately suitable and the remaining 16.2% is deemed less suitable.

In contrast, the Taita-Taveta site exhibits a higher overall suitability for apiaries. Here, 54.89% of the area is classified as highly suitable, reflecting a more extensive proportion of the region with ideal conditions for honey bee habitation and productivity. Additionally, 33.9% of the area is categorized as moderately suitable, indicating that a significant portion of Taita-Taveta also supports beekeeping, although not at the highest level of suitability. Only 11.2% of the area is less suitable, which is a smaller proportion than Yabelo.

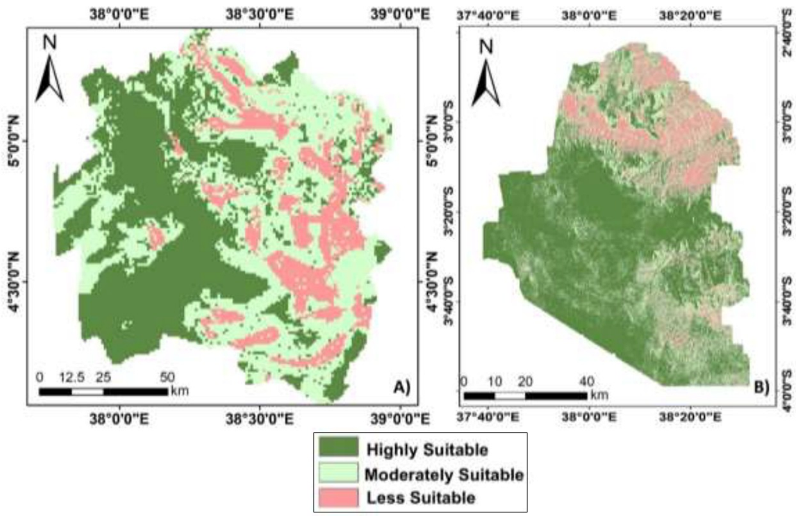

Figure 4. Current apiary suitability map of Yabelo (a) and Taita-Taveta (b) sites
Source: Authors' own creation

3.2 Land suitability for apiaries under future climate change scenarios

Analysis of apiary suitability at the Yabelo and Taita-Taveta study sites over different time periods and under various SSPs revealed notable trends and shifts in suitability categories (Table 5). For the Yabelo site under the SSP1-2.6 scenario, the highly suitable area decreased from 38.2% in 2021–2040 to 32.5% in 2061–2080. During the same periods, the moderately suitable area increased slightly from 44.0% to 45.9% and the less suitable area increased from 17.8% to 21.6%. This trend indicates a gradual decline in optimal conditions for apiaries. Similarly, under the SSP5-8.5 scenario, the Yabelo site experienced a decrease in highly suitable areas from 38.5% in 2021–2040 to 32.6% in 2061–2080. Whereas the moderately suitable areas increased from 43.9% to 55.3%, the less suitable areas decreased from 17.6% to 12.1%. This shift suggests that while the overall suitability becomes less optimal, there is a significant increase in moderately suitable areas, indicating a redistribution of suitability rather than an overall decline (Figure 5).

In contrast, the Taita-Taveta site under the SSP1-2.6 scenario showed a slight decrease in highly suitable areas, from 53.6% in 2021–2040 to 51.5% in 2061–2080. The moderately suitable areas had a marginal increase from 34.6% to 35.5% and the less suitable areas increased from 11.8% to 13%. Although there was a reduction in highly suitable areas, Taita-Taveta remains predominantly favorable for beekeeping, with most areas still offering good to moderate conditions (Figure 6). Under the SSP5-8.5 scenario, there was a notable decrease in highly suitable areas from 34% in 2021–2040 to 27.8% in 2061–2080. However, the moderately suitable areas increased dramatically from 56.3% to 61.4%, while the less suitable areas experienced a slight increase from 9.7% to 10.8%. Although this indicates a major shift toward moderate suitability, the overall area remains largely viable for apiary activities.

3.2 Validation of results

Evaluation of current and future suitability of existing beehive locations of Yabelo and Taita-Taveta under different climate change scenarios provide insights into how climate change may impact the productivity and sustainability of these apiary sites (Table 6). In Yabelo, the current suitability analysis shows 73.3% of honey bee occurrences in highly suitable areas, with 13.3% each in moderately and less suitable areas. The highly suitable area decreased over time under both SSP1-2.6 and SSP5-8.5 scenarios. These trends suggest that Yabelo is more susceptible to reductions in highly suitable areas than Taita-Taveta, particularly under high-emission scenarios.

Under the current conditions, 43 (58.9%) of the existing beehive locations in Taita-Taveta are classified as highly suitable, 24 (32.9%) as moderately suitable, and 6 (8.2%) as less suitable. These results suggest that most of the current beehive locations are well-positioned for optimal beekeeping conditions.

The distribution of suitability remained relatively stable in the low-emission scenario (SSP1-2.6) for the periods 2021–2040 and 2061–2080. The moderately and less suitable classifications also showed minor changes. In the high-emission scenario (SSP5-8.5), there was a notable decline in the percentage of highly suitable areas.

4. Discussion

4.1 Current suitability of apiary sites

Consistent with previous studies (Zoccali *et al.*, 2017; Bareke and Addi, 2019a; Sari *et al.*, 2020; Tennakoon *et al.*, 2023; Gebremedhn *et al.*, 2024), we observed that areas that are highly suitable for apiary sites are strongly correlated with the presence of forage sources, emphasizing the significant role of flowering species in determining suitability for honey bees.

Table 5. Current and future suitability for apiary location

Suitability for apiary		Yabelo			Tatita-Taveta		
		Highly (area %)	Moderately (area %)	Less (area %)	Highly (area %)	Moderately (area %)	Less (area %)
Current		40.2	43.6	16.2	54.9	33.9	11.2
SSPs126	2021–2040	38.2	44.0	17.8	53.6	34.6	11.8
	2061–2080	32.5	45.9	21.6	51.5	35.5	13.0
SSPs585	2021–2040	38.5	43.9	17.6	34.0	56.3	9.7
	2061–2080	32.6	55.3	12.1	27.8	61.4	10.8

Source(s): Authors' own creation

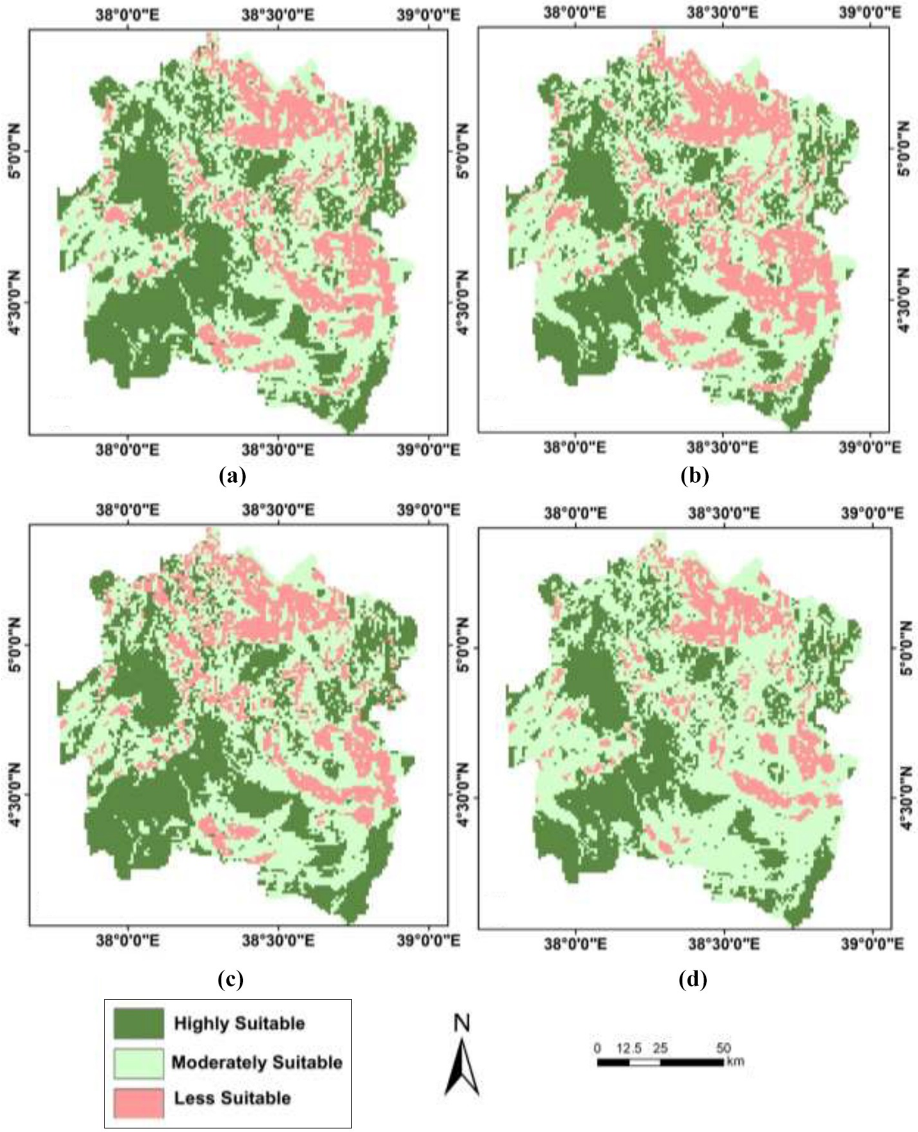

Figure 5. Apiary suitability map of Yabelo under different scenarios
Note(s): (a) SSPs126 (2021–2040); (b) SSPs126 (2061–2080); (c) SSPs585 (2021–2040) and (d) SSPs585 (2061–2080)
Source: Authors' own creation

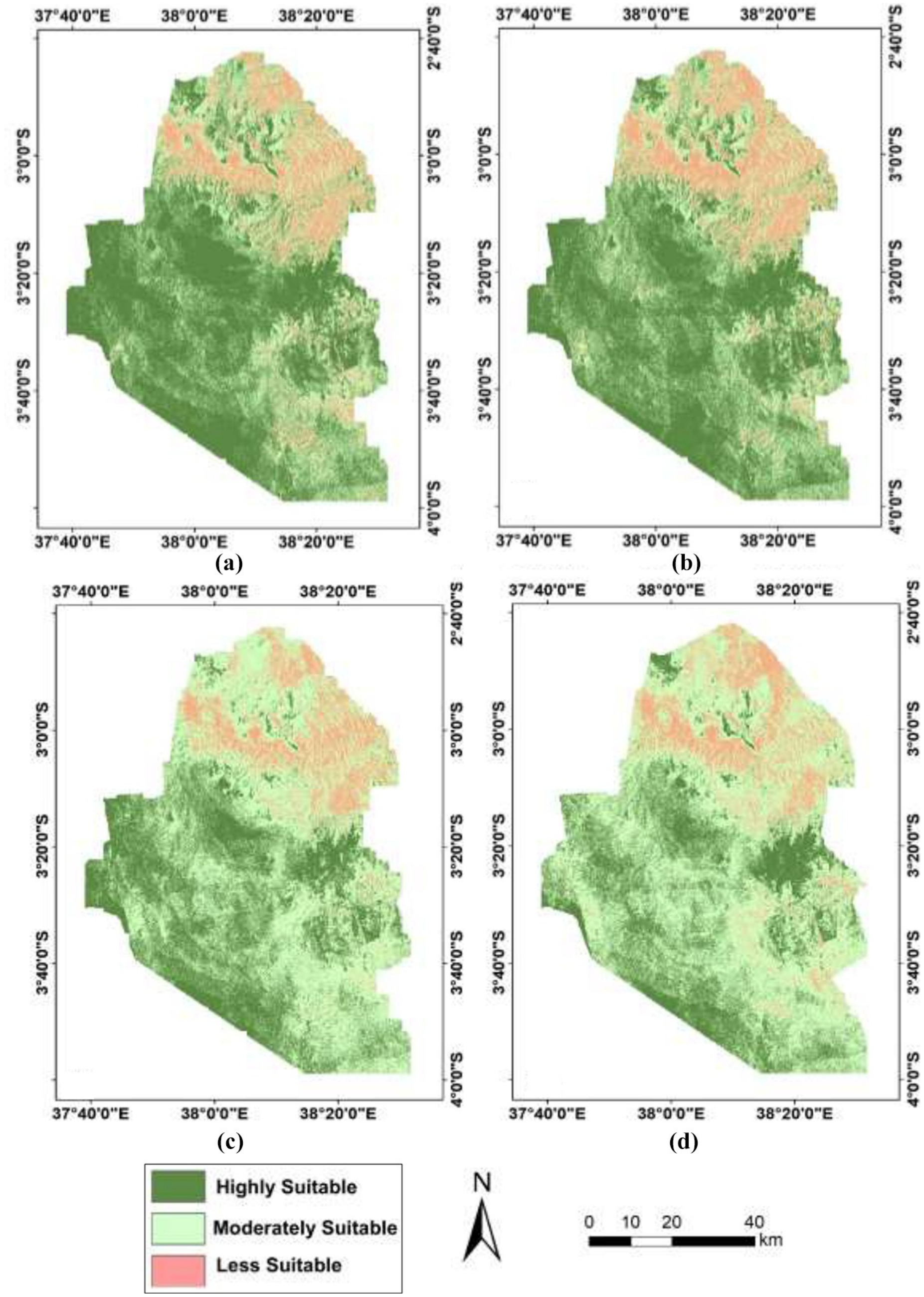

Figure 6. Apiary suitability map of Taita-Taveta under different senarios
Note(s): (a) SSPs126 (2021–2040); (b) SSPs126 (2061–2080); (c) SSPs585 (2021–2040) and (d) SSPs585 (2061–2080)
Source: Authors' own creation

Table 6. Distribution of existing beehive locations across suitability classes under current and future climate change scenarios

			SSP1-2.6				SSP5-8.5			
	Current		2021–2040		2061–2080		2021–2040		2061–2080	
Classification	No.	%	No.	%	No.	%	No.	%	No.	%
Yabelo										
Highly suitable	11	73.3	9	60.0	8	53.3	8	53.3	7	46.7
Moderately suitable	2	13.3	4	26.7	5	33.3	5	33.3	5	33.3
Less suitable	2	13.3	2	13.3	2	13.3	2	13.3	3	20.0
Total	15	100	15	100	15	100	15	100	15	100
Taita-Taveta										
Highly suitable	43	58.9	43	58.9	44	60.3	31	42.5	35	47.9
Moderately suitable	24	32.9	24	32.9	23	31.5	38	52.0	34	46.6
Less suitable	6	8.2	6	8.2	6	8.2	4	5.5	4	5.5
Total	73	100	73	100	73	100	73	100	73	100

Source(s): Authors' own creation

Highly suitable habitats are typically associated with forested areas, bushland and shrubland. These ecosystems offer abundant floral resources and nesting sites essential for foraging activities. Studies indicate that diverse and dense vegetation supports higher bee diversity and abundance, making these habitats highly conducive for honey bees (Bartholomée *et al.*, 2020). In contrast, grasslands, while providing moderate resources, do not offer the same level of floral diversity and nesting opportunities and are thus considered moderately suitable. Croplands, often characterized by monocultures and pesticide use, are less suitable due to limited floral resources and higher exposure to harmful chemicals (Bond *et al.*, 2021; Brühl *et al.*, 2021; Janousek *et al.*, 2023).

Proximity to water sources significantly impacts honey bee habitat suitability. Similar studies have emphasized the importance of water access for bees, particularly concerning their needs for cooling, brood rearing and feeding. Maintaining water sources within close proximity to bee habitats improve the sustainability of honey bee colonies (Tian, 2016; Fotso Kamga *et al.*, 2024). Rainfall levels are directly correlated with habitat suitability for honey bees. Regions receiving higher rainfall are highly suitable as they support vegetation and continuous floral availability, which are crucial for bee nutrition (Balvino-Olvera *et al.*, 2024). Conversely, areas with lower rainfall are less suitable due to sparse vegetation and limited floral resources, which affects the bees' ability to sustain their colonies throughout the year (Frazier *et al.*, 2024).

The forage source criterion was given the highest weight in the fuzzy AHP analysis, consistent with findings of earlier studies (Sarı *et al.*, 2020; Tennakoon *et al.*, 2023). Consequently, incorporating information about floral resources is paramount when devising a methodology for identifying suitable apiary locations. Weather variations significantly impact forage availability, directly influencing bee success (Mishra *et al.*, 2023; Sari *et al.*, 2020; Tennakoon *et al.*, 2023). Additionally, research indicates that rising temperatures can adversely affect forage presence, leading to increased stress on bees, reduced foraging efficiency and higher mortality rates. Therefore, maintaining moderate temperatures is essential for supporting healthy bee populations (Sari *et al.*, 2020; Mishra *et al.*, 2023; Tennakoon *et al.*, 2023).

4.2 Projected changes in apiary suitability under future climate scenarios

Climate change is increasingly recognized as a significant threat to honey bee populations, primarily due to its impact on the diversity and availability of plants essential for bees to collect pollen and nectar (Bertrand *et al.*, 2011; Mishra *et al.*, 2023). Our study supports these concerns, revealing a clear decline in the suitability of areas for beekeeping due to the effects of climate change under both climate change scenarios.

The future projections for honey bee habitat suitability in both study sites under the SSP5-8.5 scenario revealed a significant shift in suitability categories, with a decrease in highly suitable areas and an increase in both moderately and less suitable areas from 2021–2040 to 2061–2080. This redistribution of suitability suggests a nuanced impact of climate change, emphasizing a transformation in habitat quality rather than an outright decline in extreme climate scenarios, which leads to a reshaping of habitat suitability rather than a complete deterioration (Conrad *et al.*, 2021). Additionally, Dupont *et al.* (2022) observed that while high-emission scenarios exacerbate climate stressors, they often result in a shift toward less optimal conditions rather than an absolute loss of habitat. This aligns with our results, which indicate that while highly suitable areas are diminishing, the expansion of moderately suitable zones suggests a more complex scenario where habitat quality is redistributed rather than entirely lost. However, the decrease in highly suitable areas points to potential challenges in maintaining peak honeybee productivity and health, as extreme temperature and precipitation increases may stress bee populations (Gebreyohans and Gebremariam, 2017; Gebremedhn *et al.*, 2024).

Validating the results of beehive suitability revealed significant trends in how climate change may impact existing beehive locations in the future. The observed decrease in the existing beehive locations from highly suitable areas in Yabelo aligns with climate change, such as higher temperatures and altered precipitation patterns, leading to reduced habitat quality for honey bees (Conrad *et al.*, 2021). In contrast, the stability of beehive locations in Taita-Taveta under the low-emission scenario (SSP1-2.6) and the relative decline under the high-emission scenario (SSP5-8.5) shows the regions experiencing moderate climate impacts tend to maintain more stable habitat conditions than areas under climate change (Frazier *et al.*, 2024).

4.3 Implications of the study

This study underscores beekeeping as a climate-resilient strategy that can enhance livelihoods and food security in East Africa. Integrating climate projections into site selection and beekeeping practices allows policymakers to prioritize beekeeping in areas with favorable conditions, enabling communities to better adapt to climate change. Refining site selection with tools like GIS and fuzzy MCDM can identify optimal apiary locations, ensuring productivity and ecological resilience. Targeted support for moderately suitable areas can boost local economies, promoting beekeeping as a climate-resilient livelihood that reduces reliance on climate-sensitive activities. Broader adaptation strategies, such as training and access to resources, can further strengthen community resilience. Ultimately, integrating beekeeping into climate adaptation plans supports long-term sustainability, fosters social cohesion and contributes to economic growth in rural communities.

4.4 Limitations and future recommendations

The limitations of this study stem from the lack of comprehensive honey bee location data, as most records come from managed apiary sites that may not reflect the natural distribution of honey bees. While these sites are assumed to represent favorable conditions for honey bees, they may not capture the full range of environmental factors supporting wild populations. To improve the reliability and validity of the research, a mixed-methods approach could be adopted. Integrating GIS, fuzzy MCDM and additional data sources such as remote sensing or citizen science can provide a more holistic view of honey bee distribution. GIS can map environmental variables, while fuzzy MCDM evaluates the suitability of sites for both managed and wild populations. Incorporating local knowledge and field surveys will further validate the findings, ensuring a more accurate representation of both managed and natural habitats. This approach would enhance the study's robustness and provide a clearer understanding of honey bee habitat suitability.

Another important limitation is the potential bias introduced by relying solely on managed apiary locations. These sites are often chosen based on practical considerations for beekeeping rather than purely ecological suitability, which may skew the analysis of habitat preferences and suitability under changing climate conditions. Additionally, managed apiaries may be subject to human interventions that do not reflect the natural foraging and nesting behaviors of wild honey bees. This study would benefit from incorporating honey bee occurrence data from natural, unmanaged locations. To address this limitation, future research should aim to gather and integrate occurrence data from wild honey bee populations. Expanding the data set to include wild honey bee locations would significantly strengthen the study's conclusions and its applicability to broader conservation and management efforts.

5. Conclusion

Climate change poses a significant threat to the development of East Africa and particularly affects agriculture, which is a basis of food and income security for the agro-pastoral community. Suitable adaptation strategies are essential to mitigate these impacts and ensure the resilience of these communities. One promising and sustainable practice is beekeeping, which not only generates income but also improves food security through essential pollination services. By integrating beekeeping into their livelihoods, agro-pastoralists can improve their economic stability and contribute to the health of their ecosystems.

Climate change presents significant challenges to honey bee habitat suitability. The resilience observed in moderately suitable areas suggests that there are opportunities for adaptation. The insights gained from this study can guide future research and policy development to support beekeeping in evolving climatic conditions. By implementing adaptive strategies, the long-term viability of agricultural practices and the protectection of livelihoods of agro-pastoral communities in East Africa can be ensured. This study reinforces the critical role of adaptive planning in safeguarding the stability of ecosystems and agricultural systems that rely on pollination, contributing to overall resilience against climate change. This study highlights the role of beekeeping as a climate-resilient strategy to enhance livelihoods and food security in East Africa. Integrating climate projections allows policymakers to prioritize beekeeping through adaptive agricultural policies, while refined site selection methods help identify climate-suitable apiary locations. Targeted support for moderately suitable areas, along with broader adaptation strategies, will help sustain productivity and resilience in climate-sensitive regions, promoting long-term rural sustainability.

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Appendix. Records of managed beehive locations

Table A1. Beehive locations in the Yabelo Study site, Ethiopia

FID	Latitude	Longitude
1	4.9987	38.2051
2	4.9967	38.2063
3	4.8756	38.1229
4	4.8743	38.1196
5	4.8889	38.0861
6	4.8828	38.0980
7	4.8862	38.0908
8	4.8902	38.0570
9	4.8757	38.1417
10	4.8786	38.1481
11	4.8141	38.3229
12	5.0101	38.2126
13	4.8889	38.0859
14	4.6762	38.1633
15	4.6740	38.1497

Source(s): Authors' own creation

Table A2. Beehive locations in the Tatita-Taveta study site, Kenya

FID	Latitude	Longitude
1	−3.4781	38.3549
2	−3.4814	38.3422
3	−3.4075	38.3625
4	−3.4087	38.3749
5	−3.4850	38.4112
6	−3.4575	38.3927
7	−3.5087	38.3549
8	−3.5056	38.3478
9	−3.5077	38.3431
10	−3.4987	38.3770
11	−3.5070	38.2667
12	−3.6413	38.3737
13	−3.4582	38.3390
14	−3.4693	38.3648
15	−3.5043	38.3355
16	−3.4802	38.3309
17	−3.6346	38.3701
18	−3.3824	38.3332
19	−3.2771	38.2993
20	−3.2880	38.3026
21	−3.3998	38.3136
22	−3.4236	38.3536
23	−3.5084	38.3507
24	−3.5043	38.3302
25	−3.4820	38.3559
26	−3.4598	38.3454
27	−3.4704	38.3466
28	−3.4667	38.3447
29	−3.6370	38.3734
30	−3.4236	38.3533
31	−3.3694	38.3526
32	−3.3716	38.3526
33	−3.3801	38.3437
34	−3.3542	38.3367
35	−3.4822	38.3118
36	−3.4314	38.2949
37	−3.4274	38.3046
38	−3.4135	38.3177
39	−3.4034	38.2891
40	−3.5240	38.3156
41	−3.3851	38.3283
42	−3.4171	38.4086
43	−3.5963	38.3359
44	−3.3752	38.4328
45	−3.4595	38.1884
46	−3.4867	38.2646
47	−3.3920	38.3763
48	−3.3867	38.3800
49	−3.3935	38.3794
50	−3.3806	38.3775

(*continued*)

Table A2. Continued

FID	Latitude	Longitude
51	−3.4556	38.4812
52	−3.4756	38.4314
53	−3.4797	38.4124
54	−3.3912	38.3727
55	−3.4258	38.1398
56	−3.4691	38.1965
57	−3.4691	38.1965
58	−3.4416	38.5009
59	−3.4576	38.3927
60	−3.4574	38.3927
61	−3.4574	38.3927
62	−3.3982	37.7300
63	−3.4881	38.4088
64	−3.4883	38.4089
65	−3.4890	38.4090
66	−3.4896	38.4094
67	−3.4901	38.4096
68	−3.4899	38.4075
69	−3.4890	38.4075
70	−3.4033	38.4422
71	−3.4030	38.4424
72	−3.6350	38.2579
73	−3.6352	38.2580

Source(s): Authors' own creation

Supplementary material

The supplementary material for this article can be found online.

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