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Sequential Relationship between Profitability and Sustainability: The Case of Migratory Beekeeping

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Abstract: When beekeeping is managed on a migratory basis, the bee colony produces physical outputs (honey) and pollination services on a sequence of forage sites. Forage sites are competitors if their flowering periods overlap, and are complementary otherwise. Viable sequences consist only of complementary forage sites. A part of the bee colony's production time is spent on each forage site in the period when the crop or wild vegetation covering it is in flower. The total period covered by the sequence of sites, including the base site, must be equal to or less than the duration (365 days) of the bee colony's annual biological cycle. The migratory beekeeper draws up viable sequences of forage sites and calculates their profitability levels. Variations in the profitability of forage sites which alter the composition of the sequence, affecting provision of the non-marketed ecosystem pollination services, impact the biodiversity of the pollinated plants with trickle-down effects on sustainability. In the case of migratory beekeeping, there is, therefore, a sequential relationship between profitability and sustainability.

Keywords: migratory beekeeping; forage sites; sequential output production; ecosystem pollination services; modelling profitability and sustainability

1. Introduction

Beekeeping is often mistakenly thought of as the production of honey and other joint products such as wax, propolis and royal jelly. Yet by the end of the First World War, beekeepers had already begun to provide commercial pollination services to growers in the USA. "Pollination services were not marketed before World War I, primarily because small farms had enough flowering plants and trees to attract wild insects" [1]. This function of beekeeping is now of economic importance [2,3] in all developed agricultural systems.

When the crops are in bloom, beekeepers transport their bee colonies to the growers' fields, henceforth referred to as forage sites, to provide the required pollination service. Once flowering is over, the bee colonies must be immediately removed from the site as the crops are then treated with chemicals that are harmful to the health of the bees.

Since crops do not all flower simultaneously, the beekeeper can move the same bee colony from one forage site to the next throughout the year to meet growers' demands for pollination. Recurrent provision of commercial pollination services has given rise to migratory beekeeping, a new type of management whereby bee colonies are moved from site to site throughout the year. There are studies [1,4,5] describing the journeys followed by migratory beekeepers in the USA, who transport loads of hives by tractor-trailer.

Commercial pollination services are not an alternative to honey production as many crops allow the two outputs to be produced simultaneously and, furthermore, because the bee colonies can carry them out in sequence during their annual migration. Commercial pollination services and honey production may therefore be complementary within the framework of migratory beekeeping. Empirical observation shows that commercial pollination services are mainly carried out in spring while honey production prevails in the summer.

Pollination services are characterized as commercial when they take place on crops, as this involves a contract: the beekeeper rents the bee colony to the farmer for a fee, which is effectively the price of the commercial pollination service. Contracts between beekeepers and growers have evolved to the extent that they have given rise to a market in pollination services with prices varying according to farm and the time of year. Almond tree pollination in California is a typical example: the cost of hiring a bee colony has passed the $162 threshold (2008 prices). If the forage site is covered by wild vegetation, no contract is involved and the bee colony produces honey jointly with a non-marketed ecosystem service.

In the case of migratory beekeeping, bee colony outputs change throughout the year according to forage site. For example, the bee colony may perform only a commercial pollination service on the first forage site of the year, produce honey and perform a commercial pollination service on the second site, and produce honey and perform ecosystem pollination services on subsequent sites. Migratory beekeeping therefore follows a sequential multi-output, multi-site process.

The sequencing of forage sites means that timing is a crucial element in the beekeeper's migration over the year. Every sequence differs from another by at least one forage site; each sequence has its own order of forage sites and its own profitability level. In fact, revenues, variable costs and gross income depend on the composition of the sequence, as will be explained in Section 3, which describes the economic model of the migratory beekeeper. If the migratory beekeeper makes changes to the sequence of forage sites, the ecosystem pollination services will also change and will impact biodiversity and the rural landscape, as will be explained in Section 4.

2. Amateur *vs.* Commercial Beekeeping Management

Before addressing the economic and ecosystem aspects of migratory beekeeping, a distinction needs to be drawn between different types of beekeepers in terms of their management/size. We identify two main types of management: amateur and commercial.

There are about 700,000 beekeepers in the EU, approximately 97% of which have fewer than 150 hives, accounting for around 67% of the total number of hives [6].

The USA has about 135,000 beekeepers with 2.4 million bee colonies [7]. Most of these—approximately 94%—manage 25 or fewer bee colonies. Commercial beekeepers account for about 1% of the total, but each manages between 300 and 60,000 bee colonies and provide most of the bee pollination services in the USA. Some authors [5] adopt a different taxonomy and classify beekeepers as semi-commercial or commercial depending on whether they have fewer or more than 300 hives. Amateur beekeepers are, therefore, more numerous at more than 90%, in both the USA and the EU.

With a few exceptions, size, as measured by the number of bee colonies, is a good discriminator between the two forms of management, commercial and amateur. The marketed output for amateurs—beekeepers with fewer than 30 colonies—is honey. The term honey includes all jointly produced physical outputs. For these operations, as with small family farms in general [8], profitability does not necessarily take first place in the hierarchy of objectives. Free time occupation or honey consumption may be the primary objectives. Therefore, explaining amateurs' production choices in terms of profitability is not a realistic assessment of their operations.

Only in exceptional cases do amateur beekeepers perform commercial pollination services. For the commercial beekeeper, on the other hand, the commercial pollination service is an important production opportunity and an incentive to foster migratory management. With this type of management, the economic problem of identifying the most profitable sequence of forage sites is of primary importance.

The existence of two types of management has repercussions on the beekeeper's response to price fluctuations. The price of honey is the only relevant factor for amateurs, while for commercial beekeepers the prices of commercial pollination services also come into play. In recent decades, these prices have shown an upward trend as the demand for commercial pollination exceeds supply [9,10]. The causes of the supply shortage are: a reduction in the wild bee population [11] with concomitant loss of the natural pollination service; the competition between crops to use bee pollination services in some periods of the year [12]; an increase in the area of crops to be pollinated [13]; a reduction in the number of colonies managed by beekeepers [14,15]. In the USA, a rise in the rental fees for bee colonies has very clearly affected the pollination of almond and plum crops [5,12].

3. Profitability

Before moving the colony, the beekeeper must draw up various sequences of sites and select the most profitable. We address this problem from a management perspective by assuming that the beekeeper calculates the annual income from each sequence of forage sites considered to be viable. We assume that the beekeeper produces under conditions of certainty and therefore knows *ex ante*: the set of viable forage sites; the length of time the bee colony will stay on each forage site; the time it takes to transport the bee colony from one site to another; the set of fixed inputs; the prices of outputs; the yields and variable unitary costs of the bee colony for each forage site in a given sequence. Given these assumptions, the beekeeper only needs to identify the sequences of forage sites and sort them according to profitability. For this purpose we define:

j = 1,2 ... s = forage sites; s is the base site;
i = 1,2, ... n = the sequences;
R_i, C_i, π_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} = quantities of honey produced and commercial pollination services performed on the *j-th* site in the *i-th* sequence;
PH_j, PS_j = prices of honey produced and commercial pollination services performed on the *j-th* site;
$T_{ji}{}^S, T_{ji}{}^E$ = start and end dates of production/service on the *j-th* site in the *i-th* sequence;
$t_{ji} = T_{ji}{}^E - T_{ji}{}^S$ = number of days spent by the bee colony on the *j-th* site in the *i-th* sequence;
v_{ji} = number of days needed to move the bee colony to the *j-th* site in the *i-th* sequence;
$z_{ji} = t_{ji} + v_{ji}$ = total number of days (stay + move) on the *j-th* site in the *i-th* sequence;
E_{ji} = membership function of the *j-th* site in the *i-th* sequence.

The migratory beekeeper's profit depends on the sequence of forage sites chosen as can be seen from the following model:

$$\pi_i = R_i - C_i = \sum_{j=1}^{s} (PH_j \cdot QH_{ji} + PS_j \cdot QS_{ji}) \cdot E_{ji} - CF_i - \sum_{j=1}^{s} CV_{ij} \cdot E_{ij} \quad (1)$$

s.t. $\sum_{j=1}^{s} z_{ji} \cdot E_{ji} \leqslant 365 \; \forall$ *i-th* sequence,
with: $E_{ji} = 1$ if the *j-th* site $\in$ *i-th* sequence;
$E_{ji} = 0$ otherwise.

All sequences end with the base site where the bee colony will spend the winter. Migration begins from the base site of the previous biological cycle.

3.1. The Objective Function

The income of each *i-th* sequence, shown in curly brackets in the objective function, is equal to the sum of revenues from the individual forage sites that comprise it. The income of each *j-th* site, reported in square brackets, is formed of two components shown in separate sets of round brackets:

the first derives from the production of honey, the second from the commercial pollination service. Income may come from honey alone, from the rental fee of the bee colony (commercial pollination service) alone or from both outputs. The ecosystem pollination service carried out jointly with honey production on a forage site covered with spontaneous vegetation does not generate any income, nor is any income generated from the base site because it does not yield any marketed product.

The income from the outputs produced on individual sites in the *j-th* sequence is calculated by multiplying the quantities produced by their respective prices. The price of the commercial pollination service is the rental fee of the bee colony. The quantities produced accumulate over the time the bee colony spends on the forage site and are, *ceteris paribus*, functions of the length of this period: $QH_{ji} = f_{ji}(t_{ji})$; $QS_{ji} = h_{ji}(t_{ji})$.

The bee colony yield from a given forage site, whether honey production or commercial pollination services, depends on the strength of the bee colony, which in turn depends on the quality of the food assimilated throughout the migration. The type of forage provided by crops covering the site cannot be ignored because it influences the honey production but also because it is an input that affects the dynamics within-year of the bee colony stock [16]. A change in the selected sequence may, due to food quality, affect the strength of the bee colony. Bee colony yields on a given forage site may therefore change as the sequence to which it belongs changes.

Output prices are also site-specific, but unlike bee colony yields they do not depend on the sequence to which the site belongs. That is, the output prices of a forage site remain unchanged when the sequence to which it belongs changes.

The production costs of each *i-th* sequence of forage sites include fixed costs and variable costs. All sequences of forage sites have the same fixed costs. The variable costs of the *i-th* sequence are equal to the sum of the variable costs of each of the forage sites in it. The variable costs of a forage site include those incurred in moving the bee colony. Disregarding exceptions, the variable cost of transport to a site depends on the location of the previous forage site in the sequence because it determines the distance to be travelled. The variable transport costs associated with a given forage site may therefore vary depending on the sequence to which it belongs.

The migratory beekeeper has all the data needed for drawing up viable sequences on the basis of the profit they will yield.

The objective function of the model formalized above can also be specified in terms of the beekeeper's gross income from each viable sequence:

$$GI_i = \pi_i + FC_i = \sum_{j=1}^{s} (R_{ji} - VC_{ji}) \cdot E_{ji} = \sum_{j=1}^{s} g_{ji} \cdot E_{ji} \tag{2}$$

where:

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

As can be seen from Equation (2), the gross income of each sequence is arrived at by adding together the gross incomes of the individual forage sites belonging to it. The orderings of the sequences of sites drawn up on the basis of either gross income or profit are necessarily the same.

3.2. The Constraint of Time

The flowering period of the crop covering each forage site has a start and end date; these dates delimit the length of time the bee colony stays on the forage site. The length of time the bee colony remains on the forage site depends on—but does not coincide with—the flowing period of the plants; for example, the optimal time to allocate a bee colony to an apple orchard is when 25% of the flowers are open, in other words when flowering is already underway. Time is also needed to move the bee colony from the previous to the current site, so that a portion of the available production time of each forage site is taken up with transporting the bee colony. The total production time of each forage site is arrived at by adding transportation time to the length of the stay.

The total time span of each sequence of forage sites (including the base site) must be equal to or less than the time of the production cycle, which is 365 days as specified by the constraint of the chosen model of the sequence. The incomes and expenditures of the estimated operational budget calculated for each sequence of forage sites span the same period.

The constraint of available time allocable to forage sites may be specified with regard to the bee colony's active period of production alone rather than the entire annual cycle. Formally:

$$\sum_{j=1}^{s-1} z_{ji} \cdot E_{ji} \leqslant 365 - z_{si} \forall\ i-th \text{ sequence} \tag{3}$$

Subtracting the number of days (z_{si}) the bee colony spends on the base wintering site from the 365 days of the annual biological cycle gives the number of properly productive days that may be allocated to the forage sites that generate revenues. A study [17] on the amount of fishing time allocated to catching fish takes such an approach.

3.3. The Membership Function

The dummy E_{ji} has a value of 1 if the forage site belongs to the sequence, otherwise the value is 0. Forage sites with overlapping flowering periods are rivals and may not belong to the same sequence; if the sequence includes a site whose membership function has a unitary value, all those rivals are necessarily excluded. When the flowering periods do not overlap, *i.e.*, they follow one after the other, the forage sites are complementary. Each sequence comprises only complementary sites with a membership function of 1. An overlap at the edges of the flowering periods of two forage sites in a sequence means that they are competitive for a part of the production time. This issue will be addressed in the next section.

Drawing up a sequence requires an algorithm to be applied to the database of forage sites. This algorithm proceeds in the following order: locating the flowering periods of the forage sites over the year; numbering them in chronological order; finding rival and complementary forage sites on the basis of overlap or no overlap of flowering periods utilized by the bee colony; building the sequences iteratively, starting from the first forage site and taking the return to the base site as the termination condition.

4. Sustainability

Migratory beekeeping produces marketable outputs but also, as is generally the case in agriculture [18,19], externalities and public benefits. A non-marketed ecosystem service could therefore be produced jointly with a marketed output [20].

When a bee colony is allocated to a forage site covered by wild vegetation, honey is produced jointly with the provision of a non-marketed ecosystem pollination service. It is a non-marketed output because the bee colony receives no rental fee nor does it pay a location fee, as access to a site covered with wild vegetation is, as a rule, free. However, by pollinating the wild vegetation, the bee colony increases the availability of plant foods to the benefit of wildlife in the surrounding area with wide-ranging effects on the food chain and surrounding ecosystem. The resulting benefits to the ecosystem are the conservation of biodiversity and the local rural landscape. Bee colonies also serve as indicators of the biological quality of pollinated sites by gathering traces of contaminants.

In the case of migratory beekeeping, the non-marketed ecosystem pollination service can be carried out at different forage sites at different times. A sequence may, of course, include only forage sites covered by wild vegetation. Hence, the contribution to maintaining biodiversity depends crucially on the composition of the beekeeper's adopted sequence and the relative numbers of crop or wild vegetation forage sites. Migratory management of bee colonies has, therefore, the variable potential to mitigate the loss of ecosystem pollination services due to the decline in wild bees [11] according to the sequences adopted by beekeepers.

Bee colonies managed by beekeepers have, unfortunately, seen a decline, particularly in the USA and Europe, as a result of a series of concomitant causes [10,14,21]. An analysis carried out recently on almond cultivation in California [21] identifies *Varroa* and other viruses as "probable causes" of the decline in managed bees, nutritional deficiency due to poor quality feed as a "possible cause", while exposure to pesticides appears to be a simple "subsidiary factor". However, other analyses [22,23] show combined exposure to pesticides to be the most significant factor in bee colony collapse. Moving the colonies also seems to have an impact on bee health, as emerged from a survey [24] which reported a higher rate of *Nosema ceranae* infection in bee colonies that are moved. The sequence composition of forage sites may affect the probability of colony collapse during the winter because it models the type and chronology of the risks to which the bee colony is exposed. The presence of forage sites covered by wild vegetation in the sequence reduces the risk of the bee colony being exposed to pesticides and generally improves food quality.

Protecting the health of bee colonies during migration poses a serious problem with respect to the selection and control of pesticides (insecticides, fungicides, herbicides) applied to the cultivated sites and surrounding areas. Health control is an issue of prime importance because the migration of bee colonies increases the risk of the spread of *Varroa* infestations, epidemics, *Nosema ceranae* and, lately, *Aethina tumida*, a beetle native to South Africa that damages the honeycombs and causes loss of honey in Mediterranean bee colonies.

The presence of crop sites and wild vegetation sites in the sequence is an integrating factor between two important social objectives: sustainability and food safety. Pollination of wild vegetation helps maintain plant biodiversity and so impacts sustainability. Pollination of agricultural crops, stabilizing or improving food crop yields, impacts food safety. Modifications in the profitability of forage sites triggering changes in the allocation of the bee colony's production time between the two types of forage sites have effects on the timing and spatial distribution of ecosystem pollination services with trickle-down effects on sustainability.

Each sequence of forage sites has its own level of sustainability. Applying Klein *et al.*'s approach [25] to the case of the migratory beekeeper, a coefficient ranging between 0 and 1 may be assigned to each forage site in the sequence, which measures the impact of pollination services on the eco-system (the provision of ecosystem services depends on site-specific characteristics, mainly to do with the type of spontaneous vegetation that covers it, but also on the environmental context of the forage site). The sequence's overall level of sustainability may be quantified by weighing the coefficients of the individual forage sites it comprises.

5. Discussion and Conclusions

Non-simultaneous crop-flowering favors the allocation and re-allocation of bee colonies to forage sites to meet farmers' demands for recurrent pollination services. The commercial nature of pollination services derives from a contract whereby the migratory beekeeper offers pollinating services to meet the farmer's demand. The price of the pollination service is the fee paid to the beekeeper by the farmer to rent the bee colony, except in the case of pollination of wild vegetation sites where the joint production of honey and provision of an ecosystem pollination service is non-marketed.

Migratory management of beekeeping allows commercial pollination services and the production of honey—the latter jointly with non-marketed ecosystem pollination services—to be carried out on sequences of forage sites over the course of the bee colony's annual cycle.

The internal composition of the sequence of forage sites impacts the timing of production and the quantity of the bee colony's output. Where it results in changes to the provision of non-marketed ecosystem pollination services, a change in the sequence adopted by the beekeeper as a consequence of changes in the profitability of the forage sites impacts biodiversity with widespread effects on the entire local ecosystem.

The analysis raises two methodological aspects and one operational aspect.

(1) In a context of sequential production, the fundamental constraint of allocation is the available production time in a given year. The total time required by a given sequence of forage sites can never be greater than the length of the bee colony's annual biological cycle. This condition applies not just to migratory beekeeping but also to marine fishing and, more generally, to all livestock activities involving transfer of the mobile production organism to different forage sites throughout the year.

(2) Analysis of the risk of bee colony collapse during the wintering period should take into account the effect of the composition of the sequence of forage sites. The types of risks to which the bee colony is susceptible and their chronological interactions depend on the composition of the sequence of forage sites adopted by the migratory beekeeper and, in particular, how production time is divided between cultivated sites and "natural" sites covered by wild vegetation.

(3) The importance of ecosystem pollination services carried out through migratory beekeeping and the health risks this type of management entails make the activation of a Common Market Organization (CMO) for honey and related outputs a necessary and urgent task. The need to activate this CMO is supported by the results of a few studies that have warned of the fragility of the Agro Environmental Schemes (AES) of the European Union [26], especially where complex landscapes are concerned, and have shown that collective management of pollination services [27,28] is preferable to separate management by individual farms. A CMO for honey and joint products could integrate market interventions and agro-environmental measures with the aim of containing the loss of managed bee colonies and strengthening the presence in the sequences adopted by the migratory beekeepers of forage sites able to perform non-market ecosystem pollination services with positive effects on biodiversity.

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