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Climate-driven synchronization of honey bee flight activity and plant phenology in Türkiye: development of a Beekeeping Climate Suitability Index (BCSI)

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Abstract

Honey bees (*Apis mellifera* L.) provide essential pollination services that depend on the temporal synchronization between flight activity and plant flowering phenology, both strongly influenced by climatic conditions. However, this relationship remains insufficiently quantified at large spatial and temporal scales. In this study, we quantified climate-driven honey bee flight activity and its alignment with flowering phenology of major nectar plants in Türkiye using ERA5-Land data for the period 1981–2023. Suitable flight days were defined based on temperature (≥12°C) and precipitation (0 mm), and seasonal suitability was evaluated at a monthly scale. A composite Beekeeping Climate Suitability Index (BCSI) was developed by integrating flight activity, flowering overlap and nectar flow window. The number of suitable flight periods ranged between 4 and 7 months (mean ≈5.5), indicating substantial interannual variability. Flight flowering synchrony was low for early-spring species (23–35%) but reached 100% for summer species. BCSI values ranged from 0.44 to 1.00, capturing variability in climatic suitability for beekeeping. These findings demonstrate that climatic variability plays a decisive role in shaping bee plant interactions and provide a quantitative basis for climate-informed beekeeping management.

Keywords: *Apis mellifera*, Climatic variability, ERA5-Land, Nectar flow, Pollinator ecology

INTRODUCTION

Honey bees (*Apis mellifera* L.) are among the most important pollinators, playing a crucial role in both natural and agricultural ecosystems. It is estimated that approximately one-third of global crop production depends on animal-mediated pollination, with honey bees contributing significantly to this process (Klein et al. 2007, Potts et al. 2010). Beyond their role in crop pollination, honey bees are essential for maintaining biodiversity and supporting the stability of plant communities (Garibaldi et al. 2013).

Honey bee foraging activity is strongly regulated by environmental and meteorological conditions. Temperature is one of the primary factors controlling flight activity, with most studies indicating that flight becomes active above approximately 12–14 °C (Heinrich 1993, Seeley 1995). In addition, precipitation can directly limit foraging activity by reducing flight opportunities, lowering nectar secretion, and decreasing floral resource accessibility (Abou-Shaara 2014, Corbet et al. 1993, Tautz 2008). Other factors such as wind speed, solar radiation, and relative humidity also influence bee activity, although their effects are often less consistently quantified at large spatial scales (Abou-Shaara 2014, Kovac et al. 2011, Vicens and Bosch 2000).

Climatic conditions not only affect honey bee activity but also strongly regulate plant phenology. Flowering time is primarily driven by temperature accumulation and seasonal climatic patterns (Cleland et al. 2007). Numerous studies have demonstrated that climate change is altering phenological processes, leading to shifts in flowering periods across many plant species (Menzel et al. 2006, Parmesan and Yohe 2003). These shifts may disrupt the temporal synchrony between pollinators and plants, potentially leading to phenological mismatches and reduced pollination efficiency (Kudo and Ida 2013, Forrest 2015). Climate change is expected to significantly affect pollinator systems and ecosystem functioning (IPCC 2021, Le Conte and Navajas 2008).

From a beekeeping perspective, the temporal overlap between honey bee flight activity and plant flowering is a key determinant of nectar resource utilization and colony productivity. The degree of synchronization between these two processes may strongly influence nectar collection efficiency, colony development, pollination services, and honey production (Abou-Shaara 2014, Goulson et al. 2015, Requier et al. 2015, Seeley 1995, Tautz 2008). However, most existing studies have examined either honey bee activity or plant phenology separately, without quantitatively integrating the two components within a unified climate-based framework.

To our knowledge, there are no studies that combine long-term climate data, honey bee flight suitability and flowering phenology into a single quantitative framework for assessing beekeeping suitability at a national scale. This gap limits our ability to evaluate how climate variability affects nectar flow dynamics and to develop climate-informed strategies for beekeeping management.

Türkiye is one of the most floristically diverse countries in the temperate zone due to its unique geographical position, topographic heterogeneity, and transitional location between Europe, Asia, and the Middle East. The country hosts approximately 12,000 vascular plant taxa, with a high level of endemism associated with Mediterranean, Euro-Siberian, and Irano-Turanian phytogeographical regions (Davis 1965–1985, Güner et al. 2012). This exceptional botanical diversity provides highly heterogeneous nectar and pollen resources for honey bees and contributes to regionally variable nectar flow dynamics across the country. Previous studies have emphasized the importance of Türkiye's melliferous flora for apicultural productivity, honey quality, and the botanical diversity of bee products (Güner et al. 2012, Özbek 2003, Özbek 2011, Sorkun 2008).

In addition, Türkiye exhibits pronounced climatic heterogeneity, including Mediterranean, continental, and Black Sea climatic influences, which further affect flowering phenology and honey bee foraging activity. Beekeeping practices and colony management principles under these diverse environmental conditions have been extensively described in previous studies (Genç and Dodoloğlu 2002, Tautz 2008). Understanding how climate-driven variability influences the alignment between honey bee activity and plant phenology in such a heterogeneous environment is therefore essential for optimizing adaptive beekeeping practices.

Therefore, the aim of this study is to (I) determine climate-based suitable periods for honey bee flight activity using long-term ERA5-Land data (1981–2023), (II) evaluate the alignment between flight activity and flowering phenology of major nectar plants and (III) develop a composite Beekeeping Climate Suitability Index (BCSI) integrating these components. By providing a quantitative and integrative framework, this study aims to improve our understanding of bee plant climate interactions and support adaptive beekeeping management under changing climatic conditions.

MATERIALS AND METHODS

Study Area

This study was conducted across the entire territory of Türkiye, which exhibits pronounced climatic heterogeneity due to its complex topography and geographical location. According to the Köppen Geiger climate classification system, Türkiye includes several major climate types, including Mediterranean climates (Csa, Csb) along the western and southern coastal regions, temperate oceanic climates (Cfb) in the eastern Black Sea region, and continental climates (Dsa, Dsb, Dfb) in the interior and eastern parts of the country (Peel et al. 2007). This climatic diversity strongly influences vegetation patterns, flowering phenology, and nectar flow dynamics, resulting in regionally variable conditions for honey bee foraging activity and beekeeping practices. Therefore, Türkiye provides a highly suitable framework for evaluating climate-bee plant interactions at a national scale.

Climate Data

Daily climate data were obtained from the ERA5-Land reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Muñoz-Sabater et al. 2021). ERA5-Land provides high-resolution (~0.1°, approximately 9 km) gridded climate data and is widely used in biometeorological and environmental studies.

The analysis covered the period 1981–2023. Daily mean temperature (°C) and daily total precipitation (mm) were used as the primary variables influencing honey bee flight activity. Grid cells corresponding to Türkiye's national boundaries were extracted using a spatial mask. Country-level indicators were derived by calculating the area-weighted mean of all grid cells.

Although this aggregation approach ensures national-scale consistency, it may mask regional variability in climatic conditions. Therefore, the results should be interpreted as representing national-scale averages rather than local conditions.

Determination of Suitable Days for Honey Bee Flight Activity

Honey bee flight activity is strongly dependent on environmental conditions, particularly temperature and precipitation (Heinrich 1993; Abou-Shaara 2014). In this study, suitable flight days were defined based on the following criteria:

- daily mean temperature ≥ 12°C
- daily precipitation = 0 mm

These thresholds are consistent with widely reported conditions for honey bee flight activity in the literature (Abou-Shaara 2014, Seeley 1995).

Other meteorological variables, including wind speed, solar radiation, and relative humidity, may also influence honey bee flight activity and foraging behavior. In addition, regional differences in honey bee races and locally adapted populations may contribute to variability in colony performance and flight responses under different environmental conditions. However, incorporating all of these variables into a consistent, long-term, national-scale framework remains methodologically challenging. Therefore, the present study focused on temperature and precipitation as the primary climatic constraints directly regulating honey bee flight activity at broad spatial and temporal scales. This simplified approach provides a reproducible framework for evaluating large-scale patterns of climate suitability, though some local and regional variability may not be fully represented.

Aggregation of Flight Suitability

To evaluate seasonal suitability, a monthly aggregation approach was applied. A month was classified as a "suitable flight period" if at least 50% of the days met the flight suitability criteria. The 50% threshold was selected as a balance between strict and permissive definitions and has been commonly used in ecological suitability assessments to identify periods dominated by favorable conditions. Although different thresholds may influence the results, the selected criterion provides a consistent and interpretable framework for long-term comparative analysis.

Flowering Phenology of Bee Plants

The flowering periods of major nectar- and pollen-producing plant species in Türkiye were compiled from published apicultural flora studies, melissopalynological research, regional flowering calendars, and phenological references related to nectar plants in different ecological regions of the country (Davis 1965–1985, Güner et al. 2012, Özbek 2011, Sorkun 2008).

Although regional atmospheric pollen calendars and local phenological datasets are available for certain provinces and plant groups, a nationally standardized long-term dataset covering all major nectar plants remains limited for comparative large-scale analyses. Therefore, flowering periods were treated as generalized seasonal intervals in order to provide a consistent national-scale framework. While this approach enables long-term comparative evaluation, it may not fully capture interannual and regional variability in flowering phenology driven by climatic fluctuations.

Beekeeping Season Length

The beekeeping season was defined as the period during which honey bees can actively forage under suitable thermal conditions. Months with mean temperatures ≥10°C were considered part of the beekeeping season (Seeley 1995). Season start and end were defined as:

- start: first month exceeding 10°C
- end: last month above 10°C

Nectar Flow Window

The nectar flow window was defined as the temporal overlap between:

(I) suitable meteorological conditions for honey bee flight activity and

(II) flowering periods of nectar plants.

This approach enables the identification of periods with simultaneous biological and climatic suitability.

Beekeeping Climate Suitability Index (BCSI)

To evaluate climatic suitability for beekeeping, a composite index, termed the Beekeeping Climate Suitability Index (BCSI), was developed by integrating three key components: (I) the number of suitable flight days (F), (II) the number of suitable flight days during flowering periods (N) and (III) the length of the nectar flow window (W). In this study, all components were first calculated annually from daily climatic data, and the resulting values were subsequently normalized and aggregated to obtain a single index value for each year.

Composite indicators integrating multiple environmental variables are widely used in ecological and agricultural studies to assess system suitability and performance. The construction of the BCSI follows the general framework for composite indicator development, including normalization, weighting, and aggregation, as outlined in established composite indicator methodology frameworks (Nardo et al. 2005, OECD 2008). Such approaches have been widely applied in climate suitability analysis, agro-ecological zoning, and habitat suitability modeling (Hargreaves and Samani 1985, Thornthwaite 1948).

Since these variables are expressed in different units and scales, min max normalization was applied to transform them into a comparable dimensionless range between 0 and 1:

$F\_norm = (F - F\_min) / (F\_max - F\_min)$ (Eq. 1)

$N\_norm = (N - N\_min) / (N\_max - N\_min)$ (Eq. 2)

$W\_norm = (W - W\_min) / (W\_max - W\_min)$ (Eq. 3)

Minmax normalization is commonly used in composite index construction to eliminate unit differences while preserving the relative variability of the data.

The BCSI was then calculated as a weighted linear combination of the normalized components:

$BCSI = 0.4 \times F\_norm + 0.4 \times N\_norm + 0.2 \times W\_norm$ (Eq. 4)

The weighting scheme was defined a priori based on ecological relevance and supported by expert judgment, as commonly applied in composite index development when empirical weighting data are unavailable (OECD 2008). Flight activity (F) and flowering synchrony (N) were each assigned higher weights (0.4) due to their direct influence on foraging efficiency, colony development and honey production. In contrast, the nectar flow window (W) was assigned a lower weight (0.2), as it represents a complementary but secondary temporal indicator of resource availability.

Although alternative weighting approaches such as equal weighting or data-driven techniques (*e.g.*, principal component analysis) could be applied, the selected weighting scheme prioritizes interpretability and ecological relevance.

It should be noted that the BCSI is designed as a relative comparative index rather than an absolute predictive model. Therefore, it is primarily intended to evaluate interannual variability and relative differences in climatic suitability for beekeeping. The index was subsequently used as a time-series variable to assess interannual variability and long-term trends in beekeeping climate suitability.

The weighting scheme was further supported by established knowledge in honey bee foraging ecology and plant pollinator interactions, which consistently emphasize the dominant role of flight activity and flowering synchrony in determining colony performance and resource acquisition.

Statistical Analysis

Temporal trends in the number of suitable flight periods were analyzed using the Mann Kendall test (Kendall 1975, Mann 1945), a non-parametric method widely used in climatological studies. The magnitude of trends was estimated using Sen's slope estimator (Sen 1968). All analyses were conducted using Python-based computational workflows. The construction of the BCSI, including normalization and weighted aggregation, was performed within the Python-based workflow prior to temporal trend analyses.

RESULTS

Flowering Phenology of Major Bee Plants

The flowering periods of major nectar- and pollen-producing plant species in Türkiye showed a clear seasonal distribution, with most species flowering between May and July (Table1 and Figure 1). Early spring species such as *Taraxacum officinale* Weber and *Prunus* spp. flowered between March and April, whereas late-season species such as *Erica manipuliflora* Salisb. extended flowering into autumn.

The concentration of flowering activity during late spring and early summer indicates that this period represents the core nectar-flow season in Türkiye.

Table 1. Representative nectar- and pollen-producing plant taxa commonly associated with beekeeping activities in Türkiye, their generalized flowering periods, and phenological characteristics compiled from apicultural flora and phenological literature.

No	Plant Name	Scientific Name	Flowering Period	Mean GDD (°C days)	Plant Type
1	Black locust	*Robinia pseudoacacia* L.	May	350–450	Forest tree
2	Chestnut	*Castanea sativa* Mill.	June	500–650	Forest tree
3	Linden	*Tilia* spp.	June–July	550–700	Forest tree
4	Milkvetch	*Astragalus* spp.	May–July	400–600	Pasture plant
5	Thyme	*Thymus* spp.	May–June	400–550	Pasture plant
6	Sage	*Salvia* spp.	May–June	400–550	Pasture plant
7	Alfalfa	*Medicago sativa* L.	May–September	450–700	Agricultural crop
8	Clover	*Trifolium* spp.	May–July	400–600	Agricultural crop
9	Wild mustard	*Sinapis arvensis* L.	April–May	300–400	Agricultural crop
10	Rapeseed	*Brassica napus* L.	April–May	300–400	Agricultural crop
11	Sunflower	*Helianthus annuus* L.	July–August	800–1000	Agricultural crop
12	Almond	*Prunus dulcis* (Mill.) D.A. Webb	March–April	150–250	Fruit tree
13	Apple	*Malus domestica* Borkh.	April–May	250–350	Fruit tree
14	Cherry	*Prunus avium* (L.) L.	April	250–350	Fruit tree
15	Pear	*Pyrus communis* L.	April–May	250–350	Fruit tree
16	Blackberry	*Rubus* spp.	May–July	400–600	Shrub species
17	Heather	*Erica manipuliflora* Salisb.	August–October	900–1100	Shrub species
18	Mullein	*Verbascum* spp.	May–July	400–600	Pasture plant
19	Dead-nettle	*Lamium* spp.	April–May	250–350	Pasture plant
20	Dandelion	*Taraxacum officinale* Weber	March–May	200–300	Pasture plant

Flowering periods and mean growing degree days (GDDs) were compiled from published apicultural flora studies, melissopalynological research, regional flowering calendars, and phenological references on nectar plants in Türkiye (Davis 1965–1985, Sorkun 2008). The presented taxa represent widely distributed nectar and pollen sources associated with beekeeping activities at the national scale. Actual flowering periods may vary depending on regional climatic conditions, altitude, local flora composition, and interannual climatic variability. Some fruit tree taxa belonging to the Rosaceae family were presented separately because of differences in flowering phenology and their contribution to seasonal nectar availability.

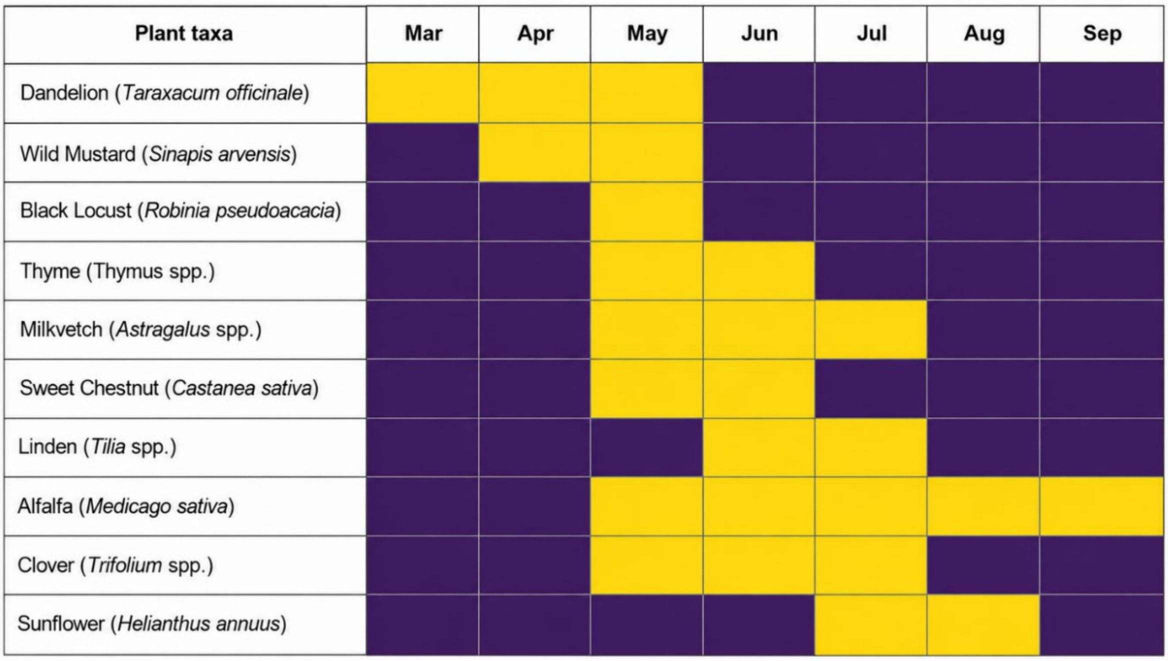

Figure 1. Beekeeping phenological calendar showing the generalized flowering periods of representative nectar plant taxa associated with beekeeping activities in Türkiye. Flowering periods were compiled from published apicultural flora studies, melissopalynological research, regional flowering calendars, and phenological references (Davis 1965–198,; Sorkun 2008). Black cells indicate the active flowering periods of the respective plant taxa.

Interannual Variability in Suitable Flight Periods

The number of suitable flight periods exhibited substantial interannual variability during 1981–2023 (Table 2). The number of suitable months ranged from 4 to 7, with a mean of approximately 5.5 months. Temporal variation and the linear trend of suitable flight periods are presented in Figure-2. The lowest values (4 months) were observed in 1992, 1994, 2014, and 2015, while the highest (7 months) were observed in 2008, 2021, and 2022. This represents a relative difference of approximately 75% between the most and least favorable years.

Years with extended flight periods were generally associated with earlier increases in spring temperature and reduced precipitation frequency. Conversely, years with shorter suitable periods coincided with cooler and wetter conditions.

Trend analysis indicated a slight increase in the number of suitable flight periods; however, this trend was not statistically significant (Mann–Kendall, $p > 0.05$).

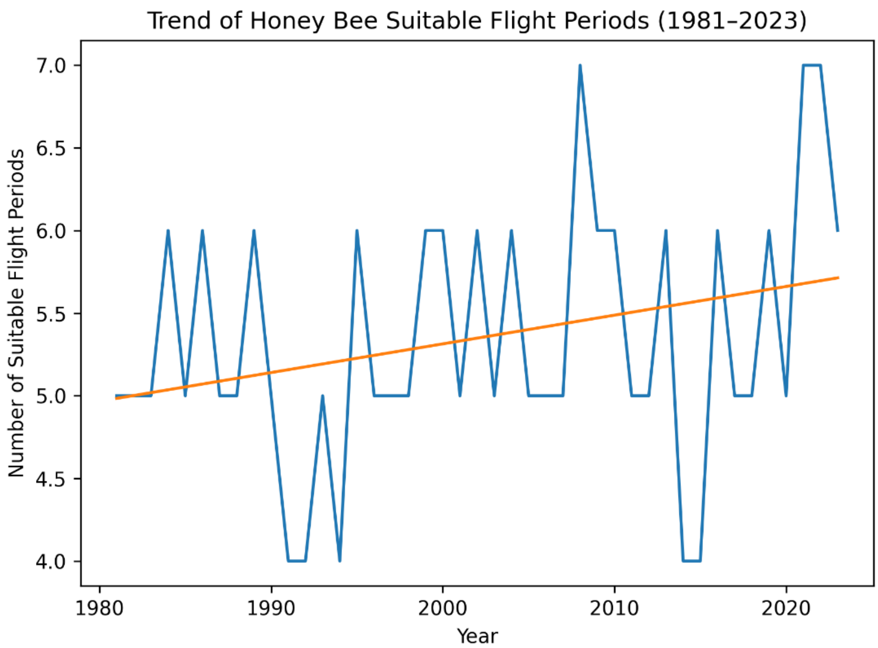

Figure 2. Temporal variation and linear trend of the number of suitable periods for honey bee flight activity in Türkiye (1981–2023). The orange line represents the linear trend.

Table 2. Interannual variability in suitable flight periods and climatic characteristics in Türkiye

Year	Number of Suitable Months for Flight Activity (months with ≥12°C and no precipitation days)	Mean Temperature (°C)	Number of Rainy Periods	Total Precipitation (mm)
1981	5	11.51	9	26.3
1982	5	10.41	10	21.9
1983	5	10.70	11	24.2
1984	6	11.19	10	20.4
1985	5	11.11	9	22.4
1986	6	11.55	10	22.7
1987	5	11.05	10	26.4
1988	5	10.99	9	27.8
1989	6	11.57	10	19.7
1990	5	11.52	10	19.1
1991	4	11.25	10	23.8
1992	4	9.78	10	22.5
1993	5	10.69	8	22.2
1994	4	12.04	9	23.2
1995	6	11.37	11	23.0
1996	5	11.72	8	24.8
1997	5	10.71	12	23.6
1998	5	12.20	10	22.7
1999	6	12.41	12	20.4
2000	6	11.53	10	19.9
2001	5	12.44	7	22.8
2002	6	11.57	12	22.5
2003	5	11.39	9	23.1
2004	6	11.48	8	21.7
2005	5	11.64	11	23.5
2006	5	11.83	10	22.8
2007	5	12.02	10	21.2
2008	7	12.01	10	17.6
2009	6	11.89	11	25.6
2010	6	13.64	8	23.8
2011	5	11.17	9	23.1
2012	5	12.23	9	24.3
2013	6	12.23	9	20.3
2014	4	12.90	10	23.2
2015	4	12.40	11	23.8
2016	6	12.52	10	23.4
2017	5	12.39	9	20.6
2018	5	13.53	11	25.8
2019	6	12.81	9	23.4
2020	5	12.99	9	20.1
2021	7	12.96	10	20.7
2022	7	12.58	7	17.6
2023	6	13.23	7	13.0

The number of suitable flight periods was calculated as the number of months in a given year in which at least 50% of the days met the conditions suitable for honey bee flight activity.

Flight Suitability During Flowering Periods

The alignment between honey bee flight activity and flowering phenology varied substantially among plant species (Table-3).

Early spring species such as *Taraxacum officinale* Weber and *Sinapis arvensis* L. exhibited low flight suitability rates (23.3% and 34.9%, respectively), reflecting suboptimal climatic conditions during their flowering periods.

In contrast, summer-flowering species such as *Tilia* spp. and *Helianthus annuus* L. showed high suitability values, reaching up to 98.8% and 100%, respectively.

Intermediate species such as *Medicago sativa* L. and *Trifolium* spp. exhibited moderate to high suitability levels (approximately 80–90%), indicating favorable overlap between flowering and flight conditions.

Overall, the results demonstrate a strong seasonal gradient in flight–flowering synchrony, with markedly higher suitability in summer than in early spring.

Table 3. Temporal alignment between flowering periods of major nectar plants and honey bee flight suitability in Türkiye

Plant Species	Flowering Period	Mean Number of Suitable Months	Flight Suitability (%)
Dandelion (*Taraxacum officinale* Weber)	March–May	0.70	23.3
Wild Mustard (*Sinapis arvensis L.*)	April–May	0.70	34.9
Black Locust (*Robinia pseudoacacia* L.)	May	0.51	51.2
Thyme (*Thymus* spp.)	May–June	1.49	74.4
Milkvetch (*Astragalus* spp.)	May–July	2.49	82.9
Sweet Chestnut (*Castanea sativa* Mill.)	June	0.98	97.7
Linden (*Tilia* spp.)	June–July	1.98	98.8
Alfalfa (*Medicago sativa* L.)	May–September	4.49	89.8
Clover (*Trifolium* spp.)	May–July	2.49	82.9
Sunflower (*Helianthus annuus* L.)	July–August	2.00	100.0

Flight suitability (%) was defined as the proportion of days (or months) within the flowering period of each plant species that met the meteorological criteria for honey bee flight activity.

Trends in Suitable Flight Days

Long-term analysis of suitable flight days revealed a slight increasing trend over the study period. Sen's slope estimates indicated a positive but low magnitude of change, suggesting gradual improvement in climatic conditions for flight activity.

The spatial distribution of annual honey bee flight days across Türkiye is illustrated in Figure 3.

However, interannual variability remained high, indicating that favorable conditions are not consistently distributed across years.

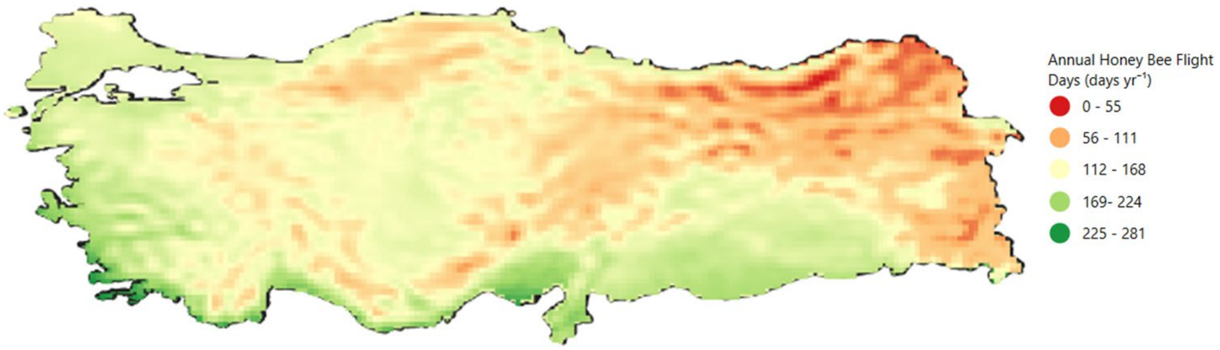

Figure 3. Spatial distribution of annual honey bee flight days in Türkiye (based on ERA5-Land data, 1981–2023).

Beekeeping Season Length

The beekeeping season lasted 4-7 months across the study period (Table 4). In years with early spring warming, the season began as early as April, whereas in cooler years it started in June. Similarly, the end of the season extended into October or November in favorable years, while it ended earlier in less favorable conditions.

These findings indicate that both the onset and duration of the beekeeping season are highly sensitive to climatic variability.

Nectar Flow Window

The nectar flow window showed considerable variation among plant species and years. Species that flower in summer exhibited longer, more stable nectar flow windows due to favorable climatic conditions. In contrast, early spring species experienced shorter, more variable nectar-flow windows, primarily due to lower temperatures and higher precipitation frequency.

Beekeeping Climate Suitability Index (BCSI)

The BCSI values exhibited substantial interannual variability, ranging from 0.44 to 1.00 (Table 5; Figure 4). The lowest values were observed in years characterized by limited flight activity and reduced overlap with flowering periods (e.g., 1992), whereas the highest values corresponded to years with extended flight periods and strong synchronization between bee activity and plant phenology (e.g., 2008).

High BCSI values were generally associated with both increased numbers of suitable flight days and longer nectar flow windows.

Overall, the index successfully captured year-to-year variability in climatic suitability for beekeeping and provided a synthetic measure of bee plant climate interactions.

Table 4. Interannual variability in the onset, termination, and duration of the honey bee flight season in Türkiye (1981–2023)

Year	Season Start	Season End	Season Length (months)
1981	June	October	5
1982	June	October	5
1983	June	October	5
1984	May	October	6
1985	May	September	5
1986	April	October	7
1987	May	September	5
1988	May	September	5
1989	April	September	6
1990	June	October	5
1991	June	September	4
1992	July	October	4
1993	June	October	5
1994	June	September	4
1995	May	October	6
1996	May	September	5
1997	May	September	5
1998	June	October	5
1999	May	October	6
2000	May	October	6
2001	June	October	5
2002	May	October	6
2003	May	September	5
2004	May	October	6
2005	June	October	5
2006	May	September	5
2007	June	October	5
2008	April	October	7
2009	May	October	6
2010	May	November	7
2011	June	October	5
2012	April	September	6
2013	May	October	6
2014	June	September	4
2015	June	September	4
2016	April	October	7
2017	June	October	5
2018	April	September	6
2019	May	October	6
2020	June	October	5
2021	April	October	7
2022	April	October	7
2023	May	October	6

The beekeeping season was determined as the period during which the monthly mean temperature was ≥10 °C. Season onset was defined as the first month meeting this criterion, whereas season termination corresponded to the last such month.

The color scale represents the number of annual flight days from low to high.

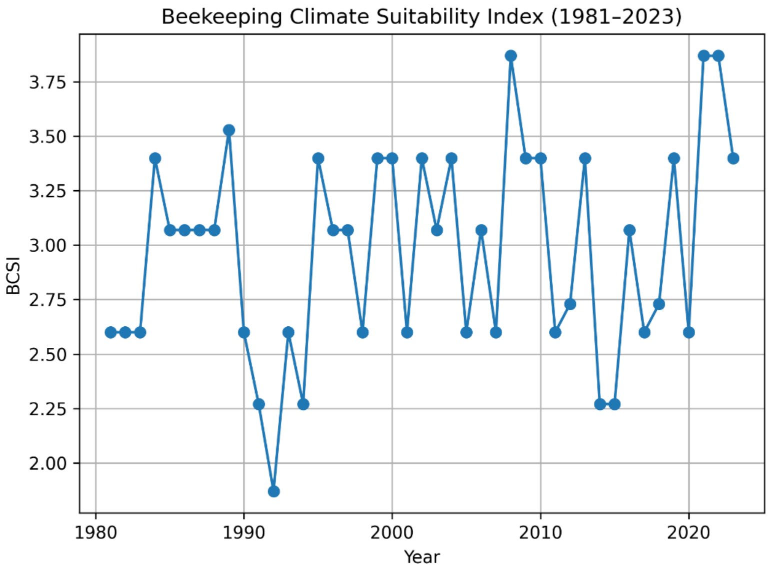

Figure 4. Temporal variation of the Beekeeping Climate Suitability Index (BCSI) in Türkiye (1981–2023). BCSI: Beekeeping Climate Suitability Index calculated based on flight days (F), flowering overlap (N), and nectar flow window (W).

Table 5. Interannual variability in the normalized beekeeping climate suitability index (BCSI) in Türkiye (1981–2023)

Year	Flight Days (F)	Flowering Flight Days (N)	Nectar Flow Window (W)	BCSI
1981	5	1.4	1.4	0.65
1982	5	1.4	1.4	0.65
1983	5	1.4	1.4	0.65
1984	6	2.1	2.1	0.87
1985	5	2.1	2.1	0.78
1986	6	1.6	1.6	0.75
1987	5	2.1	2.1	0.78
1988	5	2.1	2.1	0.78
1989	6	2.3	2.3	0.94
1990	5	1.4	1.4	0.65
1991	4	1.4	1.4	0.57
1992	4	0.8	0.8	0.44
1993	5	1.4	1.4	0.65
1994	4	1.4	1.4	0.57
1995	6	2.1	2.1	0.87
1996	5	2.1	2.1	0.78
1997	5	2.1	2.1	0.78
1998	5	1.4	1.4	0.65
1999	6	2.1	2.1	0.87
2000	6	2.1	2.1	0.87
2001	5	1.4	1.4	0.65
2002	6	2.1	2.1	0.87
2003	5	2.1	2.1	0.78
2004	6	2.1	2.1	0.87
2005	5	1.4	1.4	0.65
2006	5	2.1	2.1	0.78
2007	5	1.4	1.4	0.65
2008	7	2.3	2.3	1.00
2009	6	2.1	2.1	0.87
2010	6	2.1	2.1	0.87
2011	5	1.4	1.4	0.65
2012	5	1.6	1.6	0.71
2013	6	2.1	2.1	0.87
2014	4	1.4	1.4	0.57
2015	4	1.4	1.4	0.57
2016	6	1.6	1.6	0.75
2017	5	1.4	1.4	0.65
2018	5	1.6	1.6	0.71
2019	6	2.1	2.0	0.85

BCSI values are normalized between 0 and 1, with higher values indicating more favorable climatic conditions for beekeeping.

DISCUSSION

This study provides a comprehensive evaluation of the interactions among honey bee flight activity, plant flowering phenology, and climatic variability at the national scale in Türkiye. The results demonstrate that climatic conditions play a decisive role in shaping both the temporal availability of suitable flight conditions and their alignment with flowering periods of nectar plants. Long-term changes in honey bee populations and environmental pressures have been widely documented (Meixner 2010). Recent studies have shown that climate change is reshaping pollinator distributions globally (Soroye et al. 2020).

The observed interannual variability in suitable flight periods (4–7 months) highlights the strong influence of climate variability on beekeeping conditions. Although a slight upward trend was detected, the lack of statistical significance suggests that variability, rather than a consistent directional change, remains the dominant feature. Similar findings have been reported in previous studies emphasizing that short-term climate variability can be as important as long-term trends in determining pollinator activity (Goulson et al. 2015, Soroye et al. 2020).

One of the most important findings of this study is the pronounced seasonal gradient in flight–flowering synchrony. Early spring-flowering species exhibited low flight suitability due to suboptimal temperature and precipitation conditions, whereas summer-flowering species showed near-optimal conditions for bee activity. This result is consistent with studies reporting that climate-driven phenological shifts may lead to temporal mismatches between plants and pollinators (Forrest 2015, Kudo and Ida 2013). In this context, the findings suggest that early-season nectar sources may become increasingly unreliable under variable climatic conditions, with implications for colony buildup and early-season foraging success. In addition, climate-driven changes in atmospheric conditions may alter pollen nutritional quality, further affecting bee health and foraging efficiency (Ziska et al. 2016).

From an apicultural perspective, the observed variability has direct implications for colony development, honey yield, and migratory beekeeping practices. Reduced synchronization in early spring may limit brood development due to insufficient nectar and pollen availability, while high synchronization during summer provides optimal conditions for colony expansion and honey production. Therefore, climate-driven variability should be considered a key factor in planning colony movements and optimizing resource utilization.

From an applied perspective, these results are particularly relevant for migratory beekeeping practices. The substantial year-to-year variability in suitable flight periods and nectar-flow windows suggests that fixed beekeeping calendars may no longer be effective. Instead, adaptive strategies informed by climate are required. Integrating climate-based indicators into decision-making processes may improve the timing of colony movement, optimize nectar flow utilization, and enhance overall productivity.

The Beekeeping Climate Suitability Index (BCSI) developed in this study provides a potentially useful integrative framework for assessing climatic suitability for beekeeping. By combining flight activity, flowering overlap, and nectar flow window, the index captures multiple dimensions of bee–plant–climate interactions. Unlike approaches focusing on single variables, the BCSI enables a more holistic assessment of beekeeping conditions. Similar multi-component indices have been widely used in ecological and agricultural studies to evaluate environmental suitability and system performance. To further support the conceptual robustness of the BCSI, its components and underlying assumptions were evaluated against established ecological and apicultural knowledge, demonstrating strong consistency with previously reported mechanisms

The conceptual basis of the BCSI is consistent with established ecological and apicultural knowledge. The flight activity component reflects the well-documented dependence of honey bee foraging on suitable temperature and precipitation conditions (Abou-Shaara 2014, Heinrich 1993). The flowering overlap component represents the temporal synchronization between honey bee activity and plant flowering, which is a fundamental aspect of plant–pollinator interactions (Cleland et al. 2007, Forrest 2015). Similarly, the nectar flow window characterizes the coincidence of favorable climatic conditions with the availability of nectar resources (Abou-Shaara 2014). The seasonal variability component reflects interannual changes in climatic suitability, which are consistent with the effects of climate variability and environmental stressors on pollinator activity reported in previous studies (Goulson et al. 2015, IPCC 2021). By integrating these climatic and biological components, the BCSI provides a composite representation of beekeeping suitability and strengthens the conceptual robustness of the proposed index.

The validity of the BCSI approach is further supported by its consistency with previously reported apicultural and phenological studies conducted in Türkiye and elsewhere. Previous investigations have shown that the effective beekeeping season in Eastern Anatolia is largely confined to late spring and summer (Genç and Dodoloğlu 2002), which agrees with the shorter period of suitable climatic conditions identified by the BCSI during early spring. Likewise, climate-induced changes in flowering phenology and seasonal timing have been widely documented (Cleland et al. 2007, Kudo and Ida 2013), supporting the seasonal variability and potential plant–pollinator mismatches identified in the present study. Studies describing pollination dynamics and the importance of nectar plants in Türkiye (Özbek 2003, Özbek 2011) further support the flowering-overlap and nectar-flow components incorporated into the BCSI. Moreover, the strong influence of environmental stressors on pollinator activity reported by Goulson et al. (2015) is consistent with the climatic sensitivity reflected by the index. Finally, the considerable year-to-year variation in honey production reported by the Turkish Statistical Institute (2024), the Ministry of Agriculture and Forestry (2024), and FAO (2024) closely matches the interannual variability captured by the BCSI. Although long-term integrated datasets remain limited, the close agreement between independent apicultural observations, phenological evidence, and BCSI outputs provides robust indirect evidence supporting the ecological validity and practical applicability of the proposed index.

Importantly, the use of normalized components enables direct comparisons across years, making the index suitable for long-term monitoring applications. The results demonstrate that BCSI effectively captures interannual variability and identifies years with particularly favorable or unfavorable conditions for beekeeping.

Despite these contributions, several limitations should be acknowledged. First, the analysis was based solely on temperature and precipitation, while other relevant variables such as wind speed, solar radiation, and relative humidity were not included. These factors may influence flight behavior at local scales. Second, flowering phenology was treated as static due to the lack of long-term observational datasets, which may not fully reflect climate-driven shifts in flowering timing. Third, the use of national-scale aggregation may obscure important regional differences in climatic suitability.

Future research should focus on integrating additional meteorological variables, incorporating dynamic phenological models, and conducting region-specific analyses. The application of higher-resolution datasets and the inclusion of field-based observations would further improve model accuracy and ecological relevance.

Overall, this study advances understanding of climate-driven bee–plant interactions by providing a quantitative, integrative framework. The proposed approach has significant potential for application in climate change impact assessments and for supporting adaptive beekeeping strategies in heterogeneous environments.

In summary, the results demonstrate that climatic variability plays a decisive role in determining both the duration of suitable flight periods and their alignment with plant flowering. The observed seasonal mismatch, particularly in early-spring species, indicates potential risks to colony development and early-season resource availability. The BCSI developed in this study provides a practical and integrative tool for evaluating beekeeping suitability under variable climatic conditions. From an applied perspective, the findings suggest that fixed beekeeping calendars may no longer be sufficient, and adaptive, climate-informed management strategies are required to optimize colony productivity and nectar flow utilization.

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REFERENCES

Abou-Shaara HF. The foraging behaviour of honey bees, *Apis mellifera*: a review. Vet Med 2014; 59:1–10. http://doi.org/10.17221/7240-VETMED

Cleland EE, Chuine I, Menzel A, Mooney HA, Schwartz MD. Shifting plant phenology in response to global change. Trends Ecol Evol 2007;22:357–365. http://doi.org/10.1016/j.tree.2007.04.003

Corbet SA, Fussell M, Ake R, Fraser A, Gunson C, Savage A, Smith K. Temperature and the pollinating activity of social bees. Ecol Entomol 1993;18:17–30. http://doi.org/10.1111/j.1365-2311.1993. tb01075.x

Davis PH. Flora of Turkey and the East Aegean Islands. Vols. 1–9. Edinburgh University Press, Edinburgh, Scotland, 1965–1985

FAO. FAOSTAT database. https://www.fao.org/faostat (accessed: 20.05.2026)

Forrest J. Plant–pollinator interactions and phenological change. Oikos 2015;124:4–13. http://doi.org/10.1111/oik.01386

Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, et al. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science 2013;339:1608–1611. http://doi.org/10.1126/science.1230200

Genç F, Dodoloğlu A. Basic principles of beekeeping. Atatürk University Faculty of Agriculture Lecture Notes, Erzurum, Türkiye, 2002, p.1–338

Goulson D, Nicholls E, Botías C, Rotheray EL. Bee declines driven by combined stressors. Science 2015;347. http://doi.org/10.1126/science.1255957

Güner A, Aslan S, Ekim T, Vural M, Babaç MT (eds.). Türkiye Bitkileri Listesi (Damarlı Bitkiler). Nezahat Gökyiğit Botanik Bahçesi ve Flora Araştırmaları Derneği Yayınları, İstanbul, Türkiye, 2012

Hargreaves GH, Samani ZA. Reference crop evapotranspiration from temperature. Appl Eng Agric 1985;1(2):96–99. http://doi.org/10.13031/2013.26773

Heinrich B. The hot-blooded insects: strategies and mechanisms of thermoregulation. Harvard University Press, London, England, 1993

IPCC. Climate Change 2021: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom, 2021. http://doi.org/10.1017/9781009157896

Kendall MG. Rank Correlation Methods. Griffin, London, England, 1975

Klein AM, Vaissiere BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, et al. Importance of pollinators in changing landscapes for world crops. Proc R Soc B 2007; 274:303–313. http://doi.org/10.1098/rspb.2006.3721

Kovac H, Stabentheiner A. Thermoregulation of foraging honey bees on flowering plants: seasonal variability and influence of radiative heat gain. Ecol Entomol 2011;36:686–699. http://doi.org/10.1111/j.1365-2311.2011.01313.x

Kudo G, Ida TY. Early onset of spring increases phenological mismatch. Ecology 2013;94:2311–2320. http://doi.org/10.1890/12-2003.1

Le Conte Y, Navajas M. Climate change: impact on honey bees. Rev Sci Tech 2008;27:499–510

Mann HB. Nonparametric tests against trend. Econometrica 1945;13:245–259. http://doi.org/10.2307/1907187

Meixner MD. A historical review of managed honey bee populations in Europe and the United States. J Invertebr Pathol 2010;103:S80–S95. http://doi.org/10.1016/j.jip.2009.06.011

Menzel A, Sparks TH, Estrella N, Koch E, Aasa A, Ahas R, et al. European phenological response to climate change matches the warming pattern. Glob Change Biol 2006; 12:1969–1976. http://doi.org/10.1111/j.1365-2486.2006.01193.x

Ministry of Agriculture and Forestry. Beekeeping statistics in Türkiye (1991–2025). https://www.tarimorman.gov.tr (accessed: 20.05.2026)

Muñoz-Sabater J, Dutra E, Agustí-Panareda A, Albergel C, Arduini G, Balsamo G, et al. ERA5-Land: A global reanalysis dataset for land applications. Earth Syst Sci Data 2021; 13:4349–4383. http://doi.org/10.5194/essd-13-4349-2021

Nardo M, Saisana M, Saltelli A, Tarantola S, Hoffman A, Giovannini E. Handbook on constructing composite indicators: methodology and user guide. European Commission Joint Research Centre, Brussels, Belgium, 2005

OECD. Handbook on constructing composite indicators: methodology and user guide. OECD Publishing, Paris, France, 2008

Özbek H. Bees and pollination problem in Türkiye. Uludag Bee J 2003;3(3):41–44

Özbek H. Sainfoin (*Onobrychis viciifolia* Scop.): an important nectar plant. Uludag Bee J 2011;11(2):51–62

Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural systems. Nature 2003;421:37–42. http://doi.org/10.1038/nature01286

Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 2007; 11:1633–1644. http://doi.org/10.5194/hess-11-1633-2007

Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. Global pollinator declines: trends, impacts and drivers. Trends Ecol Evol 2010;25:345–353. http://doi.org/10.1016/j.tree.2010.01.007

Requier F, Odoux JF, Tamic T, Moreau N, Henry M, Decourtye A, Bretagnolle V. Honey bee diet in intensive farmland habitats reveals an unexpectedly high flower richness and a major role of weeds. Ecol Appl 2015; 25:881–890. http://doi.org/10.1890/14-1011.1

Seeley TD. The wisdom of the hive: the social physiology of honey bee colonies. Harvard University Press, Cambridge, USA, 1995

Sen PK. Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 1968; 63:1379–1389. http://doi.org/10.1080/01621459.1968.10480934

Sorkun K. Turkey's Nectar Plants, Pollen and Honey. Palme Publishing, Ankara, Türkiye, 2008

Soroye P, Newbold T, Kerr JT. Climate change contributes to widespread declines among bumble bees across continents. Science 2020; 367:685–688. http://doi.org/10.1126/science.aax8591

Tautz J. The Buzz about Bees. Springer, Berlin, Germany, 2008. http://doi.org/10.1007/978-3-540-78729-7

Thornthwaite CW. An approach toward a rational classification of climate. Geogr Rev 1948;38:55–94. http://doi.org/10.2307/210739

Turkish Statistical Institute (TÜİK). Livestock production statistics: honey production. http://data.tuik.gov.tr (accessed: 20.05.2026)

Vicens N, Bosch J. Weather-dependent pollinator activity in an apple orchard. Environ Entomol 2000;29:413–420. http://doi.org/10.1603/0046-225X-29.3.413

Ziska LH, Pettis JS, Edwards J, Hancock JE, Tomecek MB, Clark A, et al. Rising atmospheric CO2 reduces protein concentration of a floral pollen source. Proc Biol Sci 2016;283:20160414. http://doi.org/10.1098/rspb.2016.0414