Modeling Sequential Production: The Migratory Beekeeper Case

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Abstract

This paper formalizes a bio-economic model of migratory beekeeping activities, during the annual production cycle, so as to discern the optimal sequence of foraging sites for migratory beekeepers; it then proceeds to empirically verify the model via a case study.

The model assumes that the apiary farm produces three marketable outputs under conditions of certainty with disjunctive resources at the sites. In particular, honey, commercial pollination services and nucleus colonies are produced sequentially at foraging sites throughout the year.

The model determines a migratory beekeeper's revenues, variable costs, gross income from each sequence of foraging sites under the constraint that the total time allocated to the foraging sites be less than or equal to the annual production cycle duration. The bio-economic model allows sequential choices and jointness in foraging sites to be tested, so as to ascertain whether the various stages in the sequential production process are independent of each other. Jointness in foraging sites can arise with regard to variable costs, revenues or both simultaneously.

Keywords: *migratory beekeeper, sequential production, bio-economic model, foraging sites, price response.*

1. Introduction

When commercial beekeeping (apiculture) is conducted on a migratory basis, colonies are relocated throughout the year from a one foraging site to the next according to the flowering phases of the various crops. Outputs are thus produced in a stepwise manner at successive forage sites. From the microeconomic perspective, this situation amounts to an entrepreneurial decision-making problem regards the sequencing and timing of these migrations during the year. As is well-known, site to site migration of mobile production organisms across the territory affords beekeepers various opportunities for: increasing overall honey production; producing high-quality mono-floral honeys; providing commercial pollination services to farmers so as to enhance productivity both in terms of yield and quality, whether they involve orchards/groves or vegetable crops that are more or less dependent on entomophilic pollination.

As colonies are trucked to foraging sites according to the flowering periods of the crops, migratory beekeepers achieve substantial surpluses in honey production, in the order of 30% higher than stationary (i.e. non-migratory) production. In addition, access to large monocultures yields the mono-floral or varietal honeys preferred by consumers, whose market prices range higher than multi-floral or wildflower honeys.

Due to the dearth of wild pollinators (Bauer, Wing 2010) and the increase in pollinator-dependent crops (Garibaldi et al. 2009), agriculture has come to rely on bee colonies for commercial pollination services[1], with significant advantages for beekeepers, in particular (Breeze et al., 2016). This new commercial facet of apiculture stems from the time-honoured production of honey; in the springtime, flowering crops offer a range of commercial pollination opportunities whereas in the summer months the production of honey is prevalent thanks to the flowering of spontaneous vegetation. Unfortunately, there has been a longstanding lack of statistical data regarding the seasonal migration of bee colonies (Williams et al. 1993), especially in Europe. This shortcoming appears all the more inexplicable given that beekeepers are required to furnish the competent authorities with written advance notice of any migrations of bee colonies.

Important pollinator losses have been observed worldwide, due to a series of stressors (Brettell, Martin 2017, Becher et al., 2014; Paudel et al., 2015; Goulson et al., 2015) or from Colony Collaspe Disorder - CCD (vanEngelsdorp et al 2009, Ellis et al., 2010). Predictably, losses of managed bee colonies have increased the demand for nucleus colonies/bee packages for their reintegration. In Europe, the overall decline in honey bee populations have reached an average of 15% during winters (EPILOBEE Consortium et al 2016) with a south-north positive gradient, whereas in the US average losses have remained stable at 30% (van der Zee et al. 2014 Steinhauer et al., 2014). The annual winter mortality rate of managed bee colonies had been no greater than 14% prior to the onset of the CCD (Rucker, Thurman 2012). In order to meet this growing demand for bee colonies, and to make up for losses, some professional beekeepers have committed themselves to the commercial production of nucleus bee colonies, sequentially integrating it into their apicultural practices.

However, migrations of bee colonies from site to site accentuate the health risks to honey bees (Pettis 2013; Zhu et

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[1] Pollination services offered by managed beekeepers comprise two ambits: a commercial one, serving agricultural cultivations, and another for spontaneous vegetation.

al., 2014; Simone-Finstrom et al., 2016; Traynor et al., 2016). In fact, peaks in annual bee losses sometimes exceed the 50% mark (vanEngelsdorp et al., 2013). When honey bees are deployed to provide commercial pollination services, risk factors for honey bee health may include those from exposure to pesticides used in industrial farming (vanEngeldorf, Meixener 2009; Gill et al., 2012; Henry et al. 2012). Bee colony health risks also derive from the nutritional stress honey bees undergo along the sequence of foraging sites. Whereas a diversified diet from a broad range of flowers optimizes resistance to disease, supplement diets are less than optimal (DeGrandi-Hoffman et al., 2016). Migration practices of managed bee colonies also entail stressors from wild bees and other native pollinators, with potentially negative, as well as positive, effects (Pirk et al., 2017). When migration involves peri-urban foraging sites, other abiotic stressors come into play, such as various forms of pollution, e.g. from road traffic, anthropogenic electromagnetic/ radiofrequency (electro smog) and industrial emissions. Moreover, the migration of colonies from one site to the next may facilitate the spread of certain fruit tree viruses (Pattemore et al., 2014; Gasparoto et al 2017).

In order to cope with these hazards, the migratory beekeeper must pay particular attention to the selection of foraging sites, given that the flight range may exceed one kilometre, depending on vegetation and season (Danner et al., 2017); Invariably, migratory beekeepers must also comply with the regulations regarding distances as apply to apiaries.

The sequential adoption approach relies on an established methodological framework empirically tested in farm management, particularly with regard to innovative technologies (Khanna, 2001; Sauer and Zilberman, 2012; Ma and Shi, 2015) and crop rotations (Livingston et al., 2015).

However, the site-chronological regimes applied to migratory beekeeping have distinctive features. Firstly, the reference timespan is one year long instead of multi-year. Moreover, each site entails a discrete expenditure, timewise, as a fraction of the available time, where the sum of these expenditures cannot exceed the total time available for any given sequence. In addition, in the case of migratory beekeeping, the sequence of outputs is generated in a series of sites, whereas in the rotation of crops the output sequence is confined to a single site. The sites of each sequence comprise different geographical locations, but are also chronologically complementary, in contrast to the case addressed by Albers and Robinson (2011) concerning apiculture as a means of protecting forests.

Migratory apiculture is multi-site, multi-output and multi-period. This specificity requires the formalization of an ad hoc bio-economic model.

Herein we formalize a bio-economic production model for determining the optimal sequencing, i.e. the most profitable site-chronological regime, for migratory beekeepers. We also discuss the results of case study applying the model to the site-chronological regime of a 32-colony apiary.

2. Material and Methods

2.1. Sequence of Foraging Sites and Outputs

Migration of apiaries/colonies during the year does not follow established routes for droving livestock (i.e. drovers' roads, or droveways) consolidated over the centuries, as is the case with the transhumance of other livestock, especially herds of sheep. Nonetheless, we are starting to notice patterns wherever, such as in the USA (Burgett et al. 2010), migration practices are sufficiently customary. In addition, climate change alters vegetation flowering periods, according to some reports (Wang et al., 2014; Gezon et al., 2016), thus requiring continuous updates to the foraging site sequences.

Migratory beekeepers have a decision-making task regards the adoption of a site-chronological regime i.e. the sequence of sites arranged in chronological order. To solve this problem, first of all, we must circumscribe the list of practicable sites into a set from which to tease out the optimal sequencing; then each site must be coupled to: the timeframe during which the apiary will be foraging according to the flowering phase of the crop[2]; The quantities and output prices; Costs and in particular variable costs. After this stage, the migratory beekeeper is able to compile the practicable sequence of options and identify the one to be adopted as the annual migration schedule.

Each site has specific, biophysical, abiotic, biotic and economic characteristics (Antle, Stoorvogel 2001, Wossink, Swinton 2007). The most significant site-specific biophysical properties in the case of migratory apiculture are: (a) the type of vegetation or flora present; B) area in hectares; C) location; (D) the level of contamination.

With regard to the vegetation at the foraging site, a crucial distinction is the one between cultivated vegetation (or agricultural cultivation), and spontaneous vegetation. The characteristics of the vegetation dictate the types of honey produced and, above all, categorise pollination as either commercial or ecosystemic services. A given vegetation, whether cultivated or spontaneous, is simultaneously present on a number of foraging sites and sometimes even at different times of the year. In fact, the same vegetation may be flowering at different times of the year depending on the altitude and latitude of the site (Rucker, Thurman, Burgett 2012). The same kind of vegetation could therefore appear several times in a sequence of foraging sites, as is actually the case in the optimal sequence shown in tab.2.

The area of the foraging site may become a limiting factor if the optimal density in colonies per hectare (Cheung 1973 tab.1; Rucker, Thurman, Burgett 2012) is inadequate to accommodate the bee population of the apiary. The beekeeper assesses site suitability in the preliminary identification phase of the eligible sites.

The location features of foraging sites may be specified at the macro and micro-scale level. Macro-scale location is defined with reference to site altitude distinguishing between plains, hills and mountains; The macro-scale location of foraging sites relative to latitude is seldom a concern in Europe.

Relative to the micro-scale location features of the site, relevant aspects are the locale where the colonies travel to, the distance from where the beekeeper’s farm is based and the distance separating pairs of chronologically coupled sites. Other micro-localization parameters are the acclivity and amount of sun exposure of the foraging site for their effects on the beginning and end dates of flowering periods and the productivity of bee colonies.

With regard to the eventual contamination of the foraging site, the effects of agrochemicals, especially pesticides, applied in the defence of the crops visited, are the overriding consideration. The contamination of forage can lead to declines in the bee population, even to loss of the entire colony, negatively impacting revenues and assets[3].

The specific make-up of nectar-producing plants of each foraging site makes it possible to harvest particular varieties of honey, each with a corresponding market value and a yield per colony as shown in tab.1. Honey bee rental fees per colony,

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[2] The period during which the apiary stations at the foraging site does not necessarily coincide with the flowering period of the vegetation that covers it because the migration to the site often takes place with bloom already started and because it also includes the transport times from one site to the next in the sequence.

[3] Commercial pollination service contracts for agricultural crops normally provide for compensation for loss of bee colonies caused by contamination of the foraging site.

which represent the price of the commercial pollinating services, vary according to the pollination-dependent cultivation. Data reported by Rucker, Thurman, Burgett (2012) demonstrate the high variability of rental rates in the US Pacific Northwest in the period 1987-2009: the average rate was $75.61 for a colonies allocated to almond groves in contrast to the $ 3.11 for vetch cultivations. Even the production of nucleus colonies is site specific, operatively speaking, given that in our case study at the end of the migrations, bee colonies are transferred to another site and subdivided into nucleus colonies to which new queen bees are added. The production of nucleus and full colonies requires an across-the-board commitment, on the part of the beekeeper, throughout the entire sequence (harvesting of royal jelly and pollen, swarm retrieval, etc.). Prior to wintering, professional beekeepers prepare for restocking winterkilled hives by producing a sufficient number of nucleus colonies (Rucker, Thurman 2012). However, there is still a market demand the part of professionals to make up for unforeseen losses as well as to cater to amateur beekeepers.

2.2. Sequential Bio-Economic Model of the Migratory Beekeeping Farm

Let us assume that the technical-biological unit of reference for the migratory beekeeper consists of an apiary having a fixed number of colonies.

For purposes of sequencing of foraging sites that could be implemented by the migratory beekeeper, we used none of the well-known crop-sequencing techniques, i.e. network flows (Detlefsen, Jensen 2007), maximum entropy or Markov chain (Aurbacher, Dabbert 2011). Instead, an ad hoc linear model consisting of an objective function (i.e. utility function) and an allocation constraint was adopted. This site-chronological regime simulates the effects of the variation in output prices on the optimal sequence.

The model assumes conditions of certainty regards: (a) the start and end dates of the timespans during which colonies would be engaged in pollination at each foraging site[4]; (b) prices of outputs; (c) the yield at each foraging site[5]. It also assumes disjunctive or unary resources (sometimes also referred to as machines) in the sequence of sites so as to focus on the effects of the practicable site-chronological regimes.

2.2.1. Objective function

Let us define:

j =1,2…k… s = foraging sites; j=1 is the base site; j=s is the identical site observed at the end of migration;

j = 1,2,…n = is the foraging site sequence;

R_i, C_i, GI_i = revenues, costs and profit of the *i-th* sequence;

FC_i = fixed costs of the *i-th* sequence;

VC_{ji} = variable costs of the *j-th* site in the *i-th* sequence;

QH_{ji}, QS_{ji}, QN_{ji} = honey yield, commercial pollination services performed and nucleus colonies produced at the *j-th* site in the *i-th* sequence;

PH_j, PS_j, PN_j = prices of honey produced, commercial pollination services performed and nucleus colonies produced at the *j-th* site;

T_j^S , T_j^E = start and end dates of the timespan at the *j-th* site in the *i-th* sequence;

t_j = interval during which hives are employed at the j-th site;

z_j = number of days hives are stationed at the *j-th* site;

D_{ji} = inclusion function of the *j-th* site in the *i-th* sequence.

Abstractly, the set of practicable foraging sites from which sequences could be generated is unlimited, theoretically expanding the range of migration at will. In actuality, the beekeeper considers only a small finite subset (j = 1,2 ... s) of potentially viable foraging sites by selecting those deemed most practicable based on their bio-physical characteristics, the company's economic shape in terms of production factors, revenues and variable costs as well as the site-specific transaction costs likely to be incurred. Generally, there is also competition for access to the most productive foraging sites among beekeepers.

The revenue generated by the apiary at the *j-th* site consist of three components from the proceeds of: a) the honey yield; (B) the renting of commercial pollination services; C) the sales from the production of nucleus bee colonies.

With the exception of the sites for wintering and for splitting hives to make nucleus colonies, at each foraging site either honey, pollination services or both outputs can be obtained, depending on the vegetation present. At sites where nucleus colonies are made, they are the sole output. At the beekeeper's farm, during wintering, hives similarly produce no outputs, whether at the beginning or end of the site-chronological sequence.

Let us assume that the apiary's production quantities at each site are independent of the sequence to which they belong, thus $QH_{ji} = QH_j$, $QS_{ji} = QS_j$, $QN_{ji} = QN_j$, $\forall$ *j-th site*; $\forall$ *j-th sequence*. This is the first condition necessary for the disjunctive resource constraint as applies to sequences among sites. The revenues generated by the apiary at a site are calculated as the sum of revenues from its outputs:

$$R_j = PH_j \cdot QH_j + PS_j \cdot QS_j + PN_j \cdot QN_j \qquad (1)$$

by virtue of the assumption of conditions of certainty, QH_j, QS_j, QN_j, i.e. the quantities produced, are known *ex ante* at the time of the planning phase of the migratory site-chronological regime. In addition, the prices are independent of the quantities produced by the apiary and in conditions of certainty are known *ex ante* to the beekeeper[6].

The total revenues of each sequence corresponds to the sum of the revenues generated at the foraging sites that form it:

$$R_i = \sum_{j=1}^{s} R_j \cdot D_{ji} = \sum_{j=1}^{s} (PH_j \cdot QH_j + PS_j \cdot QS_j + PN_j \cdot QN_j) \cdot D_{ji} \qquad (2)$$

Which foraging sites are included in each *i-th* sequence is determined by the dummy variable:

D_{ji} = 1 if the *j-th* site $\in$ the *i-th* sequence;
D_{ji} = 0 otherwise.

Sequences only include complementary sites within an ordered set (i.e. a scale) of blooming periods. Foraging sites with overlapping start and end date intervals cannot belong to the same sequence. Superimposition between two sites is avoided when the colonies' end date at one site is not beyond the start date at another site.

The production cost C_i of each *i-th* sequence corresponds to the sum of the fixed FC_i and variable costs VC_i. All costs incurred independently of the composition of the sequence are

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[4] The intervals at sites 1 and s are not fixed because they depend on the selected sequence; the durations of these two periods shall be calculated in residual form: for site 1, starting from the beginning of the year until the start date of the subsequent interval at the next site in the sequence; for the site s, starting with the end date of the apiary presence at the penultimate site of the sequence until Dec. 31.

[5] At the conclusion of the interval during which the apiary stations at each site, the beekeeper records the number of supers which he has removed to safeguard the mono-floral quality of honey, thus avoiding the formation of mixtures. From the number of supers, the yield of honey produced by the apiary at each forage site is estimated (tab.1)

[6] As the price of the commercial pollination service corresponds to the rental fee of a bee colony, the amount of service produced is measured by the number of bee colonies.

classified as fixed[7] ($FC_i = FC, \forall$ *i-th* sequence). Consequently, fixed costs are the same for all sequences ($FC_i = FC, \forall$ *i-th* sequence). All other costs are classified as variable. Let us assume that the variable costs at each site are the same for every inclusion sequence[8]: $VC_{ji} = VC_j, \forall$ *j-th* site; $\forall$ *i-th* sequence. This is the second condition necessary for the disjunctive resource between sequences of sites.

The variable costs of the *i-th* sequence are equal to the sum of the variable costs of the sites it includes:

$$VC_i = \sum_{j=1}^{s} VC_j \cdot D_{ji} \tag{3}$$

Now we proceed to express the objective function, i.e. utility function, of the sequential production model in terms of gross income of each sequence regime, calculated as the difference between revenues and variable costs, i.e. the sum of the gross incomes of the foraging sites it includes:

$$GI_i = R_i - VC_i = \sum_{j=1}^{s}(R_j - VC_j)\cdot D_{ji} = \sum_{j=1}^{s} GI_j \cdot D_{ji} \quad \forall \text{ i-th sequence} \tag{4}$$

with: $GI_j = R_j - CV_j$ = gross income at the *j-th* site.

Gross income, thus, represents a synthesis of the two disjunctive constraint conditions that apply to the sequences, namely the site-specific quantities produced and the variable costs. A sufficient condition for disjunctive resources of sequences of sites is that $GI_{ji} = GI_j \; \forall$ *j-th* site; $\forall$ *i-th* sequence. According to this claim the gross income of each site has the same value regardless of the inclusion sequence, as shown in *table 1*.

Table 1. Apiary data

Number of Site	**1**	**2**	**3**	**4**
Vegetation	WINTERING	CITRUS	MULTI-FLORA P.	TARAXACUM
Period stationed	01/01- D1	03/24-05/01	04/09-04/27	04/09-05/01
Quantity honey produced kg	0	563.2	176	224
Output price €/kg	0	7.5	7.7	8
Site-specific variable costs	0	2,545	112	128
Gross income €	0	1,679	1,243	1,664

Number of Site	**5**	**6**	**7**	**8**
Vegetation	ROBINIA C.	ACTINIDIA	MEDICAGO S.	ROBINIA M. (mountain)
Period stationed	04/28-05/18	05/02-05/06	05/07-05/18	05/19-06/09
Quantity honey produced kg	409.6	32(a)	230.4	460.8
Output price €/kg	8.6	15(b)	8	8.6
Site-specific variable costs	177	134	162	272
Gross income €	3,346	346	1,681	3,691

Number of Site	**9**	**10**	**11**	**12**
Vegetation	PHACELIA	TILIA	CASTANEA S.	MULTI-FLORAL M.1
Period stationed	06/10-06/24	06/10-07/04	06/25-07/14	07/05-07/14
Quantity honey produced kg	268.8	435.2	294.4	204.8
Output price €/kg	7.6	8.3	7.2	7.7
Variable costs site	332	473	320	367
Gross income site €	1,711	3,139	1,800	1,210

Number of Site	**13**	**14**	**15**	**16**
Vegetation	MULTI-FLORA M.2	NUCLEI	ABIES A.	WINTERING
Period stationed	07/05-07/27	07/15-12/15	07/28-08/09	D2-31/12
Quantity honey produced kg	345.6	58 (ce)	256	0
Output price €/kg	7.7	100 (d)	6.3	0
Variable costs site	529	2,325	400	0
Gross income site €	2,122	3,475	1,213	0

Note: D1= linked to subsequ. Site; D2 = linked to preced. Site; a=colony rental; b=€/colony; c=nuclei; d=€/nucleus

2.2.2. Allocation constraint

T_j^S, T_j^E is the pair of dates that marks out t_j, the time interval during which the apiary stations at the *j-th* site (tab.1). The number of days spent at the site is determined based on the start and end dates of the interval. A series of sites $j = 1,2\ldots s$ therefore identifies a series of time intervals t_j lasting for z_j days.

The complete series of available sites $j = 1,2\ldots s$ is chronologically ordered according to the start date of the time interval that the apiary stations at each site. When multiple sites have the same start date, priority is given to the one with the earliest end date. Every *i-th* sequence is a selection from the complete set of sites characterized by non-overlapping intervals during which the apiary stations on those sites.

The annual allotment of time constitutes the fundamental resource allocation constraint for the migratory beekeeper. The sum of the intervals during which the apiary stations at the sites included in a sequence must be 365 days or less. In formal

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[7] Among these fixed costs are included the costs of medical treatments that the beekeeper must comply with on scheduled dates, regardless of the forage site at which the apiary may be located. Transport costs on the other hand are not the same for all sequences and consequently are to be considered variables.

[8] The assumption is conceptually reductive because the variable cost of transporting the apiary to a given site may change with the sequence in which it is included due to the different location of the foraging site that precedes and hence the distance to travel to reach it.

terms, the time constraint may be expressed:

$$\sum_{j=1}^{s} z_j \cdot D_{ji} \le 365 \quad \forall \ i\text{-}th \text{ sequence} \tag{5}$$

with: $D_{ji} = 1$ if the j-th site $\in$ the i-th sequence;
$D_{ji} = 0$ otherwise.

A gap, i.e. a period of inactivity of the apiary, may occur between the end date at one site and the start date at the ensuing site. The hives could be kept at the foraging site after flowering has ceased or transported in advance to the subsequent site or even moved to a standby site. Incurring gaps reduces the sum of the time intervals of hives at the forage sites included in the sequence to less than the annual provision of time. The variable costs incurred by the apiary at unproductive times are not ascribed to any particular site, but rather are an attribute of the sequence as a whole.

2.2.3. Operational model

The entire bio-economic model, expressed in formal operational terms, becomes:

$$max\, GI_i = \sum_{j=1}^{s} \left[(PH_j \cdot QH_j + PS_j \cdot QS_j + PN_j \cdot QN_j) - VC_j \right] \cdot D_{ji}$$

$$\text{s.t.} \quad \sum_{j=1}^{s} z_j \cdot D_{ji} \le 365 \qquad \forall \ i\text{-}th \text{ sequence} \tag{6}$$

with: $D_{ji} = 1$ if the j-th site $\in$ the i-th sequence;
$D_{ji} = 0$ otherwise.

By recursively[9] applying the *dummy* inclusion variable D_{ji}, all the possible sequences are identified. Based on the value the objective function assumes, sequences may be ranked thus allowing the optimal sequence to be identified. The following are known *ex ante*: sites = j =1,2,...s; the t_j intervals; the number of days z_j; quantities QH_j, QS_j, QN_j; prices PH_j, PS_j, PN_j; variable costs VC_j. What remains to be identified is the optimal sequence. Instead, the sequence actually adopted by the migratory beekeeper and its implementation are observed *ex post*.

From the objective function of the model one can infer that price variations of an output, with all other conditions remaining equal, affect the gross revenues accruing from a specific site as well as all the sequences including it. The change in price of an output can therefore alter the *ranking* of the sequences. From an operational standpoint, the only relevant effects of price are those resulting in a new optimal sequence, because only the latter will be implemented. The above holds true, however, provided the number of constituent hives (or quantities produced) remains constant. In sum, price changes have an impact to the extent that they result in re-ranking such that a prior optimal sequence is supplanted.

3. Results and Discussion

3.1. Case Study

The sequential production model formalized in the previous paragraph was applied to the data from a migratory beekeeping company based in the region of Veneto, in Italy. The producer is equipped with 96 colonies (Apis mellifera ligustica) distributed among three apiaries of 32 colonies each. The apiaries are transported individually from site to site by way of a knuckleboom truck (i.e. an articulating crane). The technical-economic unit for analysing revenues and variable costs is therefore the single apiary. Accordingly, data regarding revenues and variable costs (tab.1) are calculated on a per apiary basis. Since the technical means of transport are owned by the producer, the beekeeper is able to autonomously carry out all transfer operations along the site-to-site migratory route. The beekeeper starts out from the company's apiary farm and then trucks the colonies to the chosen migration site. Once the transfer has been completed, the beekeeper goes back to the farm, returning periodically (on average once a week) to the foraging site to check on the status of bee colonies. The beekeeper's professional experience and diligence in watching over the apiaries play a key role in maintaining the health status of the bee colonies (Jacques et al., 2017). The beekeeper carefully monitors for the presence of Varroa infestation, Nosema ceranae and more recently also of Vespa velutina, a new predator species of hornet indigenous to Southeast Asia, accidentally introduced into southwest France (Monceau et al. 2014), but also observed in Italy as of 2013.

The migration schedule, planned and implemented by the beekeeper in our case study, is inspired by a precise strategic criterion: choosing sites so as to pursue blossom times up the course of a river, with only two exceptions. After wintering at the apiary farm the colonies are transported to foraging site no. 2 consisting in a huge citrus grove. This is the only long-range migration capable of disorienting the bees (Nelson, Jay 1997; Ahn et al., 2012). However, a third-party[10] transport service is required to get the colonies to the citrus grove site. Thereafter, in June, the bee colonies could be transferred to a site with a Phacelia crop cover, a plant that bees are particularly attracted to as is widely known.

The decision to produce organic honey is based on the higher price range, but also because the beekeeper deems it a more stable market segment. Given the product quality objectives, foraging sites must be carefully selected so as to avoid the risks of honey contamination[11] during the entire production process and ensure full traceability. Commercial pollinating services are seldom compatible with the production of organic honey because agricultural crops generally rely heavily on agrochemicals. The only compatible foraging site found is an Actinidia (kiwifruit) vineyard[12] where the apiary opportunely remains for a time equal to half the flowering period. At the foraging site of the citrus grove, the bees produce honey without providing any commercial pollination service.

In addition to honey and commercial pollination services, the

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[9] The first sequence is built starting from site 1 and insert site 2 in the second position. After excluding all sites temporarily non-overlapping with site 2, the first chronologically available site is placed in the third position of the sequence; after excluding all sites temporarily non-overlapping with that site, the first chronologically available site is inserted in the fourth position of the sequence and so on until the sequence is completed by returning the base site. For the next sequence one restarts from site 1, but excludes site 2 (already used for the first sequence) and enters site 3. Then, the ordering procedure described above is continued until the sequence is completed by returning to the base site. The recursive procedure ends when all possible sequences, with at least one displacement from the base site, have been defined.

[10] The bee colonies are trucked from the base site and brought back to the same site. While at the citrus grove foraging site, the apiary does not furnish commercial pollination services.

[11] If bees visit contaminated vegetation, they transport residues into the beehive jeopardising the qualification as organic honey. Given that the flight range may exceed one kilometre, the beekeeper must know not only the foraging sites where he plans to station the colonies, but also the surrounding territory.

[12] The operation of distributing the colonies within the Actinidia vineyard site is not carried out by the beekeeper, but by the vineyard's personnel.

bee colonies produce wax, pollen, royal jelly and propolis. In order to take into account these complementary products, the revenues from foraging sites should be increased to varying degrees depending on the vegetation covering them[13]. However, due to the lack of precise evaluation parameters, this aspect was neglected.

Table 1 shows the data used in our empirical verification of the bio-economic model of migratory beekeeping. The company schedules a series of 15 sites. Sites 1 and 16 are the same, i.e. the apiary farm site at the start and end of the sequence, respectively. Site 14 is the locale where nucleus bee colonies are made. On average, from the separation of the 32 bee colonies and from swarm retrieval, the beekeeper obtains 58 marketable nucleus colonies. All other sites are covered by vegetation and therefore are foraging sites, strictly speaking. In particular, foraging sites 2 and 4 have an agricultural crop cover while all others have spontaneous vegetation[14].

The intervals during which the colonies station at sites and the quantities of per apiary production (tab.1) are in line with expectations of the beekeeper. The output prices, on the other hand, are average values, recorded by the authors, on the wholesale market for the reference area. Variable costs include: variable cost of migration transport; the costs of access to forage; the costs for eventual supplement diets for colonies; Honey harvesting costs; the costs of making nucleus bee colonies. We assessed all the above costs.

3.2. Results

In the optimal sequence, shown in tab.2, migration begins on April 9th with colony transfer from the base site 1 to site 3 where the honeybees produce multi-floral honey; the migration ends December 15th with the transfer of the colonies from site 14, where the beekeeper makes nucleus bee colonies, back to the base site 16. The beekeeper's outputs in chronological order are: wildflower (poly-flora) honey produced in the lowlands; Robinia pseudoacacia (Black locust) honey from hilly areas; mountainous Robinia honey; lime honey; multi-floral honey from mountainous areas; honey bee nucleus colonies. In the optimal sequence there is no provision of commercial pollination services. The intervals during which the colonies station at the various sites, listed in Table 2, span the entire yearly provision of time. In the optimal sequence, the 32 honey bee colonies that constitute the bee population generate revenues amounting to € 19,830 and incur site-specific variable costs totalling € 3,726; gross income amounts to €16,104[15].

Table 2. Optimal Sequence

Number of Site	**1**	**3**	**5**	**8**	**10**	**11**	**14**	**16**
Vegetation	WINTERING	MULTI-FLORA P.	ROBINIA C. (hillside)	ROBINIA M. (mountain)	TILIA	MULTI-FLORA M.1	NUCLEI	WINTERING
Period stationed	01/01-04/08	04/09-04/27	04/28-05/18	05/19-06/09	06/10-07/04	07/05-07/14	07/15-12/15	12/16-12/31
Revenue site €	0	1,355	3,523	3,963	3,612	1,577	5,800	0
Variable cost site €	0	112	177	272	473	367	2,325	0
Gross income site €	0	1,243	3,346	3,691	3,139	1,210	3,475	0
Gross income sequence €	0	1,243	4,589	8,280	11,419	12,629	16,104	16,104

The model simulates the effects on the optimal sequence of variations in output prices. The variations in output prices elicit changes only when they cause the optimal sequence to be replaced. For example, the increase in the price of nucleus bee colonies, i.e. the output of site 14 that appears in the optimal sequence, fails to alter the production response. Precisely, nucleus bee colony price drops that had nonetheless remained above the threshold of €76.7/nucleus, i.e. the break-even point (with the next best ranking sequence) in terms of gross income, would still have entailed no re-ranking of the optimal sequence. Below the price €76.7/nucleus threshold, the previous optimal sequence would have been supplanted by a new one (tab.3), no longer including site 14, and thus would have zeroed nucleus bee colony production: if $P_{14} > 76.7$ €/kg: $Q_{14} = 64$ nuclei; $P_{14} < 76.7$ €/kg: $Q_{14} = 0$ nuclei nuclei. The elimination of site 14 from the optimal sequence drags site 11 with it due to their chronological connectedness. Consequently, sites 11 and 14 are replaced by sites 12 and 15 (tab.3). Moreover, the interval the apiary is stationed at site 16 gets prolonged. Nucleus bee colony price drops below the threshold of €76.7/nucleus, in the case herein analysed, therefore result in an increase in honeydew honey production and, as a result of the exit of site 11 and entry of site 12, in an increased production of mountain multi-floral honey.

Let us now consider the price variation of citrus honey produced at site 2, which is not included in the optimal sequence. A decrease in the price of citrus honey leaves the initial optimal sequence unchanged; if, on the other hand, its price rises above the threshold of €9.07/kg (tab.3), a new optimal sequence supervenes, with the inclusion of site 2, where citrus honey is produced, but also of sites 6, where Actinidia pollination services are provided, and 7, where Medicago sativa (i.e. alfalfa) honey is produced (tab.3); in addition, migration begins sooner, on March 24th. Thus, in the optimal sequence, sites 2,6,7 are included, whereas sites 3,4 are excluded, with variations in overall outputs. Citrus honey price increases exceeding the threshold of €9.07/kg activate the production of citrus and Medicago sativa honeys as well as the delivery of the Actinidia pollination services while disabling the production of honeys collected from wildflower (multi-floral) of the lowlands and from Robinia pseudoacacia from hilly areas.

The time-allotment constraint, notwithstanding of the presence of disjunctive resources in terms of the sequencing of sites, makes it so that one output responds to the price variation of another, as is the case for models of non-joint production in the presence of a land constraints (Gorddard 2013), with the two outputs belonging to different sequences being interchangeable. Nevertheless the overlaps of non-gap intervals (in which apia-

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[13] Some vegetation, such as Actinidia and chestnut, have higher pollen-producing potential than the other in the practicable sites.

[14] Medicago sativa and Phacelia are semi-spontaneous perennial vegetation as they require planting, but not subsequent cultivation. The Medicago sativa site is a hypothetical alternative because it had never been used before by the beekeeper.

[15] The first sub-optimal sequence yields a gross income of €15,266.

Table 3. Simulations of Optimal Sequence

WITH P14 < 76.7 €/nucleus					
Number of Site	**1**	**3**	**5**	**8**	
Vegetation	WINTERING	MULTI-FLORAL P.	ROBINIA C. (hillside)	ROBINIA M. (mountain)	
Period stationed	01/01-04/08	04/09-04/27	04/28-05/18	05/19-06/09	
Gross income sequence €	0	1,243	4,589	8,280	
WITH P14 < 76.7 €/nucleus					
Number of Site	**10**	**13**	**15**	**16**	
Vegetation	TILIA	MULTI-FLORAL M.2	ABIES A.	WINTERING	
Period stationed	06/10-07/04	07/05-07/27	07/28-08/09	08/10-12/31	
Gross income sequence €	11,419	12,629	14,753	14,753	
WITH P2 = 9.59 €/kg					
Number of Site	**1**	**2**	**6**	**7**	
Vegetation	WINTERING	CITRUS	ACTINIDIA	MEDICAGO S.	
Period stationed	01/01-03/23	03/24-05/01	05/02-05/06	05/07-05/18	
Gross income sequence €	0	2,563	2,909	4,590	
WITH P2 = 9.59 €/kg					
Number of Site	**8**	**10**	**11**	**14**	**16**
Vegetation	ROBINIA M.	TILIA	MULTI-FLORAL M.1	NUCLEI	WINTERING
Period stationed	05/19-06/09	06/10-07/04	07/05-07/14	07/15-12/15	12/16-12/31
Gross income sequence €	8,281	11,420	12,630	16,105	16,105
WITH P5,P8=6.45 €/kg					
Number of Site	**1**	**2**	**6**	**7**	
Vegetation	WINTERING	CITRUS	ACTINIDIA	MEDICAGO S.	
Period stationed	01/01-03/23	03/24-05/01	05/02-05/06	05/07-05/18	
Gross income sequence €	0	1,679	2,025	3,706	
WITH P5,P8=6.45 €/kg					
Number of Site	**8**	**10**	**11**	**14**	**16**
Vegetation	ROBINIA M. (mountain)	TILIA	MULTI-FLORAL M.1	NUCLEI	WINTERING
Period stationed	05/19-06/09	06/10-07/03	07/05-07/14	07/15-12/15	12/16-12/31
Gross income sequence €	6,406	9,545	10,755	14,230	14,230
WITH P5,P8 < 0.59 €/kg					
Number of Site	**1**	**2**	**6**	**7**	
Vegetation	WINTERING	CITRUS	ACTINIDIA	MEDICAGO S.	
Period stationed	01/01-03/23	03/24-05/01	05/02-05/06	05/07-05/18	05/19-06/09
Gross income sequence €	0	1,679	2,025	3,706	
WITH P5,P8 < 0.59 €/kg					
Number of Site	**10**	**11**	**14**	**16**	
Vegetation	TILIA	MULTI-FLORAL M.1	NUCLEI	WINTERING	
Period stationed	06/10-07/04	07/05-07/14	07/15-12/15	11/16-12/31	
Gross income sequence €	6,845	8,055	11,530	11,530	
WITH P5,P8= 4.95 €/kg (e)					
Number of Site	**1**	**3**		**6**	**7**
Vegetation	WINTERING	MULTI-FLORAL P.		ACTINIDIA	MEDICAGO S.
Period stationed	01/01-04/08	04/09-04/27	05/28-05/01	05/02-05/06	05/07-05/18
Gross income sequence €	0	1,243		1,589	3,270
WITH P5,P8= 4.95 €/kg (e)					
Number of Site	**8**	**10**	**11**	**14**	**16**
Vegetation	ROBINIA M. (mountain)	TILIA	MULTI-FLORAL M.1	NUCLEI	WINTERING
Period stationed	05/19-06/09	06/10-07/04	07/05-07/14	07/15-12/15	16/11-31/12
Gross income sequence €	5,279	8,418	9,628	13,103	13,103

e = variat. at site 3

ries station at foraging sites) causes an output to respond to a price variation of another output (belonging to the same sequence) by rendering the outputs complementary.

If there is a fall in the price of Robinia honey produced at sites 5 and 8 of the optimal sequence, we observe two differentiated responses. When the price drops below €6.45/kg, the optimal sequence is supplanted (tab.3) such that both site 5 (Robinia, hilly area) and site 4 (multi-floral, lowlands) are replaced by sites 2 (Citrus grove), 6 (Actinidia vineyard) and 7 (Medicago sativa crop). In the new optimal sequence, site 8 (mountainous Robinia) still appears; this site has no substitutes because it is the only one available in the May 19th to June 9th time interval. Site 8 persists in the optimal sequence until the price of Robinia honey reaches the threshold of €0.59/kg, below which it is excluded from the optimal sequence because the gross income assumes a negative value. Upon exclusion of site 8 from the optimal sequence, a gap is formed from May 19th to June 9th (tab.3). The yield of Robinia honey produced at foraging sites 5 and 8 is thus:

$Q_5 + Q_8 = 870.4$ kg if $(P_5,P_8) > 6.45$;
$Q_5 + Q_8 = 460.8$ kg if $0.59 < (P_5,P_8) < 6.45$ €/kg;
$Q_5 + Q_8 = 0$ kg if $(P_5,P_8) < 0.59$ €/kg.

From the simulations we also see that the price variation of an output elicits differentiated responses depending on its timing within the sequence in which it occurs. If, for example, the drop in the price of Robinia honey does not occur ex ante, as previously considered under the assumption of its certainty, but in the context of a sequence already underway, the production response also changes. If, for example, the bee colonies are foraging at site 3, with the production of multi-floral honey, only with a price drop of honey to less than €4.95/kg (thus, no longer €6.45/kg) will a new optimal sequence supervene, while also eliminating site 5; with the exclusion from the optimal sequence of the Robinia (hilly area) site, both the actinidia site (from April 28th to May 1st) and the Medicago sativa site 7 (from May 7th to 18th) become included; as a result, the April 28th to may 1st interval is a remaining gap.

4. Conclusions

The bio-economic sequential production model herein formalized assumes conditions of certainty and disjunctive or unary resources regards sequences of sites. It also assumes that the beekeeper pursues the objective of maximizing income under the constraint that the time allocated to any sequence of sites must not surpass 365 days.

Application of the model to the data of an Italian migratory beekeeping farm has identified the optimal sequence of sites. In the optimal sequence, each apiary made up of 32 bee colonies generates a gross income of €16,104 while consuming the entire annual allotment of time.

From the simulations carried out via the model, the effect of variations in the price of an output on the optimal sequence are asymmetrical and discontinuous: the increase in the price of a output of a site already comprised in the optimal sequence, with all other output prices remaining constant, does not alter its composition, whereas output price drops below a critical threshold result in a re-ranking, which supplants the previous optimal sequence. The new optimal sequence and its predecessor differ due to a substitution of a foraging site, whose output price has decreased, along with any other chronologically linked sites, whether antecedent or subsequent in the chain. Should the decrease in the output price of a site not occur ex ante, but rather within a sequence already underway, it may surpass the critical threshold, thus supplanting the prior optimal sequence. Additionally, any optimal sequence may nevertheless comprise a gap during which the bee colonies remain unproductive.

In synthesis, as far as migratory beekeeping activities are concerned, output responses to prices are asymmetrical, discontinuous, chronologically linked and variable depending on the degree and timing within the sequence of reference.

The model herein formalized: affords the advantage of explaining the behaviour of entrepreneurs who practice migratory beekeeping, while allowing simulations of responses to changes in output prices; presents the limits of assuming conditions of certainty and disjunctive constraints regards site sequences. Lastly, although it should come as no surprise, the proposed bio-economic model is based on the underlying, albeit restrictive, hypothesis that the price elasticity of demand at the company level is zero. It follows that the model is only applicable to companies producing "apiary products of the highest quality" with direct-to-consumer retailing.

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