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Sequencing the Movements of Honey Bee Colonies between the Forage Sites with the Microeconomic Model of the Migratory Beekeeper

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Abstract

A beekeeper who moves his honeybee colonies from one forage site to another during the productive season does not passively follow a prefixed sequence, but must create one by comparing a wide range of forage sites. How can migratory beekeeper sequence the movements of his honeybee colonies from one forage site to another? The microeconomic model formalized in Section 3 offers a solution to this question. The model assumes that the migratory beekeeper is following, in conditions of certainty, a profitability target under the constraint that the time taken up by each sequence of sites is less than or equal to the duration of the honeybee colonies' annual biological cycle. Each forage site that the honeybee colonies visit contributes not just to the profitability but also to the sustainability of the sequence to which it belongs. Replacing one or more forage sites within a sequence therefore simultaneously affects the levels of profitability and sustainability. In Section 4, the sustainability of the sequence will be explained in terms of the characteristics of the sites, their agro-environmental context, the honey bee well-being and the timing and duration of the placement period of the honeybee colonies on the site.

Keywords: migratory beekeeper, forage sites, sequential movements, microeconomic model, ecosystem service, sustainability

1. Introduction

The honey bee colony is a moveable organism, which is easy to transport and manage; it is suitable for pollinating a very wide range of wild and cultivated vegetation [1, 2]. Thanks to its polylectic nature, the honey bee colony is widely used throughout the world for cross-pollination of crops.

The widespread use of managed honey bee colonies to pollinate crops is a response to the need to compensate for the pollination deficit resulting from the decline in wild pollinating insect populations [3–6]. Although growers use managed honey bee colonies, they are able to ensure consistent pollination of their crops, even when adverse climatic conditions limit the pollination range of wild pollinators.

Crop pollination is optimized by placing the honey bee colonies on the forage site once flowering is underway (when 20–40% of the flowers are open) in small batches according to a precise density per acre—the stocking density [7]—which varies according to the crop requiring pollination. The honey bee colonies must be removed before the resumption of antiparasite treatments on the forage site to avoid harming their health. The commercial pollination service therefore enters the cultivation process at a precise point in time determined by the flowering periods of the crops.

The spread of the practice of commercial crop pollination has given rise to a specific market [8–11] with prices, that is, with colony rental fees, varying from crop to crop and from year to year [12–14]. This market provides economic benefits both to the beekeeper and, perhaps even more so [15], to the grower. The former collects the colony rental fees paid by the grower for pollination and in addition, if the pollinated crop produces valuable nectar, obtains an income from honey production; the latter benefits from increased crop yield and/or improvement in the quality of the fruit [16, 17].

Plants flower in succession throughout the year and beekeepers can move their honey bee colonies from one forage site to another to meet the sequential demand for pollination services and/or to produce honey. Empirical observation reveals that crop pollination services take place mainly in the spring, while spontaneous/wild vegetation pollination services take place mainly in the summer. By moving the honey bee colonies between forage sites covered with spontaneous vegetation in full bloom, beekeepers can increase their honey yield and produce monofloral honey, which is highly sought-after by consumers.

The migratory beekeeper cannot passively follow a preset sequence because of changes over the years in pollination calendars, as a result of climate changes shifting the onset of the flowering period [18]; the price of honey and commercial pollination services; production factor costs; and forage sites available for the movement of honey bee colonies. In the USA, where commercial crop pollination is a well-established agricultural practice, the migratory routes most frequently taken by beekeepers are becoming clearly defined [13, 19, 20]. Jabr [20] notes in this regard, “*After the almond bloom some beekeepers take their honeybees to cherry, plum and avocado orchards in California and apple and cherry orchards in Washington State. Come summer time, many beekeepers head east to fields of alfalfa, sunflowers and clover in North and South Dakota, where the bees produce the bulk of their honey for the year. Other beekeepers visit squashes in Texas, clementines and tangerines in Florida, cranberries in Wisconsin and blueberries in Michigan and Maine. All along the east coast migratory beekeepers pollinate apples, cherries, pumpkins, cranberries and various vegetables. By November, beekeepers begin moving their colonies to warm locales to wait out the winter: California, Texas, Florida and even temperature-controlled potato cellars in Idaho. The bees stay inside their hives, eating the honey they made in the summer and fall.*” Migratory beekeepers need, therefore, to sequence their honey bee colony movements from one forage site to another; in other words, they must plan the migratory route they will follow during the year. To this end, they have to evaluate a range of forage sites in different locations [21, 22] and with different botanical and economic characteristics. The question that arises here is how can migratory beekeepers sequence the movements of their honey bee colonies and how can they determine the best sequence?

The microeconomic model formalized in Section 3 solves this problem by sequencing the movements of honey bee colonies and drawing up a ranking of the most profitable sequences. The model is microeconomic in that it establishes revenues, costs, profit and the gross income to be drawn from the sequences of

sites that the beekeeper may follow assuming conditions of certainty; it also has operational capacity and can simulate the effect of variation in output prices on the sequence ranking [23].

Pollination of the forage site contributes to both the profitability and the sustainability of the sequence to which it belongs [24]. When the forage site is covered by spontaneous vegetation, in addition to producing honey, the colonies also provide an ecosystem pollination service that helps maintain the sustainability of the local ecosystem by propagating numerous spontaneous/wild plant species [2]. In Section 4, the sustainability of the sequence will be correlated with the characteristics of the forage sites, their agro-environmental context, the honey bee well-being, the timing and duration of the placement period of the honey bee colonies on the site.

2. Methods

This chapter has an exclusively theoretical profile; in the absence of materials to comment, the focus will be on the methodological aspects.

The decision of the migratory beekeeper in order to sequence the movements of the honey bee colonies over the year can be assessed in terms of both profitability and sustainability. The interface between these two evaluations consists of the sequence of sites implemented by the migratory beekeeper. In other words, the sequence of sites represents the innovative methodological tool for correlating profitability and sustainability.

The evaluation of the profitability of the sequence is based on the microeconomic model of the migratory beekeeper. The model is formalized in stages: (a) for each site, the model calculates the revenue multiplying the quantities of honey and commercial pollination services produced on the site for the corresponding prices; (b) the variable costs of the site correspond to the sum of the costs of the variable factors applied on the site itself; (c) the revenue of the sequence is obtained by adding the revenues of the sites that form it; (d) the variable cost of the sequence is obtained by adding the variable costs of the sites that form it; (e) all costs that do not depend on the composition of the sequences are considered fixed; (f) the profit of the sequence is calculated by subtracting the variable cost and the fixed cost from the revenue; and (g) the gross income of the sequence is obtained by adding the gross incomes of the sites that form it.

In the composition of the sequences, the migratory beekeeper must respect an inviolable temporal constraint: the sum of the durations of the periods of colony stationing on the sites (placement periods) must not exceed the duration (365 days) of the annual biological cycle of the bee colonies. This is an innovative methodological aspect of the migratory beekeeper model.

The sequencing of sites is based on the start and the end dates of honeybee colony placement periods on forage sites. Forage sites with overlapping placement periods are alternative; otherwise, the sites are complementary. The inclusion of a site in the sequence involves the exclusion of all those alternatives to it. The model of the migratory beekeeper formalizes this condition by assigning the value 1 or 0 to a dummy variable that establishes the inclusion of the site in the sequence or its exclusion. The sequence is therefore composed only of sites that are complementary to each other from a chronological point of view.

The composition of the sequences is done by applying a recursive procedure to the complete set of sites that the migratory beekeeper can visit. After having numbered the sites in chronological order, according to the start date of the placement period, the method starts from the first site and ends in the overwintering

site, which is the base site. All the sequences that the migratory beekeeper can implement are identified proceeding recursively. In order to reduce the number of sequences to be computed, the recursive procedure may be subject to compliance with certain efficiency conditions. Finally, the ranking of the sequences is established by the level of gross income they could reach.

Conducting the evaluation of the sustainability of all the sequences that the migratory beekeeper can implement would be extremely dispersive and wasteful. It is necessary to limit the evaluation to the sequences that reach a satisfactory level of profitability and therefore appear in the first places of the ranking. Not having a case study to deal with, the chapter can only outline the link between sustainability and the explanatory variables of sites and sequences.

The relationship between the sustainability of the sequence and the sustainability of the sites that compose it is not however simple and additive because the conditions of sustainability on the sites are not independent of each other. For example, the winter mortality rate of the honeybee colonies is not only explained by the conditions observed on the wintering site but also may derive from other causes that change with the composition of the sequence. In general, the consistency of the population of a honeybee colony observed on a site critically depends on the characteristics of the previous sites. In some situations, the contamination of honey bees with harmful substances on a site could exert its effects on subsequent sites. The assessment of the sustainability of the sites therefore also presupposes the identification of the complete sequence. The evaluation of the sustainability of a sequence must also take into account the ecosystem service that the honey bees of the migratory beekeeper can perform at each site. The possibility of interaction with the spontaneous flora present in the various sites must therefore also be considered. Innovative from the methodological point of view is also the evaluation of the aspects concerning the biological and genetic peculiarities of the honeybee (*Apis mellifera* Linnaeus, 1758). The sustainability of the entire sequences must then take into account the ecological and ethological requirements of honey bees. In this regard, the number of sites per sequence is an aspect that significantly influences the overall sustainability of the sequences. Following these simple criteria, completely new in the discussions on the sustainability of beekeeping practices, some sequences (even for only one site) could be unsustainable because they cause serious damage to honey bee conservation and therefore to the conservation of biodiversity.

3. Sequencing profitability: The microeconomic model

The microeconomic model formalized in this section assumes that the migratory beekeeper has already selected feasible forage sites. In order to sequence the movements of the honey bee colonies over the year, the migratory beekeeper must first draw up a the list of forage sites compatible with the array of available fixed factors, in particular the means of transport and labor. It is essential that the list of sites is drawn up before the start of migration because an agreement has to be made with the owner of the forage site, sometimes with the help of a bee broker [7], before the bee colonies can be placed there.

The microeconomic model formalizes the process of chronological accumulation of the revenues, variable costs and profit (gross income) of the sequences. The technical unit that is moved sequentially from one forage site to another is an apiary, managed in a nomadic way and formed of a number of honey bee colonies that is, by assumption, invariant during their annual biological cycle. The productive scale of the beekeeping activity is therefore settled in advance. Simplified, honey bee

colonies have two market outputs: honey and the commercial pollination service. These outputs are differentiated by the type of vegetation found on the forage sites; by the same token, the prices of the outputs obtained on the forage sites also differ. Of course, honey bee colonies also produce pollen, propolis, royal jelly, wax, bee venom and bees. For the sake of simplicity, the model takes into account only the most important physical output in terms of income generation: the honey.

3.1 The forage site

We define a forage site as field covered by vegetation from which honey bees may collect nectar. The most important characteristics of the foraging site from a beekeeping perspective are (a) its location, (b) its size, (c) the vegetation covering it and (d) the flowering period.

Regarding the location of the forage site, the distance between it and the preceding one in the sequence is of great importance because it affects the time and cost of transporting the honey bee colonies. Regarding the vegetation, it is assumed that the forage sites are covered either by a crop or by spontaneous vegetation. Within each of these two basic types of vegetation, there are differences in terms of their botanical characteristics. All forage sites are by assumption monofloral; as a consequence, each forage site has a single flowering period and cannot appear more than once in the sequence. Each forage site is associated with a period during which the honey bee colonies are placed there, delimited by start and end dates. In addition to the time during which nectar is collected from the flowers, the placement period also includes the time taken to transport the honey bee colonies to the site from the one preceding it in the sequence.

3.1.1 Revenues from the site

The revenue generated by the honey bee colonies on a forage site j th belonging to the sequence has two components: the revenue from honey and the revenue from the commercial pollination service. The revenue of each component is calculated by multiplying the quantities produced for the respective prices:

$$R_{ji} = RH_{ji} + RS_{ji} = PH_j \cdot QH_{ji} + PS_j \cdot QS_{ji} \quad (1)$$

where R_{ji} = revenue from the j th site in the sequence i th; RH_{ji}, RS_{ji} = revenue from honey and commercial pollination service on the j th site in the sequence i th; QH_{ji}, QS_{ji} = honey and commercial pollination service produced on the j th site in the sequence i th; PH_j, PS_j = price of the honey and commercial pollination service on the j th site; $j = 1, 2, \dots, s$ = sites; and $i = 1, 2, \dots, n$ = sequences of sites.

The honey bee colony's annual biological cycle is divided into two phases: the first is the productive phase, which takes place on the forage sites $j = 1, 2, \dots, s-1$; the second is the wintering phase of the honey bee colony, which takes place on the site $j = s$; the honey bee colonies produce neither honey nor commercial pollination services on the latter site. The base site where the honey bee colonies overwinter is not strictly speaking a forage site because there does not need to be any vegetation.

All the honey bee colony placement periods on the forage sites $j = 1, 2, \dots, s-1$ are, for assumption, fixed and are independent of the sequences, while placement on the base site $j = s$ begins at the end of the placement period of the honey bee colonies on the penultimate forage site of the sequence, which varies with the sequences. The prices PH_j, PS_j of the honey and the commercial pollination service are assumed to be exogenous or independent of the quantities produced by the beekeeper. The

pollination fee per colony (hive) is the price of commercial pollination service. Output prices change with the type of vegetation on the forage site but are independent of the sequence to which the site belongs. We assume that the honey bee colonies produce on each site a quantity of extractable honey. The amount of commercial pollination service produced on the site is equal to the number of colonies used in the pollination of crop. The quantities of outputs obtained on a given site may vary with the sequence to which the site belongs.

3.1.2 The variable costs of the site

Instantaneous production models make a distinction between fixed and variable costs, which relate to the effects of variations in the quantity produced. In the model of the migratory beekeeper who conforms to the sequential production, step-by-step production during the year [23], fixed and variable costs are instead classified on the basis of the effects caused by replacing a forage site within the sequence. For example, the costs relating to monitoring the health of the honey bee colonies are variable as they vary from site to site depending on how long the honey bee colonies remain there and hence with the sequences. The costs involved in providing the honey bee colonies with supplementary feed are also variable because it is only needed on some forage sites. Health treatments for honey bee colonies are classified as fixed costs as they must be carried out on specific dates regardless of the forage site on which the honey bee colonies are located. Costs relating to the rates of depreciation of the buildings, mechanical devices and equipment used by the beekeeper are also, as is usually the case, fixed. Ultimately, all costs that remain constant, regardless of any changes in the composition of the sequences, are fixed. Fixed costs are therefore the same for all sequences.

The variable cost VC_{ji} of the j th site in the sequence i th is obtained by summing the costs vc_{jik} of the $k = 1, 2, \dots, m$ variable production factors used on the site itself:

$$VC_{ji} = \sum_{k=1}^m vc_{jik} \quad (2)$$

The variable costs of a given site may vary with the sequence to which the site belongs. The base site $j = s$ also generates variable costs, even though it neither produces honey nor provides a commercial pollination service.

3.2 The sequence of forage sites

A sequence is defined as a series of sites that are chronologically complementary. Each sequence differs from another in at least one of the forage sites that form it. All the sequences begin at the base site of the previous biological cycle of the honey bees and end at the base site $j = s$. In order to assemble sequences, forage sites are classified as either alternative or complementary. Forage sites with overlapping placement periods are alternative; otherwise, they are complementary. The inclusion of a forage site in a sequence implies the exclusion of all those that alternate with it. Each sequence is therefore made up only of sites that are chronologically complementary.

3.2.1 The revenues from the sequence

The revenue generated by a sequence is calculated by summing the revenues of the forage sites that form it:

$$R_i = \sum_{j=1}^s (RH_{ji} + RS_{ji}) \cdot D_{ji} = \sum_{j=1}^s (PH_j \cdot QH_{ji} + PS_j \cdot QH_{ji}) \cdot D_{ji} \quad (3)$$

where R_i = revenue from the i th sequence; RH_{ji} , RS_{ji} = revenue from the honey and commercial pollination service on the j th site in the i th sequence; and $i = 1, 2, \dots, n$ = sequences of forage sites.

The j th forage site is established as belonging to the i th sequence by the value assigned to the dummy variable: $D_{ji} = 1$ if the site j th belongs to the i th sequence; $D_{ji} = 0$ otherwise.

3.2.2 Variable and fixed costs of the sequence

The variable cost of the sequence VC_i is calculated by summing the variable costs of the sites VC_{ji} that comprise it. The fixed production cost is, as mentioned above, the same for all the sequences: $FC_i = FC \forall$ i th sequence.

The total production cost C_i of each i th sequence corresponds to the sum of the fixed cost FC_i and the variable cost VC_i .

$$C_i = FC_i + VC_i = FC + \sum_{j=1}^s VC_{ji} \cdot D_{ji} \quad (4)$$

3.3 The profitability of the sequence

The profit that the beekeeper draws by following the i th sequence will be:

$$\pi_i = R_i - C_i = \sum_{j=1}^s (PH_j \cdot QH_{ji} + PS_j \cdot QH_{ji}) \cdot D_{ji} - FC - \sum_{j=1}^s VC_{ji} \cdot D_{ji} \quad (5)$$

where π_i = profit from the i th sequence.

Shifting the fixed cost to the first member of Eq. (5), we get:

$$GI_i = \pi_i + FC = \sum_{j=1}^s [(PH_j \cdot QH_{ji} + PS_j \cdot QH_{ji}) - VC_{ji}] \cdot D_{ji} = \sum_{j=1}^s gi_{ji} \cdot D_{ji} \quad (6)$$

where GI_i = gross income from the i th sequence; gi_{ji} = gross income from the j th site of the i th sequence; and $gi_{ji} = R_{ji} - VC_{ji}$.

The gross income from each sequence is obtained by summing the gross incomes obtained from each of the sites that comprise it.

The ranking of the sequences remains unchanged regardless of whether it is drawn up on the basis of profit or gross income. The latter is obtained by adding a constant to the profit drawn from the sequence. Drawing up a ranking of sequences based on gross income has, however, an obvious operational advantage because it does not require migratory beekeepers to know their fixed costs, which they often do not record in their business accounts.

3.4 The constraint of the time

In microeconomic models of the farm, the allocative constraint is typically constituted by the amount of the land [25, 26]. The total amount of this input is fixed, but it may be allocated among the crops. The constraint requires the sum of the areas allocated to crops, all rivals, to be less than or equal to the total amount of land on the farm. In the case of the migratory beekeeper, the total area of the forage sites does not constitute an operational constraint because each sequence includes only some forage sites with complementary placement periods. In the case of the migratory beekeeper, which is similar to that of sea fishing [27], the main allocative constraint is constituted by the time that may be allocated to each

sequence of sites. At each site is associated a placement period of the honey bee colonies characterized by the start and end dates, as well as a duration (number of days). For any sequence of sites, the sum of the durations of the honey bee colonies' placement periods must be equal to or less than the amount of time available. The sum of the placement periods of any sequence must therefore be equal to or less than 365 days.

$$\begin{aligned} \sum_{j=1}^s z_j \cdot D_{ji} &\leq 365 \quad \forall \text{ } i\text{-th sequence} \\ D_{ji} &= 1 \quad \text{if the site } j\text{-th} \in i\text{-th sequence} \\ D_{ji} &= 0 \quad \text{otherwise} \end{aligned} \quad (7)$$

where z_j = placement period (number of days) of the honey bee colonies on the site j th.

Between the end of the honey bee colonies' period of placement on one site and the beginning of the placement on the next site, there may be an empty period, a phase when the honey bee colonies are inactive. The beekeeper may decide to transfer them to an emergency site or keep them on the site after the end of flowering or move them earlier to the next site. The occurrence of an unproductive phase means that the sum of the periods of time that the honey bee colonies spend on the sites in a given sequence may be less than the annual amount of time. The variable costs that the honey bee colonies incur during the unproductive period of time are to be attributed to the entire sequence. Operationally, these variable costs are associated with the base site $j = s$. The same goes for those variable costs due to any delays that may arise in starting the sequence.

3.5 The complete model

The microeconomic model of the migratory beekeeping may be specified in the following form:

$$\begin{aligned} GI_i &= \sum_{j=1}^s (PH_j \cdot QH_{ji} + PS_j \cdot QH_{ji} - CV_{ji}) \cdot D_{ji} = \sum_{j=1}^s gi_{ji} \cdot D_{ji} \\ \text{s.t. } \sum_{j=1}^s z_j \cdot D_{ji} &\leq 365 \\ D_{ji} &= 1 \quad \text{if the site } j\text{-th} \in i\text{-th sequence} \\ D_{ji} &= 0 \quad \text{otherwise} \end{aligned} \quad (8)$$

The exogenous variables of model (8) in conditions of certainty are the prices, the quantities of outputs, the variable cost of each site and the placement periods of each forage sites. The value of the *dummy* variable D_{ji} is defined on the basis of the start and end dates of the placement periods. The ranking of the sequences in terms of gross income obtained can be determined on the basis of model (8).

The migratory beekeeper who keeps regular business accounts has the database needed to calculate: the revenues, variable costs and placement periods for each site. The model can therefore be applied to a database to calculate the gross income of the sequences and to verify *ex post* the position that the sequence adopted by the migratory beekeeper has in the ranking.

3.6 The recursive procedure of sequencing and the ranking

In order to sequence the forage sites and rank the sequences, the sites must first be numbered in chronological order according to the start date of the placement period. If two or more sites have the same start date, priority is given to the one with the nearest end date.

To assemble the first sequence, one begins by the forage site that comes first chronologically. The inclusion in the sequence of the forage site assigned no. 1 in the chronology implies the exclusion of all the sites alternative to it. Having completed this first step, a new forage site is added to the sequence, chronologically complementary to the first one; the inclusion of the new forage site in the sequence again implies the exclusion of all the sites alternative to it; having completed the second step, a new site, the third, chronologically complementary to the previous one, is added to the sequence. The procedure continues in the same way until the base site is reached, where the sequence ends.

Once the first sequence is completed, one goes back to site no. 1 in the chronology; all the alternative sites are excluded, and the second site in the sequence previously completed is replaced with a new site subsequent and chronologically complementary to site no. 1. The second sequence is completed by repeating the procedure described above, as are all the other sequences that begin with the forage site in the first chronological position. Having assembled all the sequences that begin with site no. 1 in the chronology, the sequences beginning with site no. 2 are completed by proceeding recursively and so on to assemble all the other sequences. Two conditions may be imposed in order to reduce the number of sequences to be computed: the recursive procedure (a) is halted when the placement period of the honey bee colonies on the forage site begins beyond a set date limit and (b) excludes all the sequences that contain one or more sites in less than others, all the other sites contained in the sequence being equal.

These two conditions are justified by the fact that when honey bee colonies are inactive, the variable costs rise but there is no increase in revenues. Each sequence is therefore a selection from the complete series of sites, where the placement periods of the honey bee colonies on these same sites do not coincide.

Once the recursive procedure has been applied, the gross income of each sequence can be calculated by summing the gross incomes of the sites that comprise it (Eq. (6)) and the sequences can be ranked on the basis of gross income.

4. Sequencing sustainability

The concept of sustainability is defined, according to the *Encyclopedia Britannica* [28], as “the long-term viability of a community, set of social institutions, or societal practice”. The idea of sustainability rose to prominence with the modern environmental movement, which rebuked the unsustainable character of contemporary societies where patterns of resource use, growth, and consumption threatened the integrity of ecosystems and the well-being of future generations. Sustainability is presented as an alternative to short-term, myopic, and wasteful behavior. The concept of sustainability is nowadays closely linked to that of biodiversity and in the case of nomadic beekeeping biodiversity must consider both the biodiversity of the environment as well that concerning honey bee, which will be explained in detail below.

The aim of this paragraph is to associate to each site a level of sustainability related to the presence of honey bee colonies and to evaluate overall the sustainability of the sequences of sites already identified with the recursive sequencing

method described in Section 3. The evaluation is done with regard to the effects that managed honey bee colonies can generate and undergo. Associating a level of sustainability to each sequence of sites would allow drawing up a new and further ranking to be compared to that established based on profitability. The sustainability of the activity of honey bee colonies referred to the single site and even more to the sequence is not easily assessed because the factors involved are manifold, complex and difficult to identify and measure.

A preliminary issue concerns the relationship between the overall sustainability level of the sequence and the levels of sustainability of the sites that compose it. The relationship is not simple and additive because the sustainability conditions on the sites are not independent of each other. For example, the mortality rate of overwintering honey bee colonies is not only explained by the conditions observed on the overwintering site but also may be derived from other causes detectable in the composition of the sequence. In other words, the mortality of honey bee colonies in overwintering sites could be derived in part from problems related to one or more of the previous sites (in relation also to the time of positioning in a given site) but also to the negative effects of the number of movements and therefore from the number of sites in the entire sequence. The consistency of the honey bee colony arrived at a site depends partly also on the characteristics of the previous sites. The assessment of the sustainability of sites also presupposes the identification of the complete sequence, since the effect of a site starts from the removal from the previous site. Not having a case study to deal with is therefore possible only to tentatively define the link between sustainability and the explanatory variables of sites and sequences.

Before actually entering into the topic of this paragraph, however, we must make a fundamental premise. All bees, whether they are solitary, gregarious or living in temporary or permanent societies (such as *Apis mellifera*), are sedentary organisms that base their survival on the perfect adaptation to the climate and vegetation of the habitats in which they live and where they play their role of pollinators [29]. The connection between bees and environment, effective on different spatial scales in species with different social structure [30], influenced both the evolutionary path of bees as well as deeply determined the vegetation structure and therefore the whole biodiversity at the local level. The close link between these insects and the reproduction of a very high number of plants means that the plants that can best attract the most efficient, abundant and well-distributed local pollinators are also those that will have a greater reproductive success in the same environment. The pollinating insects and firstly the bees, which base all their existence and prosperity on the presence and abundance of pollen and nectar, are decisive in the floristic composition of many terrestrial ecosystems. Starting from this fundamental and preliminary consideration, in terms of sustainability, this obviously decreases, *ceteris paribus*, to the increasing of the distance from site to site.

Consequently, the sustainability of the presence of honey bee colonies in a single site can be interpreted and evaluated on the basis of four drivers: (1) vegetation present on the forage site; (2) agro-environmental and animal context in which the forage site is inserted; (3) well-being of both managed and wild honey bees; and (4) timing and duration of the placement period on the site.

4.1 Site vegetation

The honey bee colonies managed by beekeepers cannot live without adequate sources of pollen, nectar and possibly honeydew, which they collect from the vegetation and mostly on the flowers of angiosperm plants. The activity of honey bees therefore always involves the pollination of a huge number of flowers.

Bee pollination is considered a pollination service when the pollinated flowers produce seeds, fruit or, after germination, other plant products, destined to be harvested by humans for their feeding and for that of their own livestock or however for precise human purposes (plants for industrial use). Honey bee pollination is defined as an eco-systemic service when seeds, fruits or, after germination, other plant products feed the wildlife and therefore support the entire biodiversity. The role of pollination in crop production (both food and nonfood) has been assessed in many ways, from the point of view of both quantitative [1] and qualitative results [16]. The strong reduction in pollinating insects naturally present in intensely cultivated areas, determined both by landscape changes [31] and by the serious impact of the use of crop protection products [32], in recent years has led to a high demand in Europe for honey bee colonies for pollination service on a growing number of crops, also cultivated for nonfood purposes. This increase in demand for pollination services in agriculture is offset by an inadequate number of honey bee colonies managed by European beekeepers [33]. The fundamental driver of a site is its vegetation, and the sustainability of a site is therefore closely linked to the type and structure of the vegetation that covers it. A site can be completely covered by one or more crops or by wild vegetation, or by a puzzle of crops and wild vegetation. Crops can be classified as annual, poliannual or permanent. Annual crops requiring insect pollination, such as sunflower, rapeseed, buckwheat and many other herbaceous crops, often offer an interesting yield of nectar and pollen and therefore the beekeeper greatly benefits both from the production of honey and from the beneficial effect on bees (well-being and development of colonies). For this reason, annual crops are usually pollinated by beekeepers for free, and indeed, among beekeepers, there may be some competition to grab these flowering surfaces. These plants generally have a long flowering period and therefore it is not easy to foresee two or more close pollination cycles/sites on one of these crops. The same scheme can be applied to poliannual crops, mostly belonging to the group of fodder plants. Only in cases where the annual or poliannual insect-pollinated crop is implemented to produce seeds, the need for abundant pollination can make the farmers willing to pay for the pollination service offered by migrant beekeepers. In the case of permanent crops, like orchards, the blooms are usually concentrated and not very profitable for the beekeeper from the point of view of the honey harvest. It is the case with apples, pears and most of the drupaceous (cherry, peach, apricot, etc.) orchards. In addition to the poor honey harvest by quantity and quality, permanent crops are generally characterized by the short but very precise period when the pollinators are desired to stay in the site. The constant and generalized need for the use of crop-protection products in these crops is a deterrent to beekeepers who in fact prefer farms that adopt sustainable cultural practices oriented to the preservation of honey bees and other pollinating insects. As far as vegetation is concerned, in some cases, usually limited and circumscribed, managed honey bees as well as other pollinators can produce eco-systemic “disservices” and reduce the level of sustainability of their presence, contributing to spread on the site some orchard diseases transmissible also at flower level. This is the case, for example, with *Erwinia amylovora* [34], mainly on pear and apple trees, *Pseudomonas syringae*, on Actinidia [35] and *Colletotrichum acutatum* and *C. gloeosporioides* on citrus trees [36].

4.2 The agro-environmental and animal context

The wide and specialized agro-environmental context of modern agriculture, in many cases, does not allow the survival of permanent populations of wild pollinators nor their arrival from nearby areas as these insects generally have a home range of a few hundred meters or even less. Landscape composition, determined by

cultivated, natural and anthropogenic areas, has a decisive role on biodiversity [37] and significantly determining the presence and abundance of permanent pollinators (managed or not), due to the necessity or not of specialized pollination services. The actions aimed to diversify the bloom potential in the agricultural context, such as the so-called flower strips [38], have a positive effect on the consistency of local populations of wild bees, with a clear enhancement of the pollination service to neighboring crops [39]. In some cases, the presence of wild vegetation near the site can be negatively evaluated by the farmer, who paying for a pollination service fears, sometimes rightly, that honey bees could be distracted by other plants and neglect the flowers for which they are requested. The beekeeper, on the other hand, can in some cases obtain an extra well-being for his honey bees and reduce the risk of poisoning and contamination by crop-protection products if, in addition to the flowers for which he brought his bees in the site, there are other blooms not reached by crop-protection products in the surrounding areas.

In the agro-environmental context in which the site is inserted, there must also be factors that can make the pollination service more risky. Sites located near industrial areas or infrastructure such as power lines or repeaters [40] are not very appealing to migratory beekeepers.

4.2.1 Animal context

In context assessment, it should be borne in mind that honey bees are part of indigenous biodiversity in most of Europe, throughout Africa, the Middle East and some small areas of Central Asia. The fact that honey bees are wild organisms linked to their environment of origin, and that beekeeping is not a true form of animal husbandry but something very special [41], explains why migratory beekeeping with transfers of honey bee colonies on a large scale for crop pollination has recently been identified as one of the main causes of the phenomenon known as bee decline [4, 42]. Indeed, this factor would be the one responsible for making other causes even more serious. The fact that *Apis mellifera* is divided into 31 subspecies [43–45], each indigenous and well adapted to a specific geographic area, should set very precise boundaries to the movement of honey bee colonies in order to ensure sustainability to the pollination service on a precise forage site. This problem was clearly stated in a consensus paper drafted by the major Italian entomologists involved in honey bee research and officially presented on Jun 12, 2018, at the Edmund Mach Foundation in San Michele all'Adige (Trento, Italy): the San Michele all'Adige Declaration [46], or Appeal for Biodiversity Protection of Native Honeybee Subspecies of *Apis mellifera* Linnaeus, 1758 in Italy. The movement of honey bee colonies through the different areas of origin of the indigenous subspecies, the sale on a large scale of selected queens and the loss of most of the feral populations of *Apis mellifera* due to the parasitic mite *Varroa destructor* have led to a serious deterioration of the local honey bee populations, up to the possibility of extinction of some subspecies, for example, *Apis mellifera siciliana* [47]. This does not mean that the natural populations (subspecies and ecotypes) of *Apis mellifera* should be considered irremediably lost. Due to the effect of resilience, eliminating the perturbation factors, in this case the introduction of nonindigenous honey bees, local populations can most probably be restored due to the greater adaptation of the latter compared to the introduced ones [48].

Even the massive temporary transfer of managed honey bees in already impoverished areas with regard to the fauna of native pollinating insects (commonly called wild bees) could further impact negatively on the sustainability of the presence of bee colonies on forage sites. In recent years, several scientific papers have highlighted the risk of a possible interaction between honey bees managed by beekeepers in very large apiaries and wild bees, highlighting a possible

contraposition between the safeguarding of agricultural and apiculture productions on one hand and conservation of biodiversity on the other. *A. mellifera* could act, in some contexts, as an invasive species with a great impact on biodiversity, especially in the newly introduced areas (Oceania and the Americas). However, although the honey bee has become widespread in nature and has established wild populations in these “New Continents,” the extent to which the introduced honey bees alter local biodiversity and have negative effects on the composition and density of indigenous pollinating faunas remains controversial [49, 50].

Finally, the context can have negative effects on the sustainability of beekeeping due to the presence of bears or other organisms potentially harmful to honey bees up to the phenomenon of thefts of hives.

4.3 Honey bees' well-being

First of all, it must be emphasized that the movement of the hives puts the honey bees under stress due to loading and unloading operations and the forced enclosure along the way from one site to another. Transport and unloading can in many ways affect the welfare of worker bees, brood and queen bees and therefore cause serious damage to the beekeeper in terms of loss of colonies [51]. These damages to honey bees' well-being are quite evident when the journey from one site to another is very long. The permanence of the colonies in the forage sites covered by spontaneous vegetation has very positive effects on the health of the honey bees, deriving mainly from the variety of botanical species that they can visit and therefore from different kinds of pollen, their primary source of food [52], that bees can collect.

Migratory beekeeping, especially if aimed to provide commercial pollination services to farmers, can produce a large-scale transfer of pathogens and parasites of honey bees and there are many known cases in this regard. Transfers can affect both migratory and sedentary beekeepers' bees [53]; migratory beekeepers' bees can receive pathogens and parasites at a given site but can also bring new diseases and parasites to the permanent beekeepers' bees. In both cases, the pathogens or the parasites will then be carried by the migratory beekeepers' bees also on the sites that follow along the sequence.

Another problem to the health of the migratory beekeepers' bees is the proximity between the pollination site and other forage sites covered by spontaneous and cultivated vegetation. During the stop on a forage site, the treatments with agrochemicals on the contiguous vegetation, due to the drift, can in fact cause damage to the health of honey bees and often also a contamination of the bee products, which would in some cases be unsellable. Honey bees generally fly within a radius of 1–3 km but can go much further, up to 10 km and more, in search of pollen. This feature makes honey bees able to come into contact with risk factors not strictly related to the pollinating service site. To prevent these risks, it is important to know very well the agro-environmental context and to take appropriate countermeasures.

Another critical aspect for the well-being of honey bees can be derived from the interference that can be created between the genetic pulls of the honey bees managed by the migratory beekeeper, those managed by sedentary beekeepers and also the feral colonies present on the site. Feral honey bee colonies have dramatically reduced in the last decades [54], coinciding with the advent of the parasitic mite *Varroa destructor*. The migration between the areas of origin of the different subspecies of *Apis mellifera* causes genetic pollution and, in the case of queen bee farmers (but obviously not only), a serious damage for local beekeepers, who try to preserve the native honey bees as they are perfectly adapted to the environment. Even the genetic pulls of the honey bees managed by the migratory beekeepers can be genetically contaminated, if the colonies transferred have queens in fertilization, which could mate with drones of a different subspecies or ecotype.

4.4 Timing and duration of the placement period on the site

The site is a place where honey bee colonies stay for a defined period of time depending on the duration of the flowering or from the requirements of the pollination service. The timing of the placement period on the site is defined by the flowering phenological phase of the plants on which honey bees must perform their pollination/foraging activity.

Timing and duration of placement period of the honey bee colonies on the forage site greatly vary depending not only on the species to be pollinated but also on the basis of the purpose of the stay on the site. In some cases, honey bee colonies must stop only for a time much shorter than the actual duration of the flowering, for example, to avoid running into the scheduled treatments with crop-protection products. In other cases, however, especially in crops cultivated to produce seeds of fodder or oleaginous plants for the production of alimentary oil or biofuels, honey bees must stand on the site for the entire flowering period.

In forage sites covered by wild vegetation, in the case of a prolonged placement period on the site, the pollinating and foraging effects are greater, since honey bees succeed, through their cognitive abilities, to better exploit the resources of a site that they “learn” to know and manage [55, 56]. The prolonged stay in the sites, especially if not in correspondence with a conspicuous bloom (producing monofloral honey) also improves the value of the ecosystemic service. From the point of view of sustainability, it is essential that bees manage to pollinate a broader spectrum of plants, creating the benefit of pollination to a large number of plant species and contributing substantially to ensure the conservation of the plant and overall biodiversity.

Timing can affect the level of sustainability of beekeeping as early blooms occur often when honey bee colonies may not yet be well developed but, on the other hand, these early blooms may allow honey bee colonies to complete their development in view of the transfer on further sites of the sequence or of their multiplication. Late blooms can bring another big advantage to the beekeeper, allowing the honey bees to breed winter bees in the presence of abundant food sources (pollen is the limiting factor in this regard) and at the same time to store significant stocks of honey, with a large saving of sugary foods that the beekeeper should provide to bees in the absence of such flowering. Autumnal blooms, however, can affect the survival of honey bees since the life span of a working bee depends on its more or less intense foraging activity. Pollination and the consequent production of honey of buckwheat (*Fagopyrum esculentum*) in the Alpine areas until the 1950s are interesting in this sense. The late flowering of this crop forced local beekeepers to ward off most of their colonies. Honey bees that were left on the buckwheat harvested abundant honey but were destined in large part to succumb by the end of winter, brittle from the intense harvest but without being then replaced, for the arrival of winter, by other new and strong bees. The migratory beekeeper in the selection of the site had to evaluate the advantages obtained with the production of honey in relation to the risks of widespread winter colony losses.

5. Conclusions

The microeconomic model of the migratory beekeeper formalized in this chapter allows calculating revenues, variable costs and gross income per each site and each sequence of sites. The sequence with the highest gross income, identified by applying the recursive procedure to the data provided by the migratory beekeeper, can be compared ex post with the one it has actually implemented to verify which

divergences exist in the visited sites. Ex ante, during the planning of the migration itinerary, the sequences with a gross income equal or lower by a predetermined percentage of the maximum can be submitted to the migratory beekeeper for the choice of the one to be implemented. The comparison between the sequences of sites is in fact an important decision factor because their composition provides the migratory beekeeper information on the possible variability of the gross income that the microeconomic model has not considered.

Migratory beekeeping is currently a necessity for the supply of pollination services to the growers and for the production of honey, especially monofloral honey, and other honey bee products. The migration between the sites, however, should occur respecting both the environmental and honey bee biodiversity, *Apis mellifera* indigenous subspecies and their relative local ecotypes.

A certain level of sustainability corresponds to each forage site belonging to a given sequence. The analysis conducted on the sustainability drivers of migratory beekeeping has identified some critical issues that should be carefully considered in the definition of best management practices for crop pollination [57]. In particular, the high number of movements in the sequence and the possible impairment of the genetic pool of honey bees at the sites are highly detrimental to the sustainability of the sequence of forage sites.

It is therefore necessary to update the policies to support professional beekeeping but also those relating to the management of agricultural environments, by encouraging sequences characterized by higher levels of sustainability and by protecting in a more concrete way the conservation of the genetic biodiversity of bees.

The integration between profitability and sustainability of the sequences of forage sites discussed in this chapter raises useful premises for the implementation of a pollinator habitat policy [58], which could effectively orientate migratory beekeeping toward higher levels of sustainability. The challenge is therefore to identify a path of environmental sustainability [59] that does not compromise but reconciles the profitability and sustainability of migratory beekeeping.

Conflict of interest

No conflict of interest.

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