MULTIFRACTAL DETRENDED FLUCTUATION ANALYSIS TO CHARACTERIZE HONEY BEE PRODUCTION IN SEMI-ARID ECOSYSTEMS

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SUMMARY

*Honey bee production could be considered as a reliable economic indicator of the biodiversity and availability of ecosystem services. The scaling behaviour of honey bee was analysed and associated to the natural ecosystem characteristics by using multifractal detrended fluctuation analysis (MF-DFA). Records of honey harvests and climatic conditions were collected monthly from 1998 to 2012 of 83 apiaries (Database=14,940 records) located in 24 different micro-regions (in central-north Mexico) where 'mesquite' (*Prosopis laevigata*) and plants of* Asteraceae *family are the primarily endemic sources of nectar and pollen. Micro-regions were classified as semi-warm semi-arid, semi-arid, or humid subtropical (Köppen Climate clasification; KC), and according to the agricultural uses of their surrounding areas as secondary vegetation (S), irrigated agriculture (IA) or rainfed agriculture (RA). Hurst exponents of segments (Hq) of honey bee production time series showed small fluctuations but random walk characteristic of multifractal (MF) structure. Left truncation and parameter values of honey bee harvests fractal spectra suggest local fluctuations of large magnitude with self-affine properties which represent long-term correlations useful for long-term predictions. Major variations of honey bee production in semi-arid climates have been produced by S, but it is also affected for the minimum temperature (T) and precipitation (P). MF-DFA allowed to identify fluctuations in honey bee production time series, associating it with climatic and land use variables, useful to make reliable long-term predictions of pollinators' diversity and honey bee harvests, and to design strategies to maintain ecosystems and increase the economic feasibility of apiculture.*

Introduction

Honey bees *(Apis mellifera)* are the most important pollinators for the commercial crops grown in many regions (Rucker *et al*., 2012; Champtier *et al*., 2015), their presence is related to other pollinator species (Gordo and Sanz, 2006) and therefore to the availability of forages which depend on pollinator (Medina-Cuéllar *et al*., 2014). Some authors have argued that using honey bees the pollinator-dependent crops can generate up to twice the income per hectare (Klein *et al*., 2007; Ashworth *et al*., 2009). Gallai *et al.* (2009) reported that USD 153×10^9 was spent globally on insect pollination for agriculture in 2005. In the USA, Ashworth *et al*. (2009) identified 145 pollinator-dependent cultivated plant species with a rural yield value of USD 5×10^9. Potential losses due to the disappearance of pollinators have been estimated as USD 15×10^9 (Rucker *et al*., 2012).

KEYWORDS / Climatic Change / Honey Harvest / Sustainable Development / Territorial Planning / Time Series /

Received: 01/16/2018. Modified: 06/11/2018. Accepted: 06/18/2018.

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ANÁLISIS MULTIFRACTAL DE FLUCTUACIÓN SIN TENDENCIA (MF-DFA) EN LA CARACTERIZACIÓN DE PRODUCCIÓN DE MIEL EN ECOSISTEMAS SEMI-ÁRIDOS

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RESUMEN

*La producción de miel de abeja podría considerarse un indicador de la biodiversidad y la disponibilidad de los servicios del ecosistema. A través de análisis multifractal de fluctuación sin tendencia (MF-DFA) se analizó el comportamiento escalar de producción de miel de abeja y se asoció con las características ambientales de ecosistemas semi-áridos. Se utilizaron registros de datos mensuales de cosechas de miel, variables climáticas y de uso del suelo de 83 colmenas de 1998 a 2012 (base de datos de 14,940 registros), ubicadas en 24 regiones del centro-norte de México, donde el mezquite (*Prosopis laevigata*) y flores de la familia* Asteraceae *son las principales fuentes de néctar y polen. Las regiones circundantes a los apiarios fueron clasificadas como semi-cálidas semiáridas, semiáridas o subtropicales húmedas (clasificación de Köppen), con vegetación secundaria (S), agricultura de riego (IA) o agricultura de temporal (RA). Los exponentes Hurst de segmentos de series de tiempo (Hq) de producción de miel mostraron fluctuaciones aleatorias, indicando una estructura multifractal (MF). El truncamiento izquierdo y valores de parámetros de espectros fractales mostraron propiedades autoafines útiles para pronósticos a largo plazo. Las principales variaciones en la producción de miel se atribuyen a cambios en S, y en segundo término a la temperatura mínima (T) y precipitación (P). Se muestra el potencial de MF-DFA para identificar fluctuaciones en la series de tiempo de producción de miel y asociarlas con variables climáticas y de uso del suelo, útiles para diseño y planeación de estrategias a largo plazo para mantener los ecosistemas y aumentar la viabilidad económica de la apicultura.*

ANÁLISE MULTIFRACTAL DE FLUTUAÇÃO SEM TENDÊNCIA (MF-DFA) NA CARACTERIZAÇÃO DE PRODUÇÃO DE MEL EM ECOSISTEMAS SEMIÁRIDOS

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RESUMO

A produção de mel de abelha poderia considerar-se um indicador da biodiversidade e da disponibilidade dos serviços do ecossistema. A través de análise multifractal de flutuação sem tendência (MF-DFA) se analisou o comportamento de escala de produção de mel de abelha e se associou com as características ambientais de ecossistemas semiáridos. Utilizaram-se registros de dados mensais de colheitas de mel, variáveis climáticas e de uso do solo de 83 colmeias entre 1998 e 2012 (base de dados de 14,940 registros), localizadas em 24 regiões do centro-norte do México, onde o mesquite (Prosopis laevigata) e flores da família Asteraceae são as principais fontes de néctar e pólen. As regiões circundantes aos apiários foram classificadas como moderadamente quente semiáridas, semiáridas ou subtropicais úmidas (classificação de Köppen), com vegetação secundária (S), agricultura de irrigação (IA) ou agricultura de sequeiro (RA). Os exponentes Hurst de segmentos de séries de tempo (Hq) de produção de mel mostraram flutuações aleatórias, indicando uma estrutura multifractal (MF). O truncamento esquerdo e valores de parâmetros de espectros fractais mostraram propriedades auto-afins úteis para prognósticos de longo prazo. As principais variações na produção de mel se atribuem a mudanças em S, e em segundo lugar a temperatura mínima (T) e precipitação (P). Mostra-se o potencial de MF-DFA para identificar flutuações na série de tempo de produção de mel e associá-las com variáveis climáticas e de uso do solo, úteis para desenho e planejamento de estratégias de longo prazo para manter os ecossistemas e aumentar a viabilidade econômica da apicultura.

Regardless the importance of honey bee production as a reliable local economic index for the production of pollinator-dependent crops (Klein *et al.*, 2007), maintaining semi-natural favorable areas to pollination also contributes to achieve sustainability (Ricou *et al.*, 2014). In some semi-arid zones of central-north of Mexico, 'mesquite' (*Prosopis laevigata*), a Fabaceae, is the most important source of pollen and nectar for pollinators (Gelviz-Galvez and Pavón-Hernández, 2013; Valenzuela *et al.*, 2015), and as in other regions wild flowers play a key role for honey production in other seasons (Wratten *et al.*, 2012; Benelli *et al.*, 2014; Campolo *et al.*, 2014, 2016).

In order to protect ecosystems it is necessary to quantify the impact of productive activities and planning strategies to maintain or restore the natural covers (Menz *et al.*, 2011; Wratten *et al.*, 2012; Benelli *et al.*, 2014). Deforestation and intensive production contribute to global greenhouse gases emission (GHG; Tirado-Estrada *et al.*, 2018), to desertification process, soil impoverishment, and negative impact the water quality (Menz *et al.*, 2011; Wratten *et al.*, 2012). Consequently, the modeling of honey production can associate climatic changes, availability of predominant nectar sources, and the phenological development of the bees (Lobell and Burke, 2010; Zoccali *et al.*, 2017), and calculate these environmental services in local incomes (Medina-Cuéllar *et al.*, 2014, 2018).

Short time series and very short fluctuations cannot always be adequately represented (Medina-Cuéllar *et al.*, 2014; Thompson and Wilson, 2016), and detrended fluctuation analysis (DFA) can be an alternative to identify correlations in time series. A fractal is a rough or fragmented geometrical shape that can be subdivided into parts, which are reduced-size copies of the whole (Mali and Mukhopadhyay, 2015). The use of multifractal detrended fluctuation analysis (MF-DFA) was introduced to characterize the correlations and fluctuations of specific segments of nonstationary time series that are affected by trends, or that cannot be normalized (Kantelhardt *et al.*, 2001). MF-DFA is sensitive enough to identify small or large fluctuations, as long-term correlations, even in short time series (Gu and Zhou, 2010), allowing the clustering of information into time periods or geographical spaces of time series (Baranowski *et al.*, 2015; Mali and Mukhopadhyay, 2015).

DFA has been extensively used in the identification of short and long-range correlations in time series that exhibit a nonstationary behaviour (Peng *et al.*, 1994; Mali and Mukhopadhyay, 2015) and to study complex dynamic systems (Ivanova and Ausloos, 1999), such as stock indexes (Matia *et al.*, 2003; Lu *et al.*, 2013), econometrics (Ausloos and Ivanova, 2002), and markets (Mali and Mukhopadhyay, 2015).

In order to model the honey harvest, the aim of present study was to apply MF-DFA to identify spatial and temporal correlations and to cluster honey harvest according to geographical regions differentiated by their climatic and agriculture conditions.

Materials and Methods

Data collection and statistical analysis

Data source. Honey bee production data was collected from 4,901 beehives from Aguascalientes, México, located at 22º27'-21º38'N and 101º53'-102º52›W, which accounted for 55% of the region inventory (SAGARPA, 2012). Final database included records of climatic conditions as precipitation (P) and average medium temperature (T), and honey production collected monthly from 1998 to 2012 of 83 apiaries. Thus, the database contained 14,940 records (12 months × 15 years × 83 apiaries; 4,901 beehives nested in 83 apiaries).

Environmental and climatic conditions. Georeferenced information was collected from 24 local meteorological stations was provided by INEGI (2013) and included data about land use in the surrounding areas (ha) used for irrigated agriculture (IA), rainfed agriculture (RA), secondary vegetation (primarily scrubs; S), and urban areas. The 83 apiaries were associated with the nearest meteorological stations, each one represented a micro-region of 6km diameter, and minimum temperatures (T; ºC) and rainfalls (P; mm) were daily collected and monthly calculated (CONAGUA, 2010) from 1998 to 2012. Surrounded areas to meteorological stations were classified according to the Köppen climatic classification (Kottek *et al.*, 2006).

Mathematical descriptions

Detrended fluctuation analysis (DFA). According to the equations and algorithms described by Kantelhardt *et al.* (2002) and Gu and Zhou (2010), honey bee production time series (x1, x2, . . . , xN) were converted into a random walk integrating the deviations from the average, after that random walk trajectory was divided into segments $n = \frac{N}{s}$ of length (s). Trends were eliminated in each segment, integrating a fitting time series to a polynomial function yf it(i), which represents the local trend of segment (ν). The polynomial m degree is the eliminated trend (DFA-m). To measure the fitting of fluctuation (F), root mean squares of segments (Ihlen, 2012), and means of the fluctuations F(s) were estimated. F(s) ~sα, and alpha (α) was the linear fitting function on a log −log plot of F(s) against s; thereby α is an estimation of the Hurst exponent (H) of the time series (Peng *et al.*, 1995; Kantelhardt *et al.*, 2001).

The *multifractal detrended fluctuation analysis* (MF-DFA). The DFA was modified by evaluating different q moments to weight fluctuations, following the same procedure but including segments starting from the opposite end of the series to obtain 2Ns segments together (Kantelhardt *et al.*, 2002). The power-law relation between function Fq (s) and the size scale s is Fq (s) $\approx s^{h(q)}$, and H(q) were considered as the standard multifractal formalism [τ (q)] (Mandelbrot, 1982, 1989; Evertsz and Mandelbrot, 1992) to the multifractal scalingexponents [considering that τ(q)= qh(q) - 1 (when q= 2)] (Kantelhardt *et al.*, 2002; Gu and Zhou, 2010). Generalized multifractal dimensions were $\left(D_{(q)} = \frac{\tau(q)}{q-1} = \frac{qh(q)-1}{q-1}\right)$. Singularity strength α represents an H associated with a different moment q (Hq) (Chhabra and Jensen, 1989), and singularity multifractal spectrum f (α) is the dimension of the series characterized by α, therefore f (α) was related to τ (q) through a Legendre transform.

Differential evolution (DE). To optimize scaling and the degree of polynomial fitting on our method, a DE algorithm was implemented to obtain optimized non-fixed parameters according to the methods described by Storn and Price (1997). The objective of DE was to minimize the cost function: Fobj ($\vec{X}$): Ω ⊆ RD→ R. The DE procedure begins with NP D-dimensional parameter vectors $\vec{X}_{i,G}$ i=1, . . . , NP at generation G, and floating point values represent populations of potential solutions, assuming ∈ R^D when executing mutation and crossover operations. An initial vector was randomly obtained to generate a population of solutions, establishing upper and lower boundaries for each parameter. During vector generation, G + 1 DE was tested for each vector of the population. The problem domain Ω was explored by proposing a 'differential mutation', which defines a mutant $\mathbf{V}_{i,G}$ vector for each target vector with index **i**. Next, a crossover operation was executed by combining the components of the target $\vec{\mathbf{X}}_{i,G}$ and mutant $\vec{\mathbf{V}}_{i,G}$ vectors. The selection operation that was done after a trial vector ($\vec{\mathbf{U}}_{i,G}$) by comparing it with the corresponding target vector ($\vec{\mathbf{V}}_{i,G}$), which will be replaced in the next generation (G + 1) if it is best fitted. DE steps are repeated some generations (G) until the number of predetermined iterations is reached.

Objective function target for DE optimization. To find an adequate objective function (Fobj) it was defined a set (Q= {qk_1 , . . . , qk_r}) containing the moment values of q. The global optimization of the function (Fobj) minimized the error for fitting logarithmic values of Fq and sq (Fq (s) ≈ $s^{h(q)}$). The vector for optimization included the degree (m) of the polynomial y_v, used for fitting the segments ν.

Program implementation

MF-DFA and DE were modified to work together and to communicate at each iteration so that the MF-DFA process was optimized by DE. MF-DFA was implemented in MATLAB (Math-works, 2015) using available algorithms (Gu and Zhou, 2010; Ihlen, 2012, 2013). The method of differential algorithms was implemented in the MATLAB environment using the DE algorithms of López *et al.* (2003). For the DE implementation a random initial population was considered. Each vector's elements were delimited maintaining original floating point representations for the differential operations of DE. The population size was N P= 60, DE scale factor F= 0.80, and crossover probability Cr= 0.50. To reach the nearest optimal value of Fobj using DE, each value was found in a convergence rate after running each execution for 1 to 250 iterations, and each optimization was made 20 times (20 repetitions).

To minimize the run time of the program for fitting the data segments for detrending, we applied a low-level routine provided by the GNU Scientific Library (GSL) (Galassi, 2009), performed in parallel the selection of vectors target xxi,G and mutant xvi,G using the code described by Lampinen (1999).

Statistical analysis

Statistical analysis was performed using the SAS statistical software (Statistical Analysis System, 2013). For the variables T and P an analysis of variance (ANOVA) was carried out using a completely randomized statistical design (CRD), considering the fixed effect of the meteorological station (St) and the random effects of the months (Rep) within the Years [Rep(Year)], according to Model 1. W (Spectrum width: $\alpha_{max} - \alpha_{min}$) and α_0 [maximum of the $f(\alpha)$ function] were also analysed using ANOVA in a CRD considering the fixed effects of Köppen climate classification (KC) meteorological stations, and the description of agricultural use of the surrounding areas (SD) in proximity to apiaries, according to Model 2. The general lineal model procedure (Proc GLM) was used to obtain the coefficients of variation and of determination. Least squares means were estimated (LsMeans) and reported. Minimum significant differences (MSE= 0.05) were calculated to find statistical differences between means.

$$Y=\mu+[Rep(Year)]_{i(j)}+St_k+\varepsilon_{ijk} \text{ (Model 1)}$$

where Y: average minimum temperature and precipitation, μ: general mean, $[Rep(Year)]_{i(j)}$: random effect of the i-th month in the j-th sampled year, St_k: effect of the k-th station (micro-region), and ε_{ijk}: random error.

$$Y= \mu + [SD(KC)]_{i(j)} + \varepsilon_{ijk} \text{ (Model 2)}$$

where Y: width of the spectrum and the maximum of the $f(\alpha)$ function, μ: general mean, $[SD(KC)]_{i(j)}$: effect of the i^{th} description of agricultural use of surrounding areas nested in the j^{th} Köppen climate classification, and ε_{ijk}: random error.

Clustering analysis

Clusters-in operations were performed to find the order-of-magnitude relations between the parameter values of honey bee production spectra (α_0 and W), using average linkage clustering analysis (ALCA), implemented using a cluster procedure in SAS (Proc Cluster; Statistical Analysis System V. 9.2).

Results and Discussion

Characterization of the study zone

The regions including the surroundings of apiaries near meteorological stations are presented in Table I. These micro-regions had an annual adjusted T of 17.52 ±3.42ºC and P of 42.49 ±12.71mm/month (509.64mm/year). Precipitation occurs mainly from June to September. Six micro-regions are classified as semi-warm semi-arid (BS1hw) with T and P 18.02 ±3.48ºC and 48.24 ±13.16mm/month, 16 micro-regions as warm semi-arid (BS1k”w) with T=17.20 ±3.40ºC and P=40.19 ±12.60 mm/month, and two were humid subtropical [C(Wo)] micro-regions, with T= 18.57 ±3.38ºC, and P= 43.52±12.2 mm/month. Surrounding areas (ha) to apiaries located in BS1hW areas have been used for IA and RA, apiaries in BS1k”w have been near IA, RA and S areas, and apiaries in C(Wo) are near S areas (with secondary vegetation).

Overall, in semi-natural areas *Asteraceae* and *Fabaceae* species are the primary source of nectar for pollinators in the region (Gelviz-Galvez and Pavón-Hernández, 2013), specially ‘mesquite’ (*Prosopis laevigata*), and temperature-dependent wild flowers such as *Tithonia tubiformis* (Jacq.) Cass. and *Bidens leucantha* Willd., with the highest densities observed in S areas. They have been positively correlated with honey bee production (Medina-Cuéllar *et al*., 2014, 2018).

Multifractal spectrum of honey production

The use of different range scales and degrees for detrending polynomials over the same set of data {xi} on the calculated values of H and their spectra generates different range scales and degrees for detrending polynomials, and lead to different values of H. DE was implemented to select MF-DFA parameters. The standard deviations of convergence to Fobj for 20 repetitions, showed a standard deviation of 0.016 after 250 interactions, after which MF-DFA reached adequate logarithmic fitting for the evaluation of the scaling exponents. Since DE applies mutation and crossover to obtain optimized parameters not fixed at local minimums (Ló-

TABLE I
ADJUSTED MEANS§ FOR PRECIPITATION AND MINIMUM TEMPERATURE AT EACH OF THE METEOROLOGICAL STATIONS FOR THE YEARS 1998 TO 2012.

Region*	Station	T (ºC/d)	S.D.	P (mm/month)	S.D.	KC classification	Description
Ags.	1005	18.52	3.33	47.8	12.21	BS1hw	Irrigated
Ags.	1022	17.68	3.29	44.84	14.85	BS1hw	Rainfed
Ags.	1079	17.99	3.31	49.44	14.7	BS1hw	Rainfed
Calv.	1012	18.97	3.67	53.49	11.33	BS1hw	Irrigated
Calv.	1023	17.62	3.73	48	13.02	BS1hw	Irrigated
JM	1080	17.32	3.55	45.84	12.83	BS1hw	Urban area
Ags.	1024	17.47	3.36	33.11	10.85	BS1k”w	Rainfed
Ags.	1076	17.8	3.67	46.66	12.56	BS1k”w	Irrigated
Ags.	1096	15.61	3.38	46.13	13.17	BS1k”w	Rainfed
Asi.	1028	16.73	2.64	40.34	12.71	BS1k”w	Irrigated
Asi.	1085	15.92	3.74	41.51	12.1	BS1k”w	Irrigated
Cosio	1088	17.66	3.27	36.65	11.58	BS1k”w	Irrigated
Llano	1015	17.56	3.44	47.58	12.56	BS1k”w	Secondary
Llano	1033	17.06	3.36	43.14	10.74	BS1k”w	Rainfed
Llano	1034	16.19	2.91	41.95	13.45	BS1k”w	Secondary
Llano	1073	18.32	3.27	43.47	11.55	BS1k”w	Secondary
Llano	1101	16.58	3.27	39.28	14.01	BS1k”w	Rainfed
PA	1014	17.33	3.68	36.67	13.83	BS1k”w	Irrigated
RR	1082	16.35	3.78	35.23	16.13	BS1k”w	Irrigated
SFR	1083	17.87	3.92	36.48	13.33	BS1k”w	Irrigated
SJG	1019	18.75	3.28	39.69	11.69	BS1k”w	Rainfed
Tep.	1026	18.05	3.38	35.07	11.34	BS1k”w	Rainfed
Ags.	1074	18.17	3.30	37.57	11.25	C(Wo)	Secondary
Calv.	1020	18.97	3.46	49.47	13.25	C(Wo)	Secondary

§ Adjusted means: LsMeans obtained from Model 1.
* Meteorological station. Ags.: Aguascalientes, Calv.: Calvillo: Asi.: Asientos, JM: Jesús María, Cosio: Cosío, Llano: El Llano, PA: Pabellón de Arteaga, RR: Rincón de Romos, SFR: San Francisco de los Romos, SJG: San José de Gracia, Tep.: Tepezalá.
T: annual average minimum temperature from 1998 to 2012, P: annual average precipitation from 1998 to 2012, S.D.: standard deviation, KC: Köppen classification, BS1hw: semi-warm semi-arid, BS1k”w: semi-arid, C(Wo): humid subtropical.

pez *et al.*, 2003), in combination with MF-DFA reduced the errors (Mandelbrot, 1982, 1989; Evertsz and Mandelbrot, 1992), allowing to reach reliable multifractal spectra of honey production time series useful in identifying both short- and long-range correlations.

In Figure 1 the set of generalized H and multifractal curves correspond to the maximum, mean and minimum values of Fobj, and the points plotted are the best set of scales adjusted with DE. Although Q exponents were small, the decreasing Hq indicates that these segments have small fluctuations but random walk and thus multifractal structures (Gu and Zhou, 2010; Ihlen, 2012).

The multifractal spectra represent the honey harvest production of micro-regions (Figure 2). Because almost all of the fractal spectra in our study show a left truncation, those multifractal structures were especially sensitive to large magnitude, local fluctuations (Ihlen, 2012). This suggests that MF-DFA is useful to identify long-term correlations in time series and to make long-term predictions even through short-term variables.

The present study is consistent with scaling properties (statistical-self-similarity) previously reported for agrometeorological variables (Baranowski *et al.*, 2015), where the term fractal has been used to describe functions of invariant scales and, thus, each function is similar to the whole (self-similarity) (De Souza and Pires, 2011). MF-DFA could identify long-term self-similarities or irregular behaviour in honey bee production time series caused by micro-regions or climate changes. Although it is not possible to control natural climate changes, long-term forecasts about the effect of climatic variations on production allow to propose valid strategies for different geographic and temporal scenarios. Long-term conservation strategies of pollinator habitat would consist in promoting the semi-natural biodiversity by preventing deforestation, restoring plantings to attract and sustain pollinators, preserving flower species near crop systems, introducing wild flowers to no-cropped farms, and avoiding pesticide usage (Menz *et al.*, 2011; Ricou *et al.*, 2014; Wratten *et al.*, 2012; Benelli *et al.*, 2014).

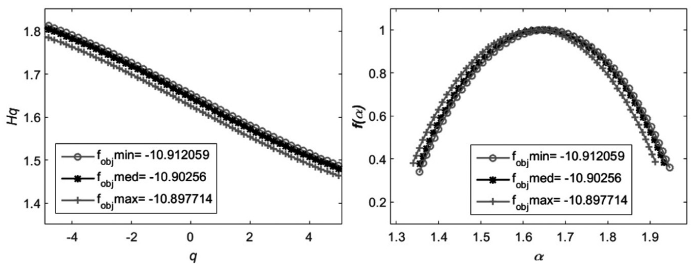

Figure 1. Multifractal spectrum optimized by differential evolution (DE) on multifractal detrended fluctuation analysis (MF-DFA). Maximum, median, and minimum values of the objective function.

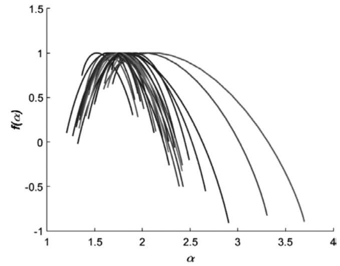

Figure 2. Multifractal spectrum of honey bee production time series (1998 to 2012) assigned to meteorological stations (micro-regions).

Relation between production spectra and land use

Average linkage clustering analysis was used to identify the relationships of honey harvest production spectra in micro-regions and climate or geographical factors (Figure 3). In Figure 3a, the signatures corresponding to the semi-arid climates (BS1hw and BS1k"w) present a narrow spectrum of α_0 and W exponents, whereas the humid subtropical climate [C(Wo)] present wider ranges, tending more to a MF behaviour. Cluster analysis of W primarily identified two distinct groups of micro-regions (Figure 3b): 1) semi-arid (BS1hw and BS1k"w) climates; and 2) humid subtropical [C(Wo)] climates. Afterwards, analysis showed four sub-groups. The first sub-group (Cluster-1) includes stations 1005, 1022, 1079, 1012, 1023, and 1080 in regions Aguascalientes, Calvillo and Jesús María, all with a semi-warm semi-arid (BS1hw) climate. The second sub-group (Cluster-2) includes stations 1024, 1034, 1096, 1028, 1085, 1088, 1076, 1033, 1019, 1073, 1101, 1014, 1082, 1083, 1015, and 1026 in regions Aguascalientes, Asientos, Cosío, El Llano, Pabellón de Arteaga, Rincón de Romos, San Francisco de los Romo, San José de Gracia, and Tepezalá, all with a warm semi-arid (BS1k"w) climate. The third and fourth sub-groups (Cluster-3 and Cluster-4) included the stations 1074 and 1020 in the Aguascalientes and Calvillo regions, both with humid subtropical [C(Wo)] climate. This suggests that variations of honey bee production was firstly correlated with the Köppen climatic classification and, secondly, due to vegetative cover variations among regions.

In Table II, statistical analysis for W and α_0 exponents showed differences among the areas and zones with IA, RA, and S, which represent variations in the underlying process of honey production, and the singularity multifractal spectrum exponent f(α) related to the Hq (fractal structure of the time series; H are the slopes of the regression line for each q-order of rot mean squares of the segments) (Chhabra and Jensen, 1989; Ihlen, 2012).

All the adjusted means were α_0>0.5 (1.788, 1.709, and 2.049 for IA, RA, and S, respectively; P<0.03) showing self-affine properties among all the micro-regions (Kantelhardt *et al.*, 2001; Thompson and Wilson, 2016). With long-term correlations (Ihlen, 2012), W exponents were wider in areas surrounding apiaries with S than in areas with irrigated or rainfied agriculture (P<0.004; 1.56

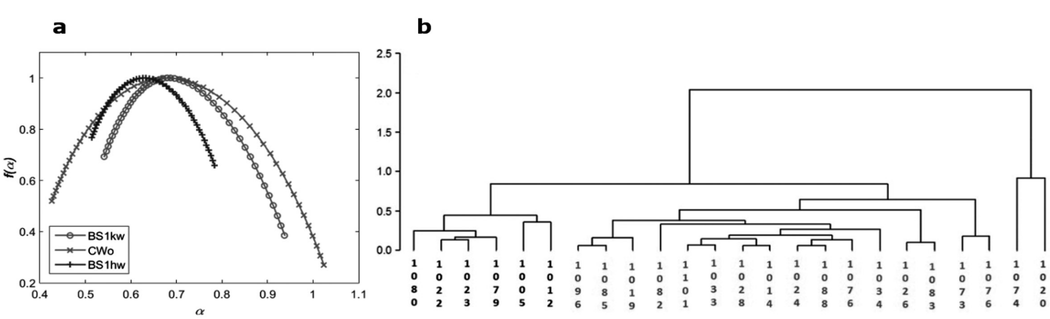

Figure 3. Clustering analysis. a: Average linkage clustering analysis. Cluster-1: the micro-regions 1080, 1022, 1023, 1079, 1005 and 1012 correspond to semi-warm semi-arid climate (BS1hw); Cluster-2: 1096, 1085, 1019, 1082, 1101, 1033, 1028, 1014, 1024, 1088, 1076, 1034, 1026, 1083, 1073 and 1076 correspond to warm semi-arid climate (BS1k"w); Cluster-3 and Cluster-4: 1074 and 1020 correspond to humid subtropical climate [C(Wo)]. 500 DPI. MATLAB Graphics V. 2015. b: Multifractal signature of honey bee production time series for BS1hw, BS1k"w and C(Wo) climate regions.

TABLE II
PARAMETER VALUES FOR MULTIFRACTAL DETRENDED FLUCTUATION ANALYSIS (MF-FDA) SPECTRA OF HONEY BEE PRODUCTION FROM 1998 TO 2012 IN 24 MICRO-REGIONS WITH DIFFERENT CLIMATES CLASSIFICATION AND LAND USES

KC Classification *	Description of land use	α_0	W
BS1hw	Irrigated agriculture	1.749 d	0.574 e
	Rainfed agriculture	1.603 e	0.534 e
BS1k”w	Irrigated agriculture	1.826 c	0.950 c
	Secondary vegetation	1.980 b	1.201 b
	Rainfed agriculture	1.814 c	0.870 d
C(Wo)	Secondary vegetation	2.118 a	1.919 a
SEM		0.02	0.024
VC (%)		5.44	12.65
R^2		0.69	0.92
P-values			
KC Classification		0.0002	<0.0001
Description land use		0.03	0.004
KC*Description		0.09	0.737

*KC, Köppen climate classification; α_0 value corresponding to the maximum f(α); W, width of spectrum ($W=\alpha_{max} - \alpha_{min}$); BS1hw, semi-warm semi-arid; BS1k”w, semi-arid; C(Wo), humid subtropical; a, b, c, d, e, means with distinct letter are significant different (SMD=0.05); P-Values, probability values of F test; SE, standard error; VC, variation coefficient, R^2, determination coefficient.

vs 0.762 and 0.702, for S *vs* IA and RF, respectively; P<0.004). This findings show that wider variations of honey bee productions can be primarily associated to changes of vegetative cover of S areas. However, W and α_0 exponents were also different among the climates, and show that less variation of honey bee production (W exponent) occurs in semi-arid climates [546 and 1.007 *vs* 1.919, for BS1hw and BS1k”w *vs* C(Wo), respectively] (P<0.0002).

Overall, areas with secondary vegetation (S) show higher diversity than those with primary vegetation in the respective ecosystems (Castillo-Campos *et al.*, 2008), which could contribute to the variation of honey bee production, but semi-arid regions with S included in present study have fewer vegetation varieties, and the pollen and nectar sources for honey bees promoting less honey production variation than in S of humid subtropical climates [C(Wo)] (P=0.05). However, the variability is not necessary related to a lower honey bee production.

The economic feasibility of apiculture is primarily compromised by the land use, the intensively managed agricultural landscapes, the loss of rich plant communities, and the negative side effects of the widespread use of agricultural pesticides (Benelli *et al.*, 2014; Zoccali *et al.*, 2017). In the regions included in the present study the positive effect of maintaining S areas with the highest diversity of species of wild flowers of *Asteraceae* family and ‘mesquite’ (*Prosopis laevigata*), and of increasing the amount of semi--natural species, could be long-term useful to sustain the honey bee production as an economically feasible productive activity (Medina-Cuéllar *et al.* 2014, 2018). Consequently, although IA and RA exponents suggest less variation of honey bee production, Medina-Cuéllar *et al.* (2014, 2018) have reported a negative relation between the increasing of IA and RA areas and honey bee production.

However, the flowering time of *Asteraceae* spp. are primarily affected by climatic changes, as previously reported for other temperature-dependant wild flowers (Benelli *et al.*, 2014; Campolo *et al.*, 2014; Campolo *et al.*, 2016). In the present study semi-arid (BS1k”w) and humid subtropical [C(Wo)] climates promoted more honey bee production variations than semi-warm semi-arid climate (BS1hw) (P=0.05). According to Abu-Shaara (2015) the increase of temperatures and water needs are the most important climatic changes that affect pollinators. Medina-Cuéllar *et al.* (2014, 2018) also found a negative correlation between the increment of minimum temperature and honey bee production in semi-arid regions of central México; the increase of minimum temperature affects negatively the ‘mesquite’ honey bee production during the spring season, but the most adverse effects occur in the fall, when temperature-dependent wild flowers are the most important source of nectar and pollen for pollinators.

Fractal spectra show that is feasible to forecast the long-term adverse effects of the temperature increase. As temperature is a variable that is out of human control, long-term strategies should focus mainly on planning the land use and agricultural systems management.

Conclusions

Although MF-DFA exponents of honey bee production time series were small, Hq presented random walk of a MF structure. Fractal spectra primarily showed left truncation suggesting large magnitude local fluctuations. Parameter values made it possible to assume that time series data of honey bee production might have self-affine properties, which could be useful to identify long-term correlations in time series and to make long-term predictions using short-term variables. In the present study, honey bee production in semi-arid climates shows wider variations primarily in non cultivated areas with secondary vegetation, but it is also affected by the temperature and precipitation. The application of MF-DFA on honey bee production allows to differentiate productive patterns among the time and geographical changes, and to relate the climatic changes and land use with the fluctuations of honey bee production which could be predicted at long-term, which would be useful to design strategies to maintain ecosystems and increase the economic feasibility of apiculture.

ACKNOWLEDGEMENTS

The present study was funded by Universidad Autónoma Chapingo (UACh) and Instituto Tecnológico Nacional de México. The authors are grateful to Jesús A. Sosa-Herrera for technical support and collaboration in some of the analysis.

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