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Iddo Kan, Yoav Motro, Nir Horvitz, Ayal Kimhi, Yossi Leshem,
Yoram Yom-Tov and Ran Nathan

P.O. Box 12, Rehovot 76100, Israel

ת.ד. 12, רחובות 76100

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Iddo Kan,*[1] Yoav Motro,[2] Nir Horvitz,[2] Ayal Kimhi,[1] Yossi Leshem,[3] Yoram Yom-Tov[3] and Ran Nathan[2]

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* Corresponding Author: Department of Agricultural Economics and Management, The Hebrew University of Jerusalem; and The Center for Agricultural Economic Research; P.O. Box 12, Rehovot 76100, Israel; Landline: 972-8-9489233, Fax: 972-8-9466267; kan@agri.huji.ac.il;

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[1] Department of Agricultural Economics and Management, Hebrew University of Jerusalem, and The Center for Agricultural Economic Research. P.O. Box 12, Rehovot 76100, Israel.

[2] Department of Ecology, Evolution and Behavior, The Hebrew University of Jerusalem; Givat Ram, Jerusalem 91904, Israel.

[3] Department of Zoology, The George S. Wise School of Life Sciences, Tel Aviv University, Tel Aviv 69978, Israel.

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Abstract

We develop an empirical framework for evaluating the profitability of the use of barn owls to control rodent populations by locating nesting boxes in agricultural areas. Barn owls' behavior is incorporated into the analysis by estimated functions that relate agricultural production to the birds' spatial patterns of hunting and nesting choices. The model was developed based on agricultural and zoological data collected in a kibbutz in northern Israel. Focusing on alfalfa, the presence of barn owls was found to increase profits by about $50 / hectare-year. Moreover, production exhibited increasing return to scale with barn owls' predation pressures. Accordingly, simulations show that redistributing boxes can considerably increase barn owls' contribution to alfalfa production's profit. These findings indicate that environmental policies aimed at encouraging the adoption of this biological control method are redundant; at the same time, they provide support for stricter regulations on rodent control using poisons.

Keywords: agriculture; barn owl; biological control; environmental economics; rodents

I. Introduction

Rodents considerably damage agricultural production around the globe. In Australia, Saunders and Robards (1983) estimated a yield reduction of 23% due to mice population eruption in sunflower fields. For Asia, Singleton (2003) estimated losses of 5-10% in annual rice production. In Tanzania, 15% of maize output is regularly lost (Leirs, 2003). Damage caused by rodents varies between 5-90% of total production in various parts of South America (Rodriguez, 1993). This situation may elucidate the low performance of conventional rodent control methods, which are based on habitat modification through tillage and sanitation measures, trapping, and poisoning (Stenseth et al., 2003). Moreover, poison treatments are frequently tardy both because rodent population outbreaks are unpredictable and poisons have short-run impacts due to the rapid immigration of rodents from adjacent untreated areas; furthermore, poisons are often considered by farmers to be too costly (Skonhoft et al., 2006; Davis et al., 2004; Stenseth et al., 2003). Brown et al. (1997) estimated that in order to cover the costs of rodenticide application, 8-13% of the yield damage to cereal crops needs to be prevented. Risks of mortality by self-poisoning (Eddleston, 2000) and detrimental impacts on non-target animals (Cox and Smith, 1990) are additional drawbacks of rodenticides. For these reasons, the use of barn owls (*Tyto alba*) is proposed as a potential biological control method.

Rodent control by barn owls is based on installation of nesting boxes in agricultural areas. Barn owls are cosmopolitan nocturnal predators favoring rodent prey to an extent greater than most other avian predators. They prey on a variety of rodent species, many of which are agricultural pests. A pair of nesting owls hunts between 2,000 and 6,000 rodents in a nesting season, from early spring till summer (Motro et al., 2010). Compared to mammalian predators such as jackals and cats, barn owls are relatively tolerant to secondary poisoning, thereby allowing integration with conventional methods. Barn owls forage in flight or from perches. They are secondary cavity nesters utilizing large, ready-made cavities (Taylor, 1994). This scheme causes scarcity in nesting sites, which therefore facilitates harnessing the barn owl's hunting abilities to rodent control by the introduction of human-made nesting boxes. However, barn owls can be spatially directed only by locating appealing nesting boxes and perches. In addition, barn owls are long-lived and need a relatively long time to build up as a population large enough to yield meaningful rodent control (Wood and Fee, 2003). These features cause a market failure associated with the development of this biological control method by the private sector.

The barn owl rodent control method follows the *conservation* approach of biological control, wherein populations of pests' natural enemies that already exist in an ecosystem are enhanced through the elimination of bottlenecks (Bellows and Fisher, 1999), in this case the scarcity of nesting locations. However, adoption of any biological control method by private entrepreneurs (i.e., farmers) is conditioned on the method's relative economic merit, which in turn depends on the method's control efficacy , its implementation costs, its effects on output quality and quantity, the demand for organic or chemical-free products, and governmental policies that encourage environmentally sound practices.

From a societal point of view, consideration of such supportive policies is justifiable provided that a biological control method fails a cost-benefit test vis-à-vis the private sector; i.e., when environmental externalities are ignored. However, unlike the *augmentation* bio-control methods, wherein populations of pests' natural enemies are artificially augmented (e.g., by the release of predatory mites to control spider mites and nematodes for the control of soil-dwelling insects), conservation biological control methods usually do not involve instruments or biological agents that can be sold commercially. For this reason, private firms do not find conservation bio-control appealing enough for investment in research and development in order to gain intellectual property rights on a produced knowledge that can be translated into profits. Therefore, development of the bio-control method might be hindered due to the free-riding phenomenon associated with the public-good attributes of knowledge. Consequently, bio-control's potential users in the private sector lack the information required for conducting cost-benefit analyses.

The objective of this study is to evaluate the potential contribution of rodent control by barn owls to farmers' profits, and thereby, to infer regarding the necessity of complementary governmental policies to promote the adoption of this method and the consequent implications for regulating the use of rodenticides. To this end, we develop an empirical model and apply it to a unique dataset of a case study in Israel.

The next section presents the evaluation methodology. Section III describes the general economic model. The data and procedures used for estimating the model's components are presented in Section IV. Section V reports and discusses the results of the profitability evaluation. Section VI concludes.

II. Evaluation Methodology

The use of barn owls began in 1969 in Malaysia with the control of rats in oil palms (Duckett, 1976), and since then has extended to other parts of the world for the control of a wide range of rodents that damage various crops; e.g., rice in India (Parshad, 1999). In Israel, its use began in 1983 at Kibbutz Sde Eliyahu (Meyrom et al., 2009), an income-sharing community with central management of agricultural lands. This local initiative was driven mainly by environmental protection ideology rather than by economic considerations, and was implemented with aid from publicly financed research programs. The ideology driving the development of this practice was in response to the widespread use of rodenticides in agriculture in Israel in the 1950s to 1990s, causing mass mortality of birds and many other animals (Yom-Tov and Mendelssohn, 1988). Other farmers in Israel began adopting the method only in 2003, when the National Initiative for the Use of Barn Owls and Kestrels as Biological Controllers in Agriculture program was launched, now a nationwide, organized system for installing and maintaining nesting boxes that operates under the financial support and supervision of the Israel Ministry of Agriculture and Rural Development (IMARD) and the Israel Ministry for Environmental Protection (IMEP, 2009). Currently there are more than 2,200 nesting boxes in Israel, occupied by barn owls whose total foraging territories are estimated at 800 square kilometers, about a fifth of Israel's arable lands. While this rapid adoption may be explained by considerable dissatisfaction of farmers with rodenticides, due to the intensive involvement of the authorities, it may not be viewed as strong evidence for method's profitability based on farmers' revealed preferences. Moreover, these developments occurred while the technique still lacks science-based knowledge on how it should be most efficiently applied, and also lacks solid support for its economic justifiability (Leshem et al., 2010). Furthermore, at least for the case of rat control in oil palms, there is inconsistent evidence on barn owls' impact on rodent populations and on reduction in production damage (Wood and Fee, 2003). At the same time, however, recall that the design of efficient pest-control systems is challenging due to the involvement of spatial and temporal external effects (Harper and Zilberman, 1989; Regev et al. 1976), uncertainty (Feder, 1979), and the dynamics of pest adaptation and resistance development (Hueth and Regev, 1974). Moreover, biological control involves the additional complexity of dynamic predator-prey relations (Rafikov et al., 2008; Feder and Regev, 1975). Analyzing the case of rodent control by avian predators is particularly challenging because of the large areas covered by the birds and the relatively long time required raptor population establishment.

The methodology employed in our empirical evaluation of barn owls' contribution to farming profits takes into account two main features of this control system. First, reliable and continuous estimates of rodent populations are unavailable due to the high costs and methodological difficulties in monitoring (Proulx, 1999; Greaves, 1989). Moreover, barn owls can reduce the damage caused by rodents by changing the latters' feeding behavior under predation pressure rather than through reducing the number of rodents (Abramsky et al., 1996). In contrast, data on nesting locations of barn owls and crop yields are readily available. Hence, our analysis overlooks the rodent populations in the actual raptor-rodent-plant trophic cascade, and instead analyzes the indirect relations between the raptors and the agricultural outputs. Moreover, a predatory act by a barn owl starts and ends at the nesting place; this pattern is termed “central place foraging” (Taylor, 1994; Orians and Pearson, 1979). Furthermore, barn owls are “single-prey loaders”, i.e., they catch a single individual each time (Lessells and Stephens, 1983). These habits make the nesting place a key factor in the spatial distribution of the predation pressure exercised by barn owls. Our evaluation methodology is based on this spatial variation: We examine whether yields are larger in locales exposed to heavier predation pressures. Barn owls' behavior is explicitly incorporated into the economic analysis through the estimation of functions that relate agricultural production to the barn owls' spatial patterns of hunting and nesting choices. By this means, farming profits are related to the spatial distribution of nesting boxes, which is the farmer's decision variable.

The study utilizes a dataset spanning 10 years, 1999-2008, covering the lands of Sde Eliyahu in the Beit She’an Valley, Israel ($32^0$30N, $35^0$30E). This is a semi-arid region with about 250 mm average annual rainfall, mild winters, and dry, hot summers. During the entire study period, 58 barn owl nesting boxes were placed in various fields between 1983 and 1996; that is, our analysis begins after the raptor population completed a sufficiently long establishment period. The 12.5 km^2 study area comprises heterogeneous land uses, including field crops, fruit plantations, and residential zones, enabling us to investigate the impact of various land uses on the barn owls’ predation pressures, as well as on the nesting boxes’ occupancy rates.

With respect to the detection of yield effects, the study focuses on alfalfa production. Alfalfa is a perennial, multi-harvested legume grown mainly for fodder. It is highly prone to rodent damage because rodents accumulate over the multi-annual crop growth period, while almost no agro-mechanical measures can be implemented in the fields (Moran and Keidar, 1993). Poisoning rodents in alfalfa exhibits low performance due to the constant presence of fresh, nutritious, green foliage favored by them (Proulx, 1998). This makes alfalfa a good case study for examining the basic economic efficiency of agricultural rodent control by barn owls.

Our analysis evaluates the profit contribution of barn owls above and beyond the effects of agronomic activities, sanitation, and other natural factors on rodents. Since unlike the majority of farmers in Israel, farmers at Sde Eliyahu completely avoid applications of rodenticides ideologically, our dataset cannot be used to directly compare biological and conventional rodent control methods. Data obtained from another alfalfa grower in the Beit She’an Valley were used for this purpose.

III. The Model

Consider a farm with I fields, where the size of each field i (i= 1,…, I) is M_i. Since our analysis relies on spatial distribution of predation pressure, intra-field variations need to be captured; therefore, we consider an artificial division of field i into M_i land units, the size of each of which is l. Let m_i, m_i=1,…,M_i , denote a specific land unit in field i. The unit m_i is geographically represented by its central point, the coordinates of which are incorporated in the two-dimensional column vector $\mathbf{u}_{m_i}$. The two-row matrix $\mathbf{u}_i = \left(\mathbf{u}_{m_1},...,\mathbf{u}_{M_i}\right)$ incorporates the coordinates of all land units in field i, and $\mathbf{u} = \left(\mathbf{u}_1,...,\mathbf{u}_I\right)$ is the coordinates matrix of all the land units in the farm. The vector $\mathbf{e}_i$ contains all other specific attributes of field i.

There are K barn owl nesting boxes spread over the farm, where $\mathbf{x}_k$ is the two-dimensional coordinate vector of box k; k = 1,..., K; and $\mathbf{x} = \left(\mathbf{x}_1,...,\mathbf{x}_K\right)$ is the matrix of the coordinates of all K boxes. Let $\mathbf{a}_k$ be the vector of all other attributes of box k, i.e., the installation year, entrance aspect, shade conditions, and nesting history. The matrix $\mathbf{a} = \left(\mathbf{a}_1,...,\mathbf{a}_K\right)$ is defined accordingly.

J crops are routinely grown on the farm. Let δ_{ij} be an indicator variable that obtains the value 1 if crop j, j = 1,…, J, is assigned to a specific field i. The $I \times J$ matrix of field crop ascriptions, δ, is defined accordingly. The function

$$r_{ij}\left(\mathbf{u},\mathbf{x},\boldsymbol{\delta},\mathbf{a}\right) = \sum_{k=1}^{K} \Pr_k\left(\mathbf{u},\mathbf{x},\boldsymbol{\delta},\mathbf{a}_k\right) s_{ikj}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i,\mathbf{x}_k\right)\right) \qquad (1)$$

represents the cumulative predation pressure applied by the K boxes on the M_i land units of field i, when this field is allotted to crop j. Cumulative predation pressure is defined as the sum of the products of two functions. The first function, $\Pr_k\left(\mathbf{u},\mathbf{x},\boldsymbol{\delta},\mathbf{a}_k\right)$, denoted as the *nesting function*, expresses the probability of nesting box k of being occupied given its own attributes $\mathbf{a}_k$ and the features of its surrounding environment, i.e., the type of crops allotted to the adjacent fields (δ), and the distances between all the boxes and land units in the farm, which in turn depend on **u** and **x**. The second function, $s_{ikj}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i,\mathbf{x}_k\right)\right)$, is called the *predation-pressure function*. It measures the fraction of time wherein a barn owl nesting in box *k* would search for prey in the area of field *i* if the field is devoted to crop *j*. This fraction in turn is a function of $\mathbf{d}_{ik}\left(\mathbf{u}_i,\mathbf{x}_k\right)$, the vector of distances from box *k* to all the M_i area units of field *i*.

Let $\mathbf{q}_{ij}$ be the vector of *N* production inputs applied to field *i* when it is assigned to crop *j*, and denote by **b** a vector of exogenous factors, including managerial skills, climate conditions, input constraints, and prices of inputs and outputs. Given **u**, **x**, **a**, **e**, and **b**, the farmer decides on the optimal assignment of crops to fields, δ^*, and application of inputs, $\mathbf{q}_{ij}^*\left(\mathbf{u},\mathbf{x},\mathbf{a},\mathbf{e}_i,\mathbf{b}\right)$, $i = 1,..., I$, $j = 1,..., J$, that maximize the farm's profit. The maximal profit is

$$w^* = \sum_{i=1}^{I}\sum_{j=1}^{J}\left[\delta_{ij}^* p_j g_{ij}\left(r_{ij}\left(\mathbf{u},\mathbf{x},\boldsymbol{\delta}^*,\mathbf{a}\right),\mathbf{e}_i,\mathbf{b}\right) - \mathbf{q}_{ij}^*\left(\mathbf{u},\mathbf{x},\mathbf{a},\mathbf{e}_i,\mathbf{b}\right)\mathbf{c}'\right] \tag{2}$$

where p_j is crop *j*'s output price, **c** is the vector of *N* input prices, and $g_{ij}\left(r_{ij}\left(\mathbf{u},\mathbf{x},\boldsymbol{\delta}^*,\mathbf{a}\right),\mathbf{e}_i,\mathbf{b}\right)$ is the reduced form production function, i.e., the optimal production with respect to the inputs applied to field *i* when assigned to crop *j*.

As aforementioned, our analyses focus on alfalfa production; that is, we do not study the nesting boxes' impact on other crops, either through application of inputs or through the assignment of crops to fields. Letting $j = 1$ denote the alfalfa crop, our objective is to empirically evaluate *K* nesting boxes' contribution to the farm's maximal profit, w^*, through their impact on both the alfalfa revenue, $p_1 g_{i1}\left(r_{i1}\left(\mathbf{u},\mathbf{x},\boldsymbol{\delta}^*,\mathbf{a}\right),\mathbf{e}_i,\mathbf{b}\right)$, and the alfalfa production cost $\mathbf{q}_{i1}^*\left(\mathbf{u},\mathbf{x},\mathbf{a},\mathbf{e}_i,\mathbf{b}\right)\mathbf{c}'$, given that the land allocation δ^* is assumed dictated primarily by considerations such as the fields’ infrastructure, soil attributes, and crop rotation, so that it is independent of **x** and **a**.

IV. Estimating the various components of the model

4.1 Estimating the predation pressure function $s_{ikj}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i,\mathbf{x}_k\right)\right)$

Recall that the predation pressure function $s_{ikj}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i,\mathbf{x}_k\right)\right)$ is the fraction of time a barn owl nesting in box *k* would search for prey in field *i* if the field is devoted to crop *j*, as a function of the distance between the box and the field. A field located farther from the nest is expected to be less appealing to the owls because of the longer flight efforts required to get there. The field’s appeal also depends on the crop grown thereon through the size of rodent population it attracts and the preying conditions it offers; for instance, the presence of perching points and the heights of plants may affect the barn owl’s chance to pinpoint its prey as well as its hunting success.

Let $d_{m_ik}\left(\mathbf{u}_{m_i},\mathbf{x}_k\right)$ be the distance between box *k* and some point m_i within field *i*. The predation pressure function for field *i*, when assigned to crop *j*, is:

$$s_{ikj}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i,\mathbf{x}_k\right)\right)=\sum_{m_i=1}^{M_i} l\,\mathrm{Pr}_j\left(d_{m_ik}\left(\mathbf{u}_{m_i},\mathbf{x}_k\right)\right) \tag{3}$$

where $\mathrm{Pr}_j\left(d_{m_ik}\left(\mathbf{u}_{m_i},\mathbf{x}_k\right)\right)$ is a probability density function specific to crop *j*, which represents the probability of the barn owl nesting in box *k* to forage at point m_i.

Estimation of $\mathrm{Pr}_j\left(d_{m_ik}\left(\mathbf{u}_{m_i},\mathbf{x}_k\right)\right)$ requires two types of datasets. The first dataset represents the barn owl’s actual hunting behavior; it includes records of barn owls’ locations while hunting, by which the crop at each hunting location can be identified and each bird’s distance from its nesting box can be computed. The second dataset is specifically required for estimating differences in crops’ appeal; it reflects the hunting opportunities available to each barn owl, given the location of its nesting box in relation to the areas of the surrounding crops. For a specific crop, these opportunities can be represented by the land share of the fields devoted to this crop, weighted by these fields' distances from the box. For consistency, however, these distance-weights should be based on the distance effect embedded in the function of interest, $\Pr_j\left(d_{m_i k}\left(\mathbf{u}_{m_i}, \mathbf{x}_k\right)\right)$. Consequently, generation of the hunting opportunities dataset depends on the actual hunting behavior dataset. In order to facilitate the estimation, we assume the following simplified functional form,

$$\Pr_j\left(d_{m_i k}\left(\mathbf{u}_{m_i}, \mathbf{x}_k\right)\right) = \alpha_j \Pr\left(d_{m_i k}\left(\mathbf{u}_{m_i}, \mathbf{x}_k\right)\right) \tag{4}$$

wherein $\Pr\left(d_{m_i k}\left(\mathbf{u}_{m_i}, \mathbf{x}_k\right)\right)$ is a canonical (for all crops) probability density function, and α_j is a parameter representing the barn owls' attitudes toward preying on rodents associated with crop j.[i] The specification in Equation (4) assumes independence between the effect of the distance d and the effect of the barn owls' crop attitude α_j on the predation pressure. This assumption enables separating the probability density function $\Pr(d)$'s estimation from the α_j parameters' estimation. Moreover, the dataset required for estimating the crop-attitude parameters can be generated by the use of the $\Pr(d)$ function. This implies employing a recursive estimation procedure: First, using the "actual hunting behavior" dataset, the function $\Pr(d)$ is estimated, where it is assumed that barn owls have no crop preferences, i.e., $\alpha_j = 1$ for all $j = 1,\ldots, J$; then, the estimated $\Pr(d)$ is used for creating the "hunting opportunities" data needed for estimating the α_j parameters.

The actual hunting data were collected during the years 2000 and 2002 in Sde Eliyahu's fields using a system wherein 16 barn owls were equipped with radio telemetry tags. Their nesting locations were identified in daytime, while inactive. Once a week, the birds were tracked during nighttime. Each barn owl's locale was recorded 4-8 times per night, while maintaining a gap of at least 50 minutes between each bird's successive positional recordings so as to avoid temporal dependence (Salvatori et al., 1999). The bird locale was set by a single mobile observer, employing triangulation principles in real time by shifting his position to obtain various directions to the same tagged bird, while avoiding eye contact to reduce intervening impacts (White and Garrott, 1990). Each bird observed outside the nesting box was considered to have been hunting at each positional recording (Kahila, 1992; Bunn et al., 1982). For each observed point, the type of crop was identified and the distance from the nest computed. Altogether there are 693 such observations, collected over 130 nights.

Let n denote some geographic locale at which the barn owl nesting in box k has been recorded, and let d_{nk} be the distance between point n and this box. Also, suppose that some crop j is grown at point n. According to Equation (4), the probability of observing this specific bird at point n is $\Pr_j(d_{nk}) = \alpha_j \Pr(d_{nk})$.

Since predatory movements begin at the nesting box and end at some distance d, survival analysis is an appropriate approach for estimating the probability function $\Pr(d)$. Let $S(\tau)$ and $f(\tau) = -S'(\tau)$ be the survivor and density functions respectively, where τ is the dimension along which survival is measured. As a barn owl flies farther from its nest, it increases the area needing to be searched in order to record its location. Thus, assuming isotropy, for a given event of a barn owl nesting in box k and recorded at some point n, the appropriate value of τ_{nk} is the area of the circle centered at box k, with a radius of d_{nk}, i.e., $\tau_{nk} = \pi d_{nk}^2$. The probability density function $f(\tau_{nk})$ expresses the probability of recording the barn owl at distance d along the circumference of this circle, $2\pi d_{nk}$. Hence, the per-area unit probability of recording this barn owl at some point n is:

$$\Pr\left(d_{nk}\right) = \left(2\pi d_{nk}\right)^{-1} f\left(\pi d_{nk}^{2}\right) \tag{5}$$

Six survivor functional forms were estimated: generalized gamma, exponential, Weibull, Gompertz, lognormal, and loglogistic. The results are reported in Table I. Based on the Akaike Information Criterion (AIC), the gamma function was selected. The selected $f(\tau)$ function is:

$$f(\tau) = \begin{cases} \gamma^{\gamma}\left(\sigma\tau\sqrt{\gamma}\,\Gamma(\gamma)\right)^{-1} \exp\left(\lambda\sqrt{\gamma} - \gamma\exp\left(|\kappa|\lambda\right)\right) & \text{if } \kappa \neq 0 \\ \left(\sigma\tau\sqrt{2\pi}\right)^{-1} \exp\left(-0.5\lambda^{2}\right) & \text{if } \kappa = 0 \end{cases} \tag{6}$$

where $\gamma = |\kappa|^{-2}$ and $\lambda = sign(\kappa)\left(\ln(\tau) - \mu\right)\sigma^{-1}$. The estimated σ and κ parameters imply that the hypothesis that the gamma distribution collapses to any of the special cases of exponential, Weibull, or lognormal distributions, is rejected. Figure 1 demonstrates the goodness of fit of the gamma function to the distribution of observations around the boxes.[ii]

Table I about here

Figure 1 about here

We turn now to the estimation of the crop-attitude parameters. A specific parameter α_j is estimable based on comparison between the fraction of barn owls observed foraging in crop *j* and the probability of observing these barn owls in the fields assigned to crop *j*; the latter represents the “hunting opportunity” of this crop. This probability is computed by the use of the estimated $\Pr(d)$ function. Formally, let

$$\tilde{P}_{kj} = \sum_{i=1}^{I} \delta_{ij} \tilde{s}_{ik}\left(\mathbf{d}_{ik}\left(\mathbf{u}_{i}, \mathbf{x}_{k}\right)\right) \tag{7}$$

be this probability for a specific barn owl nesting in box *k*, where $\tilde{s}_{ik}\left(\mathbf{d}_{ik}\left(\mathbf{u}_{i}, \mathbf{x}_{k}\right)\right) = \sum_{m_i=1}^{M_i} l \Pr\left(d_{m_i k}\left(\mathbf{u}_{m_i}, \mathbf{x}_{k}\right)\right)$ is the predation pressure function for the specific case of $\alpha_j = 1$ for all j = 1,…, J. Denote by F_{kj} the fraction of observations wherein barn owl k was recorded foraging on crop j in the telemetry searches. Then, the crop-attitude parameters α_j were estimated for each crop j using the model:

$$F_{kj} = \alpha_j \tilde{P}_{kj} + \varepsilon_{kj} \tag{8}$$

where ε_{kj} is an error term.

Our data consist of 16 observations per crop, correspondent to the number of barn owls included in the telemetry tracking. Using the parameters estimated for the probability density function, the predation pressure $\tilde{s}_{ik}\left(\mathrm{d}_{ik}\left(\mathrm{u}_i, \mathrm{x}_k\right)\right)$ was calculated for 11 land uses, encompassing nine crops, fallow fields, and the residential area of Sde Eliyahu. The analysis incorporated land uses in 54 fields (I = 54), which were divided into land units with a size (l) of 56m^2.[iii] Since the fraction F_{kj} calculated for each barn owl represents its “average” behavior, the number of recordings per barn owl served as a weight for correcting the variance of this fraction. To control for correlations among the crops, the J equations were estimated as a system, employing seemingly unrelated regression. Table II presents the estimated α_j parameters.

Table II about here

Apparently, except for the case of legumes, barn owls prefer trees, probably owing to the advantage provided by perches as hunting bases (Kay et al., 1994).

4.2. Estimating the nesting function $\Pr_k\left(\mathbf{u}, \mathbf{x}, \boldsymbol{\delta}, \mathbf{a}_k\right)$

From the farmer’s point of view, the profitability of the investment of installing and maintaining a nesting box depends on the probability that the box is in use. The proximity of the box to appealing hunting areas has a potentially important impact on the box’s probability of being occupied. Hence, the boxes’ locations are likely to be a key determinant of their occupancy rates, and in turn a key determinant of the efficacy of rodent control by avian predators overall.

Barn owls reselect their nesting places every year. Previous studies (Charter et al., 2010; Meyrom et al., 2008, 2009; Ardia et al., 2006; Martinez et al., 2006; Dhondt and Phillips, 2001; Toland and Elder, 1987) have pointed out the dependence of the probability of the boxes' occupancy on the boxes' physical features and geographical attributes, including the aspect of the boxes' entrances and shade levels. Unfortunately, to the best of our knowledge, the impact of boxes' proximity to certain crops has not yet been explored.

Our data is a panel encompassing all 58 nesting boxes distributed in Sde Eliyahu's fields, observed over a period of 10 years from 1999 to 2008. The average occupancy rate over the entire period is 43%, ranging from 20% to 62%. For comparison, Wood and Fee (2003) report occupancy rates of 70% in oil palm estates in Malaysia. Our explanatory variables can be classified into three types. The first are time-invariant features of the boxes themselves, including dummy variables for three entrance aspects and a dummy for boxes located in the shade. The second group of variables represents the boxes' environments. It is hypothesized that boxes located closer to land uses that provide better hunting conditions are more appealing for nesting. Variables in this group represent the predation pressures exercised from a box on the aforementioned 11 land uses (see Table II), conditional on its being occupied. The predation pressures were computed for each box k, land-use j, and year t, $t = 1,\ldots,10$, by:

$$P_{kjt} = \sum_{i=1}^{I} \delta_{ijt} s_{ikj}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i, \mathbf{x}_k\right)\right) \tag{9}$$

using the parameters estimated for the predation-pressure function $s_{ikj}(\mathbf{d}_{ik}(\mathbf{u}_i, \mathbf{x}_k))$ and applying to the 54 fields. Note that the pressures computed for Sde Eliyahu's residential area and for its plantations are time-invariant, since $\delta_{ijt} = \delta_{ij}$ for all t = 1,…, 10. In addition, to control for potential territorial effects, we include an "engagement-probability" variable that measures the probability of interaction between a barn owl nesting in box *k* and those nesting in all other boxes. The engagement-probability variable is calculated by applying Equation (5) to the distance from box *k* to every other box, and averaging across boxes. For all the variables in this group (i.e., the predation pressures on the 11 land uses and the engagement probability) second-degree polynomials are included to allow for nonlinearity effects.

The third group of variables includes time-specific variables, including annual rainfall as measured at Sde Eliyahu, the number of years since the box was installed, and year fixed effects. In addition, since boxes occupied in previous years may retain signs that indicate the nesting conditions therein, we include a lagged dependent variable, which indicates whether the box was occupied in the previous year. This entails estimation of a dynamic probit model, with unobserved box heterogeneity, while the initial dependent observation (denoted y_{k0}) is not uncorrelated with the unobserved heterogeneity (η_k). To overcome this problem, and to facilitate estimation, Wooldridge (2005) suggests internalizing this correlation into the model by expressing the unobserved heterogeneity as a linear function of the initial value of the dependent variable: $\eta_k = \theta_0 + \theta_1 y_{k0} + \mathbf{z}_k \boldsymbol{\theta}_2 + \varphi_k$, where $\mathbf{z}_k = (\mathbf{z}_{k1}, ..., \mathbf{z}_{k10})$ is the row vector of all explanatory variables in all time periods; θ_0, θ_1, and θ_2 are coefficients; and $\varphi_k | (y_{k0}, \mathbf{z}_k) \sim \mathrm{N}(0, \sigma_\varphi^2)$. This yields a dynamic probit model with response probability:

$$\Pr(y_{kt} = 1) = \Phi(\mathbf{z}_{kt}\boldsymbol{\psi} + \zeta y_{k,t-1} + \theta_0 + \theta_1 y_{k0} + \mathbf{z}_k \boldsymbol{\theta}_2 + \varphi_k) \qquad (10)$$

where y_{kt} is the dichotomous dependent variable, $\mathbf{z}_{kt}$ is a vector of exogenous variables, and $\boldsymbol{\psi}$ and ζ are the coefficients of interest. This equation can be estimated by standard random-effect probit software (e.g., by the xtprobit command in Stata).

Due to sample size limitations, the $\mathbf{z}_k$ vector in our application incorporates, for each year *t*, the sum of the predation pressures over all the non-perennial crops, which are the time-variant variables. The stepAIC procedure (Venables and Ripley, 2002) was employed for selecting the set of variables to be retained in the model based on the AIC. Table III reports the estimation results.

Table III about here

Only one variable from the group of time-invariant features of the boxes was retained by the stepAIC procedure: the shade conditions. As could be expected in hot environments, shaded boxes are significantly more appealing. The environment appears to play an important role in nesting box occupancy: Boxes exercising larger predation pressure on alfalfa and wheat, which are known to be appealing crops to rodents, have higher occupancy probability. Note that the variable measuring the predation pressure on alfalfa fields in their first production year was eliminated by the stepAIC procedure; this points to a possible learning process, along which barn owls gradually recognize the alfalfa fields, or figure out their appeal. Proximity to date palms also increases nesting probability,[iv] possibly due to the preference of perches thereon as prowl points and the abundance of rodents therearound, particularly rats.[v] On the other hand, barn owls tend to avoid nesting in boxes located close to residential areas. This may be attributed to territorial effects, as some barn owls routinely nest in Sde Eliyahu's residential areas, or to shyness of human presence, light, and noise. Barn owls exhibit Type B territorial behavioral patterns (Wilson, 2000; *sensu* Taylor, 1994), i.e., the area of breeding activity (i.e., the nest) is defended, yet not the foraging area, wherein barn owls may even hunt in groups, as observed in our telemetry survey. This implies that the territorial effect is expected to be limited, and even reversed, if distances between boxes become large enough; i.e., barn owls may tend to avoid nesting in boxes that are too isolated. We thus hypothesized that the distance between neighboring nests will reflect an attraction-repulsion balance, converging to some favorable intermediate distance. This hypothesis is reinforced by the opposite signs of the coefficients of the engagement-probability and engagement-probability-squared variables, which point out the existence of a distance between boxes at which occupancy rate is maximized. By employing the estimated gamma function, we found that, *ceteris paribus*, an average distance of 410 meters between boxes maximizes the boxes' occupancy probability. For comparison, the average distance in the sample is one kilometer. That is, increasing the density of the 58 boxes may increase their occupancy rates.

The coefficient of the annual rainfall variable is positive. The positive effect of rainfall on occupancy can be explained by the associated higher availability of vegetative food in fields and waterways, which in turn stimulates population growth of rodents and possibly other prey.

Occupancy in the previous year (the lagged dependent variable $y_{k,t-1}$) has a significant positive effect, indicating the potential importance of signals that might be maintained in the boxes between years. There is also a strong correlation between the unobserved heterogeneity (η_k) and the initial value of the dependent variable (occupied in 1998, y_{k0}). On the other hand, η_k is weakly correlated with the sums of the predation pressures on time-variant crops that were retained by the stepAIC procedure, and with no clear pattern to the coefficients. Employing a log-likelihood test, the hypothesis $\rho = 0$ is not rejected, implying that the panel probit estimator does not significantly differ from the pooled probit estimator.

4.3. Estimating the alfalfa production function $g_{i1}(r_{i1}(\mathbf{u}, \mathbf{x}, \boldsymbol{\delta}, \mathbf{a}), \mathbf{e}_i, \mathbf{b})$

Alfalfa is routinely grown at Sde Eliyahu. On average, each year, 0.42 square kilometers out of Sde Eliyahu's total 5.4 square kilometers of agricultural land are allocated thereto. Our data encompass a panel of 429 alfalfa harvests in 21 fields (see Figure 2) over the years 1999-2008. An alfalfa field is cultivated and sowed during the autumn, untreated during the rainy winter season, and then harvested up to eleven times during the springs and summers of up to four sequential years. Rodent control in all fields is based on barn owls and on the effects of a range of factors, including other predators, natural flooding of canals during winters, and agronomic activities such as plowing, control of other pests, and routine sanitation and maintenance of fields' margins and waterways. The fields are fertilized once every autumn and regularly irrigated following each harvest using sprinkler irrigation. Some of the fields allow irrigation by a moving platform, which enables additional treatment against rodents by flood irrigation.

Let g_{ith} denote the quantity of alfalfa harvested from field *i* during harvest number *h* in year *t*. Our model is

$$g_{ith} = \mathbf{v}_{ith}\boldsymbol{\beta} + \nu_i + \omega_t + \upsilon_{ith} \tag{11}$$

where $\mathbf{v}_{ith}$ is the set of explanatory variables; $\boldsymbol{\beta}$ is the associated vector of coefficients; and ν_i, ω_t, and υ_{ith} are the field-specific, year-specific, and observation-specific error terms respectively. The focal variable in $\mathbf{v}_{ith}$ is the cumulative predation pressure exercised by the occupied nesting boxes in the alfalfa fields. It is calculated for each field *i* that is assigned to alfalfa (i.e., $j = 1$) in year *t* by:

$$r_{i1t} = \sum_{k=1}^{K} \xi_{kt} s_{ik1}\left(\mathrm{d}_{ik}\left(\mathrm{u}_i, \mathrm{x}_k\right)\right) \tag{12}$$

where ξ_{kt} is an indicator variable obtaining a value of 1 if box k is occupied in year t, and 0 otherwise. The square of r_{i1t} is also included among the explanatory variables in order to control for a potential nonlinear effect of the predation pressure. A dummy variable indicates the availability of flood irrigation. Other variables in $\mathbf{v}_{ith}$ are the size of the field, the average temperature during the harvest period, a dummy variable indicating organic production, dummy variables for production years (ranging from 1 to 4), dummies for the serial numbers of harvests (ranging from 1 to 11), and interactions between the annual rainfall and the dummies for the serial numbers of harvests. The error components ν_i and ω_t are estimated as field-specific and year-specific effects, respectively. Calculation of the variance-inflation factor (VIF) yielded VIF values ranging from 1.65 to 330, strongly indicating a potential multicollinearity problem (O’Brien, 2007). A principal component OLS (PC-OLS) procedure was applied in order to mitigate this obstacle (see Toro-Vizcarrondo and Wallace, 1968). Table IV presents the sample means and standard deviations of the variables, and the regression results.

Table IV about here

The coefficients of the predation-pressure variable and of the predation-pressure squared are both positive and are statistically significant at 1% and 5% respectively. This finding is evidence for a real contribution of avian predators to agricultural productivity. Moreover, it indicates that, at least within the range of predation pressures incorporated into our sample, this contribution exhibits increasing marginal productivity. At the same time, however, this pattern of alfalfa production response to changes in predation pressures may be due to the rodent population’s excessive size, thereby causing extensive damage to Sde Eliyahu’s alfalfa fields. Let us elaborate.

According to the biological law of tolerance (Owen, 1975), concave responses of population are expected under favorable environmental conditions, whereas convex responses emerge when an environmental factor is pushed toward the limit of the population-growth range (Tisdell 2003, p. 36). Hence, if predation pressure is indeed low enough to allow a large rodent population, then the rodent population would diminish at an increasing rate (i.e., concavely) in response to increases in the predation pressure. If indeed yield is low due to substantial negative impact of rodents, then, the yield would increase at an increasing rate (i.e., convexly) as rodent population declines. The integration of these two effects gives a convex increase of yields with predation pressures. Support for this hypothesis comes from a study by Tores et al. (2005), which found that rodents comprised 93.9% of total prey of barn owls in Sde Eliyahu’s fields during 1997-2001. They also discovered opportunistic behavior, i.e., barn owls easily switch between types of prey in their diet, probably as a result of changes in the abundance of the main prey items in the fields. Thus, a high proportion of rodents in the diet of barn owls might be an indication of a large rodent population in the barn owls’ hunting areas. A similar survey, conducted by Charter et al. (2009) in 2006 in the environs of Sde Eliyahu found 96.6% rodents in the diet of barn owls that nest in boxes located in alfalfa fields.

Returning to Table IV, flood irrigation has no significant impact on alfalfa yields. Recall that flood irrigation is less efficient than sprinkling, since much floodwater is lost through deep-percolation flows. This direct negative impact of flood irrigation on yields may be offset by the indirect positive impact it has on rodent control. Yields are augmented in larger fields and under higher temperatures, whereas organic production does not exhibit significant impact. Production is stable in the first two production years, and then declines in the third and fourth years. Alfalfa production gradually increases from the first to the third harvest, and gradually declines in subsequent harvests. The magnitude of this profile is strengthened by annual rainfall, as can be learned from the coefficients of the interactions between annual rainfall and the indicators of the serial numbers of harvests. The relationship between rainfall and temporal changes in per-harvest yields may be attributed to direct and indirect effects that operate in opposite directions. Rain directly increases production in early harvests through the level of moisture retained in the soil from winter. The indirect effect is associated with the contribution of rain to the wild vegetation in the watercourses and fallow open spaces surrounding the fields, which in turn increases the rodent population throughout the growing season (Leirs et al., 1997).

4.4. Prices and Costs

Barn owls affect revenues by changing per-hectare productivity, and they entail fixed per-hectare costs associated with installation and maintenance of nesting boxes. The output price is \$264 / ton, as reported by the Israeli Field Crops Growers Association (2010) for alfalfa under conventional production. Variable costs associated with harvesting and hauling amount to \$38 / ton (IMARD, 2010). The per-box costs were estimated at \$50 / year, based on a 10-year lifetime, with one renovation and 0.1 working days per year for monitoring and cleaning. Attributing the costs of all 58 nesting boxes to the 0.42 square kilometers allocated to alfalfa in Sde Eliyahu on an average year, we get a cost of \$69 / hectare-year.

V. Simulations

We are now in a position to evaluate the profitability of biological rodent control by barn owls. Four scenarios are compared. Scenario 1 represents the observed situation, wherein the 58 nesting boxes are in their current locations throughout the fields of Sde Eliyahu. In Scenario 2 we simulate elimination of all the nesting boxes, such that rodents are controlled only by the aforementioned agronomic and natural factors. In Scenario 3 we allow our model to search for the locations of the 58 nesting boxes that maximize the returns from alfalfa fields. In Scenario 4 we evaluate the profitability of integrating barn owls and rodenticides, based on output data obtained from another alfalfa grower (Kibbutz Ma'oz Haim) in the region of Sde Eliyahu. The results are summarized in Table V.

Table V about here

Scenario 2 constitutes a benchmark for the calculation of rodent control contribution to profit under the other three scenarios (Table V, bottom row). The average alfalfa output attributable to the presence of the 58 nesting boxes in their current locations (Scenario 1) equals the difference between the observed production and the production under Scenario 2. The yield under Scenario 2 is computed by the use of Equation (11) while substituting $r_{i1} = 0$ (see Equation 12) for all $i = 1,..., I$, and holding all other variables at their time-average levels. This calculation results in a contribution of 0.53 tons / hectare-year, which constitutes 3.6% of the observed average production, or 14.63 tons / year-hectare. The associated profit contribution of barn owls as rodent control amounts to $49.6 / hectare-year.[vi] Thus, despite their apparently low contribution in terms of alfalfa yields, and the fact that we completely ignored the nesting boxes' potential contribution to other crops' yields, rodent control by barn owls is found to be profitable.[vii]

Scenario 3 presents our evaluation of the extent to which the returns on Sde Eliyahu's alfalfa fields can be increased by redistributing the 58 nesting boxes. The model searches for the vector of coordinates of the 58 boxes, x^*, that maximizes the alfalfa fields' expected profit. This optimization scenario, however, is associated with extrapolations of our estimated functions, and therefore, constraints may be needed in order to obtain practical results; this issue is discussed in the following paragraph.

Our estimation of the alfalfa production function $g_{i1}\left(r_{i1}\left(\mathbf{u},\mathbf{x},\boldsymbol{\delta},\mathbf{a}\right),\mathbf{e}_i,\mathbf{b}\right)$ implies that alfalfa outputs would convexly increase with the cumulative predation pressures (Table IV). The estimated predation-pressure function $s_{ikj}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i,\mathbf{x}_k\right)\right)$ tells us that the cumulative pressure on alfalfa fields would convexly increase as the distance between these fields and occupied nesting boxes diminishes. The proximity of nesting boxes to alfalfa fields may also increase their occupancy rate, as can be learned from the estimated nesting function $\Pr_k\left(\mathbf{u},\mathbf{x},\boldsymbol{\delta},\mathbf{a}_k\right)$ (Table III). The integration of these three effects implies that profits would be maximized if as many nesting boxes as possible were to be located as close as is feasible to the alfalfa fields. A counteracting factor is the occupancy rate, which diminishes as boxes become too close to each other. Nesting rates may also be restricted by the impact of the distances of the boxes from other land uses. However, while our model captures these opposing forces, the reliability of our predictions is expected to diminish as we extrapolate further. For instance, under some unknown level of predation pressure, beyond those observed in our sample, rodent population may become low enough and alfalfa outputs sufficiently high to lead to decreasing marginal productivity of the cumulative predation pressure. Nesting rates may also be limited by unobserved variables, such as the overall barn owl population in the relevant area. Competition with other predators, such as jackals, kestrels, and wildcats, may affect barn owls' hunting success.

These effects may be taken into account in the model by introducing constraints. Scenario 3 incorporates two additional constraints: (1) all the boxes are restricted to being located at least 100 meters apart; this implies an upper density limit of one box per hectare, which is about 100 times denser than the current density at Sde Eliyahu, and twice as dense as the case of oil palms in Malaysia (Wood and Fee, 2003); (2) the per-hectare alfalfa production in every field is restricted to 22 ton / year, which is 10% higher than the typical alfalfa productivity reported by IMARD (2010). Figure 2 shows current versus optimal nesting box distributions vis-à-vis the fields with positive probabilities of being assigned to alfalfa throughout crop rotations.

Figure 2 about here

Compared with the current box locations (Scenario 1), boxes in Scenario 3 are located much closer to large fields with high probabilities of being assigned to alfalfa, and the average nesting rate is higher than the observed nesting rate (see Table V).[viii] Consequently, the average per-hectare predation pressure on alfalfa fields is stronger by an order of magnitude; the portion of the production associated with the presence of barn owls increases from 3.6% to more than 13%; and the computed contribution of the barn owls to alfalfa profits is 7 times that under the observed situation.

Suppose that alfalfa is, indeed, the only crop whose profit can be increased by barn owl activity; in such a case, the current spatial distribution of nesting boxes at Sde Eliyahu is probably not optimal; the returns on some of the boxes may not even cover their installation and maintenance costs. To examine this issue further, we calculated the maximal attainable profit when the number of boxes is increased from 1 to 58. In each run, the model searches across the observed locations of the 58 boxes for the combination that maximizes the alfalfa fields' profits. This enables us to compute the per-marginal-box profit, as presented in Figure 3. A similar curve is presented for the boxes' optimal locations, as selected under Scenario 3.[ix] As suspected, in their current locations, more than half of the nesting boxes do not cover their costs; nevertheless, as aforementioned, the array of boxes as a whole is still profitable. While the marginal profit curve under Scenario 3 noticeably fluctuates and exhibits a decreasing trend, all the boxes are profitable.

Figure 3 about here

Scenario 4 in Table V presents an attempt to evaluate the profitability of rodenticides. As our sample does not include rodenticide applications, we searched for additional data in Sde Eliyahu's environs. A three-year record of annual yields in 2008-2010 was found at only one other alfalfa grower, Ma'oz Haim, where rodents are controlled by an integration of barn owls, flood irrigation, and rodenticides (sodium fluoroacetate compound 1080).[x] The average production there was 14.84 ton / hectare-year; however, the 0.21 ton / hectare-year difference between Ma'oz Haim and Sde Eliyahu (14.63 ton / hectare-year) was found statistically insignificant. Nevertheless, suppose that the barn owls and flood irrigation controls are similar at both growers, and that this yield difference is exclusively attributed to the extra control effect achieved by the application of rodenticides at Ma'oz Haim; in that case, the corresponding $47 / hectare-year revenue increase does not cover the rodenticide application costs, which are evaluated at $80 / hectare-year (IMARD, 2010). This evaluation casts doubt on the profitability of rodent control by rodenticides, at least when it is integrated with barn owls.[xi]

VI. Concluding Remarks

The take-home messages derived from our economic analysis are: (1) barn owls have the potential for making significant contributions to farming profits, and (2) the realization of this potential is highly dependent on the spatial distribution of boxes in relation to the fields wherein barn owls can make such contributions.

What are the implications of these findings with respect to the essentiality of supportive government policies to promote the adoption of rodent control by barn owls? Our results indicate that aside from spreading the information on its potential profitability, supplemental policies are unnecessary. This conclusion is particularly validated by this study for the case wherein rodenticides are absolutely prohibited. By doubting rodenticides' profitability from the farmer's point of view, we point out the potential validity of this conclusion also when rodenticides are allowed. Moreover, if policy-makers, as in Israel (IMARD, 2011), aim at reducing the considerable environmental damage caused by rodenticides (e.g., Zurita et al. 2007) by limiting their use, our findings equip them with strong arguments for more severely restricting the conditions under which rodenticides are permitted.

This study leaves plenty of room for future research. Data on this system's various ecological, zoological, and economical components can be collected at a finer resolution to elucidate the costs and benefits of biological control by raptors versus alternative actions. For example, more fine-resolution movement and behavioral data on barn owls' foraging routes can provide the means to explicitly quantify the predation pressure and actual predation they exert on rodents in various crops and seasons. This can be achieved by deploying advanced GPS biotelemetry technologies, which can also help to assess the *de facto* effects of alternative spatial arrangements of nests. Furthermore, barn owls' profit contribution may be assessed with respect to more crops, and may be compared to that of rodenticides when applied as both a substitute and a complementary control. The findings, in conjunction with valuations of the damages abated through the avoidance of rodenticides, the benefits associated with preserving barn owls, and the impacts of these birds on other endangered species, would provide a more solid base for the design of policies regarding rodent control by these conventional and biological methods.

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Table I - Estimation results for the predation-pressure function under various survivor functional forms

	Gamma	Exponential[a]	Weibull[b]	Gompertz[c]	Lognormal[d]	Loglogistic[e]
Log likelihood	-2,165.9	-4,889. 9	-2,325.8	-4,714.5	-2,438.1	-2,457.1
AIC	4,337.8	9,781.8	4,655.5	9,432.9	4,880.2	4,918.2
μ	3.253^{***}	-1.773^{***}	0.123^{***}	-1.001^{***}	-4.283^{***}	-2.919^{***}
κ	6.355^{***}		-1.686^{***}	-0.0881^{***}		4.729^{***}
σ	1.286^{**}				8.160^{***}	

* = significant at 10%, ** = significant at 5%, *** = significant at 1%

a. $S(\tau) = \exp(-\exp(\mu)\tau)$

b. $S(\tau) = \exp\left(-\exp(\mu)\tau^{\kappa}\right)$

c. $S(\tau) = \exp\left(-\exp(\mu)\kappa^{-1}(\exp(\kappa\tau)-1)\right)$

d. $S(\tau) = 1 - \Phi\left((\ln(\tau)-\mu)^{-\sigma}\right)$

e. $S(\tau) = \left(1 + (\exp(-\mu)\tau)^{\frac{1}{\kappa}}\right)^{-1}$

Table II – Estimates of crop-attitude parameters by seemingly unrelated regression

Land use	α_j (***t*** **value)**	R^2	**F-Statistic**
Fallow	0.89 (4.73)***	0.37	22.4
Alfalfa, year 1	0.42 (3.52)***	0.30	12.4
Alfalfa, year 2+	0.30 (3.29)**	0.30	10.8
Corn	0.12 (2.53)***	0.20	6.4
Legumes	1.91 (7.69)***	0.59	59.1
Wheat	0.75 (3.79)***	0.39	14.4
Vegetables	0.39 (2.74)***	0.29	7.5
Citrus	1.27 (4.18)***	0.34	17.5
Dates	2.50 (9.83)**	0.68	96.6
Olives	1.82 (2.40)***	0.19	5.8
Residential areas	0.87 (5.53)***	0.62	30.6

* = significant at 10%, ** = significant at 5%, *** = significant at 1%

Table III – Estimation results for the probit nesting function

Observations	580	
Log likelihood	-306.5	
AIC	649.1	
Pseudo R^2	0.23	
Variable	**Sample mean (St. Dev.)**	**Coefficient (*Z* value)**
Occupancy (y_{kt}, dependent variable)	0.4293 (0.4954)	-
Shaded conditions (dummy)	0.2414 (0.4283)	0.582 (2.74)***
Pressure on alfalfa, year 2+	0.0302 (0.0499)	2.452 (1.84)*
Pressure on wheat	0.1014 (0.0933)	1.696 (1.83)*
Pressure on dates	0.0407 (0.0651)	11.42 (2.20)**
Pressure on dates squared	0.0059 (0.0127)	-48.61 (-2.09)**
Pressure on residential areas	0.0105 (0.015)	-87.48 (-3.16)***
Pressure on residential areas, squared	0.0003 (0.0008)	1,278 (3.04)***
Engagement probability	0.1232 (0.0683)	7.759 (2.04)**
Engagement probability, squared	0.0198 (0.0246)	-29.40 (-2.62)***
Annual rainfall (cm / year)	24.780 (7.973)	0.047 (3.48)***
2003 (dummy)	0.1000 (0.3003)	-0.501 (-1.57)
2004 (dummy)	0.1000 (0.3003)	0.653 (3.26)***
Occupied in prev. year ($y_{k,t-1}$) (dummy)	0.3931 (0.4889)	0.793 (6.31)***
Occupied in 1998 (y_{k0}) (dummy)	0.1379 (0.3451)	0.535 (2.77)***
Sum of pressure on variant crops in 2002	0.3148 (0.1879)	-8.496 (-1.42)
Sum of pressure on variant crops in 2004	0.3223 (0.1873)	11.55 (1.60)
Sum of pressure on variant crops in 2007	0.3100 (0.1906)	-4.987 (-1.67)*
Constant		-1.725 (-4.24)***
σ_{φ}		3.49×10^{-4}
$\rho=\sigma_{\varphi}^{2}\left(1+\sigma_{\varphi}^{2}\right)^{-1}$ [a]		1.22×10^{-7}

* = significant at 10%, ** = significant at 5%, *** = significant at 1%

a. When ρ is zero, the panel estimator is not different from the pooled estimator (Stata 11, References manual).

Table IV – PC-OLS estimation results for the alfalfa production function[a]

F Statistic	F(40, 388)[b] = 5.85	
Adjusted R^2	0.31	
Variable	**Sample mean (St. Dev.)**	**PC-OLS Coefficient**[c]
Production (dependent variable, ton / harvest-ha)	1.9096 (0.6432)	-
Predation pressure	0.0028 (0.0038)	11.313 (2.78)***
Predation pressure squared	2.24×10^{-5} (4.55×10^{-5})	1639.0 (2.16)**
Flood irrigation	0.443 (0.497)	-0.0809 (-1.44)
Field size (hectares)	10.371 (4.305)	0.0001 (1.87)*
Temperature (degrees C^o)	31.523 (4.522)	0.0260 (2.35)**
Organic (dummy)	0.387 (0.488)	0.0225 (0.26)
Year no. 2	0.445 (0.498)	0.0926 (1.34)
Year no. 3	0.138 (0.345)	-0.2095 (-2.04)**
Year no. 4	0.019 (0.135)	-0.3165 (-1.26)
Harvest no. 2 (dummy)	0.131 (0.337)	0.0562 (1.62)
Harvest no. 3 (dummy)	0.131 (0.337)	0.2318 (6.65)***
Harvest no. 4 (dummy)	0.126 (0.332)	0.1991 (5.41)***
Harvest no. 5 (dummy)	0.119 (0.324)	-0.0033 (-0.09)
Harvest no. 6 (dummy)	0.110 (0.313)	-0.0889 (-2.28)**
Harvest no. 7 (dummy)	0.100 (0.301)	-0.1692 (-4.24)***
Harvest no. 8 (dummy)	0.086 (0.281)	-0.2310 (-5.29)***
Harvest no. 9 (dummy)	0.054 (0.226)	-0.2908 (-5.16)***
Harvest no. 10 (dummy)	0.012 (0.107)	-0.3947 (-3.11)***
Annual rainfall × Harvest no. 1	33.02 (89.08)	0.0008 (1.88)*
Annual rainfall × Harvest no. 2	33.02 (89.08)	0.0005 (2.41)**
Annual rainfall × Harvest no. 3	33.02 (89.08)	0.0009 (6.17)***
Annual rainfall × Harvest no. 4	31.55 (86.60)	0.0006 (4.53)***
Annual rainfall × Harvest no. 5	29.74 (84.43)	-0.0003 (-1.7)*
Annual rainfall × Harvest no. 6	26.68 (79.13)	-0.0006 (-3.12)***
Annual rainfall × Harvest no. 7	24.14 (74.91)	-0.0009 (-4.38)***
Annual rainfall × Harvest no. 8	21.18 (71.27)	-0.0011 (-5.6)***
Annual rainfall × Harvest no. 9	12.86 (54.46)	-0.0012 (-5.13)***
Annual rainfall × Harvest no. 10	3.040 (28.07)	-0.0016 (-3.32)***
Annual rainfall × Harvest no. 11	0.650 (13.48)	-0.0029 (-1.45)
Constant		0.0138

* = significant at 10%, ** = significant at 5%, *** = significant at 1%

a. Dummies for years and fields are not shown.

b. 40 out of 55 principal components were retained by the PC-OLS estimation procedure.

c. Numbers in brackets are *t* values.

Table V – Rodent-control scenarios

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Description	The 58 nesting boxes are in their current locations	The 58 nesting boxes are eliminated	The 58 nesting boxes are located so as to maximize alfalfa profits	Integration of barn owls, flood irrigation, and rodenticides (Ma'oz Haim data)
Average distance between boxes (km)	1.00	-	1.16	-
Boxes' average occupancy rate	0.43	-	0.59	-
Average per-hectare pressure on alfalfa fields	4.5×10^{-05}	0	1.9×10^{-04}	-
Average alfalfa production (ton / hectare-year)	14.63	14.10	15.98	14.84
Revenue increase ($ / hectare-year)	118.9	0	424.6	166.6[a]
Rodent control costs ($ / hectare-year)	69.4	0	69.4	149.4[b]
Rodent-control profit contribution (compared to Scenario 2, $ / hectare-year)	49.6	0	355.2	17.2

a. Based on the production increase vis-à-vis Scenario 2.

b. Assuming that the nesting boxes' costs per-hectare of alfalfa are similar at Sde Eliyahu and Ma'oz Haim

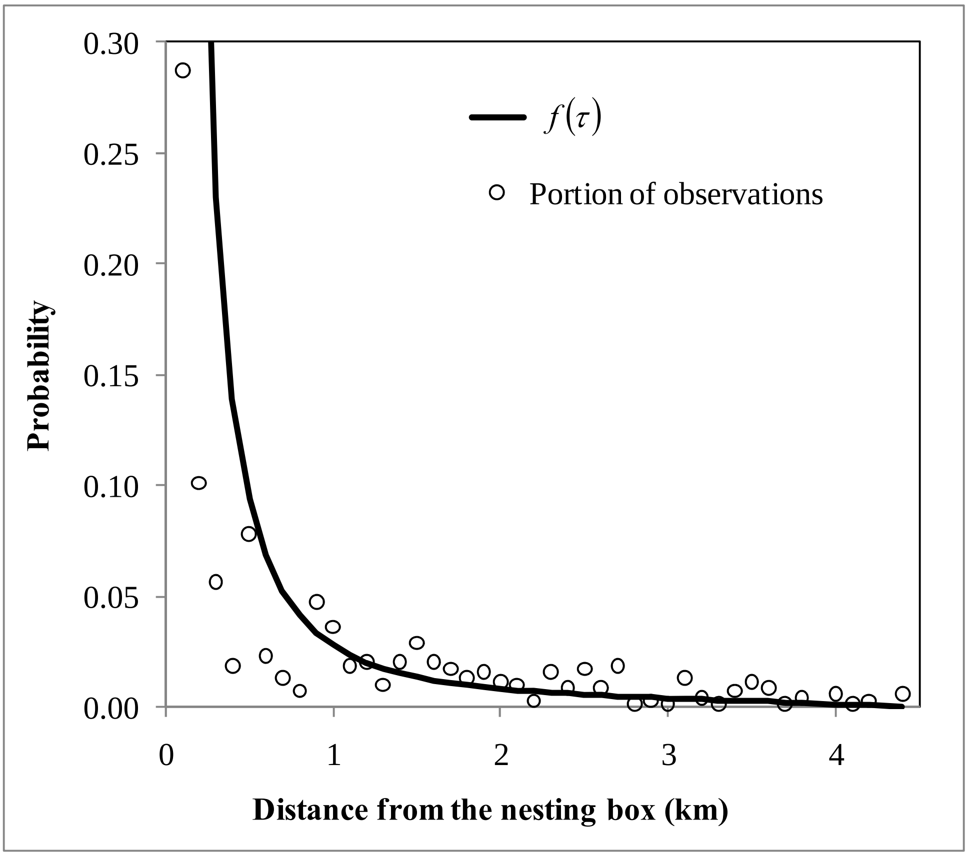

Figure 1 – Goodness-of-fit of the estimated density gamma function

Figure 2 – Model’s optimal (Scenario 3) versus current (Scenario 1) distribution of nesting boxes in relation to alfalfa crop-rotation fields

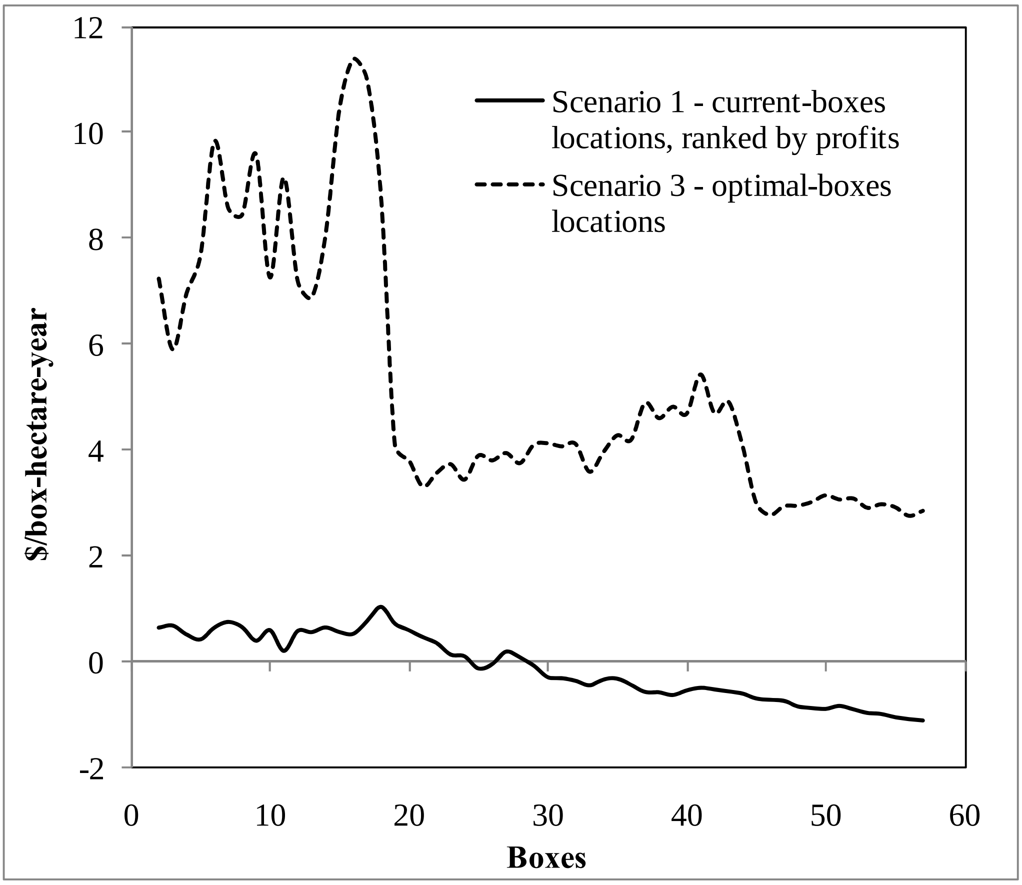

Figure 3 – Boxes' marginal profits under current and optimized locations

Notes

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[i] The cumulative density function is summed to 1 in the case of $\alpha_j = 1$ for all j = 1,…, J; i.e., $\sum_{j=1}^{J} \alpha_j \int_{-\infty}^{+\infty} \Pr(d) dd = 1$. If $\alpha_j \neq 1$ for some crops, this property is attainable by adjustment of the integration constant.

[ii] Focusing on alfalfa, we could estimate a $\Pr(d)$ function specific to alfalfa based on the registrations within alfalfa fields only; these, however, amount to only 19 observations.

[iii] To avoid infinite values at $d_{m_i k}(\mathbf{u}_{m_i}, \mathbf{x}_k) = 0$, the probability function $\Pr(d_{m_i k}(\mathbf{u}_{m_i}, \mathbf{x}_k))$ was restricted to a maximum value of 2. Given the estimated parameters, this limit holds for distances below 85 meters from the nesting box, and is effective for 1.5% of the land units under the observed location of the nesting boxes.

[iv] The marginal impacts of the predation-pressure variables with statistically significant nonlinear effects (pressures on dates and Sde Eliyahu's environs) are found to be monotonic throughout the whole sample range of these variables.

[v] Shaul Aviel, personal communication, Sde Eliyahu, March 2011.

[vi] To obtain average annual profits, we substitute in the vector δ each crop's probability of being assigned to each field, as computed based on our sample.

[vii] The profitability of alfalfa production is rather small, and may even be negative in certain years, so that an increase of about 3% in production can make a significant difference in terms of profits. Based on production studies published by extension specialists at UC-Davis (2008), Texas (2011), and University of Wisconsin (2011), an output increase of 3% implies profit increases of 9%, 20%, and 32%

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respectively. A similar study published by Iowa State University (2011) found net losses in alfalfa production, yet an output increase of 3% could have reduced the losses by 7%. Similarly, a study provided by IMARD (2010) also found net losses in alfalfa production in Israel, and here a 3% yield increase could reduce losses by 36%.

[viii] Nesting boxes are currently located within fields at Sde Eliyahu; however, the optimal distribution (see Fig. 2) may be impractical due to spatial constraints related to the use of agronomic machinery.

[ix] The curves exhibit non-monotonic patterns due to the model’s components’ nonlinearity, which entail complex spatial interrelations among the boxes.

[x] Since records of rodenticides applications are incomplete, we cannot analyze the profitability of barn owls in comparison to rodenticides based on Ma'oz Haim’s data.

[xi] Note that there is only one alfalfa grower in Israel who avoids barn owls and relies exclusively on rodenticides: Kibbutz Dovrat, located in the Jezreel Valley, wherein production levels are considerably lower than Sde Eliyahu’s.