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AGRICULTURAL RODENT CONTROL USING BARN OWLS: IS IT PROFITABLE?

IDDO KAN, YOAV MOTRO, NIR HORVITZ, AYAL KIMHI, YOSSI LESHEM, YORAM YOM-TOV, AND RAN NATHAN

We develop a model to evaluate the profitability of controlling rodent damage by placing barn owl nesting boxes in agricultural areas. The model incorporates the spatial patterns of barn owl predation pressure on rodents, and the impact of this predation pressure on nesting choices and agricultural output. We apply the model to data collected in Israel and find the installation of nesting boxes profitable. While this finding indicates that economic policy instruments to enhance the adoption of this biological control method are redundant, it does support stricter regulations on rodent control using rodenticides.

Key words: agricultural damage control, environmental regulation, barn owl, rodent.

JEL codes: Q15, Q18, Q57.

Rodent damage to agriculture results in double-digit percentages of yield reduction across the globe (Singleton 2003; Leirs 2003). This considerable damage suggests that the effectiveness of conventional rodent-control methods such as tillage, sanitation, trapping, and rodenticide applications is limited (Stenseth et al. 2003). The application of rodenticides is frequently ineffective due to the rapid immigration of rodents from adjacent untreated areas, and because rodent population outbreaks are unpredictable. Moreover, rodenticides are often considered by farmers to be too costly (Skonhoft et al. 2006; Davis et al. 2004; Stenseth et al. 2003). Risks of mortality by self-poisoning (Eddleston 2000) and detrimental impacts on non-target animals (Cox and Smith 1990) are additional drawbacks of rodenticides. The use of barn owls (*Tyto alba*) as a biological control method could be a more cost-effective alternative, which might also reduce the negative externalities associated with rodenticides.

Barn owls, nocturnal raptors having a nearly worldwide distribution, prey on a variety of rodent species, many of which are agricultural pests. Barn owls use pre-existing cavities for nesting (Taylor 1994), and therefore face a scarcity in nesting sites. This trait enables harnessing the barn owl's hunting abilities to control rodents in agricultural fields by introducing artificial nesting boxes. Nesting boxes are already used in various parts of the world to help control a wide range of crop-damaging rodents. For example, such boxes are used to protect oil palms in Malaysia (Duckett 1976) and rice in India (Parshad 1999). However, there is insufficient scientific information on how the technique can be most effectively applied (Leshem et al. 2010) and there is inconsistent evidence of its damage-prevention success (Askham 1990; Wood and Fee 2003). Moreover, to the best of our knowledge, the profitability of rodent control using barn owls has never been assessed. Consequently, there is a lack of scientific knowledge that could prove

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Iddo Kan and Ayal Kimhi are affiliated with the Department of Agricultural Economics and Management, The Hebrew University of Jerusalem, Israel, and with the Center for Agricultural Economic Research, Israel. Kimhi is also the Deputy Director of the Taub Center for Social Policy Studies in Israel. Yoav Motro, Nir Horvitz, and Ran Nathan are affiliated with the Department of Ecology, Evolution and Behavior, The Hebrew University of Jerusalem, Israel. Yossi Leshem and Yoram Yom-Tov are affiliated with the Department of Zoology, The George S. Wise School of Life Sciences, Tel Aviv University, Israel. We thank Shaul Aviel, Uria Shahak, Myriam Freund, Michael Heiman, Shaul Ginzberg, Eyal Lev, Yoav Cohen, Ruth Aviel, Neria Lifshitz, Dan Alon, Yael Chassin, Michal Azaz, Ricky Ketner, Motti Charter, Uriel Safriel, Rivka Rabinowitz, Gila Kahila Bar-Gal, Eitan Tchernov, Moshe Coll, the editor, and two anonymous reviewers. This study was partly funded by the USAid MERC, grant TA-MOU-06-M25-078, and by the Center for Agricultural Economic Research, Israel. Correspondence may be sent to: iddo.kan@mail.huji.ac.il.

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useful to farmers who are planning rodent-control activities and to regulators hoping to spur adoption. This article contributes to the literature on bioeconomics and agricultural damage-control economics by conducting a rigorous evaluation of the method's profitability. To this end, we develop a spatial bioeconomic model and apply it using unique agronomic and zoological data collected in the agricultural fields of Kibbutz Sde Eliyahu, Israel.

Economic analyses of agroecological systems face conceptual and empirical challenges (Zhang et al. 2007), particularly due to the presence of complex spatiotemporal processes. Applications depend heavily on the availability of biological and agronomic data; examples include Brown, Lynch, and Zilberman (2002), Nordblom et al. (2002), Polasky et al. (2005), Griffiths et al. (2008), and Polasky et al. (2011). Our data enabled us to develop an economic model that incorporates three functions associated with spatial processes; the development of these functions itself contributes to the scientific disciplines of agronomy, biogeography, and animal movement behavior. The first function describes barn owls' spatial predation patterns. During the breeding season (March–October), the nesting place constitutes a point source for the barn owl's predation activity.[1] Hence, the predation pressure exercised by barn owls on their surroundings is expected to diminish with distance from the nesting place. Behavioral examination of other raptors has revealed variability in predation attractiveness across land uses (Thirgood, Redpath, and Graham 2003). Using radiotelemetry records of barn owl locations, this study is, to our knowledge, the first to estimate a function of spatial distribution of barn owl predation pressure that accounts for the impact of both distance and land-use appeal. The second function models the selection of nesting boxes by barn owls for breeding. Previous estimates indicate that the probability of nest-box occupancy depends on box attributes (e.g., the entrance aspect) and on its location in relation to various land uses (Frey et al. 2011; Charter et al. 2012). Here, we estimate a nest-box occupancy probability function that explicitly incorporates the impact of a wide range of crops, the distance between one nesting box and others, and the occupancy status of the box in the previous season. Taking advantage of the spatial variability of barn owl predation pressures on fields, our third (crop-production) function treats the barn owl predation pressure as damage-control input.

An additional contribution of this study stems from the recursive estimation process we use, which ensures consistency of the biospatial processes associated with the three functions: the estimated predation-pressure function is used for computing predation-pressure variables that serve as explanatory variables in the estimation of both the box-occupancy probability function and the crop-production function. As a result, we obtain an integrative functional system that enables us to evaluate the contribution of barn owls to agricultural outputs through simulations of nesting-box locations. The locations of the boxes in relation to land uses impact field outputs by determining the expected predation pressures applied on the fields, where these expected pressures are the products of the predation pressures exercised on the fields from occupied boxes, and the probability of the boxes being occupied. Specifically, we use the model to compute alfalfa (*Medicago sativa*) outputs under three scenarios of nesting-box distribution: (*a*) under the observed locations of the 58 boxes currently placed in the Kibbutz's fields, (*b*) in the absence of these boxes, and (*c*) under a simulated distribution of the 58 boxes that maximizes alfalfa-production profits. These three simulations enable us to evaluate both the contribution of the boxes to profit in their current locations and the extent to which profits could potentially be increased.

Our dataset is a panel of detailed zoological and agronomic information that is unique in its suitability to our study. First, barn owl nesting boxes have been placed in the Kibbutz's fields since 1983 (Motro et al. 2010), so that during the period covered by our data (1999–2008), the barn owl population was already familiar with the presence of the boxes.[2] Second, the area covered is

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[1] A barn owl's predatory act starts and ends at its nesting place, and the bird catches a single prey in each hunting act (Lessells and Stephens 1983). These habits make the nesting place the point source of the barn owl's spatial impact on rodents.

[2] According to Wood and Fee (2003), the presence of nesting boxes may also affect the barn owl population, and thus the occupancy probability of boxes and rodent-damage control. We controlled for this potential dynamic effect in the estimation of

sufficiently large to encompass the sizable spatial range influenced by barn owls. Third, the agricultural lands are heterogeneous, so that our analysis can account for the impact of different land uses on the spatial patterns of barn owl predation pressure, and on the selection of nesting places. Finally, agricultural production is centrally managed by the Kibbutz, so that variability in skills, constraints, and other management factors is minimized.

Barn owls affect agricultural outputs only indirectly through their predation impact on rodents, which in turn affect crops through herbivory. The impact of rodent herbivory is spatially distributed in relation to rodents' breeding places. Thus, a comprehensive analysis should account for the spatial distributions of both the raptors and their prey. Unfortunately, due to high monitoring costs and methodological difficulties, reliable and continuous estimates of rodent spatial distribution and population size were not obtainable. Therefore, our analysis overlooks the explicit process by which rodents channel the impact of barn owls on yield. To separate the indirect damage-control effect of the barn owls from the direct impact of production inputs, we adopt the formulation approach used by Lichtenberg and Zilberman (1986), Babcock, Lichtenberg, and Zilberman (1992), Blackwell and Pagoulatos (1992), and others, wherein a damage-abatement function is integrated into the production function. Specifically, we apply the model developed by Saha, Shumway, and Havenner (1997), which also allows controlling for the interactive effects of production inputs, damage-abatement inputs, and external factors.

Due to data availability, we focus on alfalfa production, which is a perennial, multiharvested legume grown mainly for fodder. Alfalfa is highly prone to rodent damage because rodents accumulate over the multiannual crop growth period, while almost no agromechanical measures can be implemented in the fields (Moran and Keidar 1993). Poisoning rodents in alfalfa exhibits low performance due to the constant presence of the fresh, nutritious, green foliage favored by the rodents (Proulx 1998). This makes alfalfa a good case study for examining the economic efficiency of agricultural rodent control by using barn owls.

Our results indicate that barn owls' contribution to the Kibbutz's alfalfa outputs, under the observed locations of the nesting boxes, amounts to nearly 10%, yielding a net-profit increase of more than $200/ha per year. Given that we overlook potential contributions to the outputs of other crops, our evaluation probably underestimates the overall profit contribution of barn owls. Note that our evaluation refers to the profit contribution of the barn owls nesting in the Kibbutz's nesting boxes only, and it measures the profit contribution above and beyond the rodent-control effects of agronomic activities, sanitation, and farmer-independent factors within and outside of the studied area (e.g., barn owls and other raptors nesting in unmonitored places). However, as farmers at Sde Eliyahu completely avoid rodenticide application for ideological reasons, our dataset cannot be used to directly compare biological and conventional rodent-control methods.

The Model

Our model describes the management of a nesting box system subdivided into I fields in a farm area, where all other agrobiological impacts are considered exogenous. Since our analysis relies on the spatial distribution of predation pressure, intra-field variations need to be captured; therefore, we consider an artificial division of field i, $i = 1, \ldots, I$, into M_i uniform-sized land units (e.g., hectares). Let m_i, $m_i = 1, \ldots, M_i$, 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 $\mathbf{u}_i = \left(\mathbf{u}_{m_1}, \ldots, \mathbf{u}_{M_i}\right)$ incorporates the coordinates of all land units in field i, and $\mathbf{u} = (\mathbf{u}_1, \ldots, \mathbf{u}_I)$ is the coordinate matrix of all land units on the farm. The vector $\mathbf{v}_i$ contains all other specific attributes of field i, such as soil type, microclimate, and installed infrastructures, and $\mathbf{v} = (\mathbf{v}_1, \ldots, \mathbf{v}_I)$ is defined accordingly.

Spread over the farm are K nesting boxes, where $\mathbf{x}_k$ is the two-dimensional coordinate vector of the location of nesting box k; $k = 1, \ldots, K$; and $\mathbf{x} = (\mathbf{x}_1, \ldots, \mathbf{x}_K)$ is the matrix of the coordinates of all K boxes. The

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the box-occupancy probability function, but found no significant impact.

suitability of box k as a nest is affected by a vector of exogenous attributes, $\mathbf{a}_k$, such as shading conditions, and by a set of features of the box, denoted $\mathbf{h}_k$, including the box's height, color, and entrance direction. The matrices $\mathbf{a} = (\mathbf{a}_1, \ldots, \mathbf{a}_K)$ and $\mathbf{h} = (\mathbf{h}_1, \ldots, \mathbf{h}_K)$ are defined accordingly.

Various crops, j, are routinely grown on the farm. Let δ_{ij} be an indicator variable that has a value of 1 if crop j, $j = 1, \ldots, J$, is assigned to a specific field, i. The $I \times J$ matrix of crop attributions to fields, $\boldsymbol{\delta}$, is defined accordingly. The function

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

represents the cumulative predation pressure applied by barn owls nesting in the K boxes on the rodents within M_i land units of field i, when this field is allotted to crop j. Cumulative pressure is defined as the sum of the products of two functions. The first function in equation (1), $l_{ikj}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i, \mathbf{x}\right)\right)$, is called the *predation-pressure function*, and represents the intensity of the predation activity applied by a barn owl nesting in box k in the area of field i if the field is devoted to crop j. This intensity is measured by the probability that the barn owl will hunt in field i, which 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 M_i area units of field i. The predation-pressure function is crop-specific, and therefore differentiates the hunting preferences of barn owls toward different crops. The second function in equation (1), $S_k\left(\mathbf{u}, \mathbf{x}, \boldsymbol{\delta}, \mathbf{a}_k, \mathbf{h}_k\right)$, is termed the *box-selection function*, and expresses the probability of box k being selected as a nesting place by a pair of barn owls. This probability depends on the box's attributes $\mathbf{a}_k$ and $\mathbf{h}_k$; it also depends on the features of the box's surrounding environment, including the type of crops allotted to the farm's fields, represented by $\boldsymbol{\delta}$, and the distances to all other boxes and land units in the farm, which in turn depend on the locations of all the boxes $(\mathbf{x})$ and land units $(\mathbf{u})$. The land use around the box may affect its occupancy rate if barn owls prefer nesting in boxes close to land uses that are favored for predation. The relevance of the distance to other boxes stems from the potential territorial behavior of barn owls. In our empirical estimation of the box-selection function, we control for these spatial effects using variables, which, for consistency, were calculated based on the estimated predation-pressure function.

Let $\mathbf{q}_{ij}$ be the vector of production inputs applied to field i when it is assigned to crop j, and let matrix $\mathbf{q}$ incorporate the $I \times J$ sets of $\mathbf{q}_{ij}$ production inputs. The vectors $\mathbf{b}_1$ and $\mathbf{b}_2$ incorporate exogenous factors associated with production and costs, respectively, including managerial skills, climate conditions, input constraints, and prices of inputs and outputs. Given $\mathbf{u}$, $\mathbf{a}$, $\mathbf{v}$, $\mathbf{b}_1$, and $\mathbf{b}_2$, a profit-maximizing farmer will decide on the optimal assignment of crops to the fields, $\boldsymbol{\delta}^*$, the application of inputs to the fields, $\mathbf{q}_{ij}^*$, $i = 1, \ldots, I$, $j = 1, \ldots, J$, the features of the boxes, $\mathbf{h}_k^*$, $k = 1, \ldots, K$, and the location of the boxes, $\mathbf{x}^*$. The maximal profit is:

$$(2) \qquad w^* = \sum_{i=1}^{I} \sum_{j=1}^{J} \delta_{ij}^* p_j H_{ij}(r_{ij}(\mathbf{u}, \mathbf{x}^*, \boldsymbol{\delta}^*, \mathbf{a}, \mathbf{h}^*), \mathbf{q}_{ij}^*, \mathbf{v}_i, \mathbf{b}_1) - c(\mathbf{q}^*, \mathbf{h}^*, \mathbf{x}^*, \boldsymbol{\delta}^*, \mathbf{b}_2)$$

where p_j is crop j's output price, $H_{ij}(r_{ij}(\mathbf{u}, \mathbf{x}^*, \boldsymbol{\delta}^*, \mathbf{a}, \mathbf{h}^*), \mathbf{q}_{ij}^*, \mathbf{v}_i, \mathbf{b}_1)$ is a production function specific to field i and crop j, and $c(\cdot)$ is a farm-level cost function.

Equation (2) integrates the management tools and the spatial agrobiological relationships into one comprehensive function, which constitutes the basis for our empirical analysis. Note that our estimation of the production function $H_{ij}(r_{ij}(\mathbf{u}, \mathbf{x}^*, \boldsymbol{\delta}^*, \mathbf{a}, \mathbf{h}^*), \mathbf{q}_{ij}^*, \mathbf{v}_i, \mathbf{b}_1)$ uses the model developed by Saha, Shumway, and Havenner (1997), wherein the field-level inputs $\mathbf{q}$, field characteristics $\mathbf{v}$, and farm-level attributes $\mathbf{b}_1$ are all associated with direct production impact, as well as indirect effects through damage control. In addition, while deciding on the assignment of crops to fields, $\boldsymbol{\delta}$, farmers may account for the box locations, $\mathbf{x}$. However, in our empirical analysis we found that the observed assignment $\boldsymbol{\delta}^*$ is independent of $\mathbf{x}$; that is, $\boldsymbol{\delta}^*$ is dictated primarily by other considerations, such as crop rotation, and is therefore exogenous.

Empirical Specifications and Estimation Results

Our empirical application uses data from 1999–2008, covering the lands of Kibbutz

Sde Eliyahu in the Beit She'an Valley, Israel (32°30N, 35°30E). This is a semi-arid region with average annual rainfall of about 250 mm, mild winters, and dry, hot summers. Fifty-eight barn owl nesting boxes were placed in various fields between 1983 and 1996. The 12.5 km^2 study area comprises heterogeneous land uses—altogether $11 (J = 11)$—including residential zones, field crops, and fruit plantations. There were 54 fields ($I = 54$), which we divided into land units (m_i) of 56 m^2 each. The spatial distribution of boxes across diverse land uses enabled us to investigate how the variation in land use affects the predation pressure exerted on rodents by barn owls, as well as the occupancy rates of nesting boxes. In the following sub-section, we apply a survival analysis to estimate a function describing the spatial distribution of the predation pressure exercised by the barn owls on the various land uses around the nesting boxes. This function generates explanatory variables that we used to estimate both the box-selection function and the alfalfa-production function.

The Predation-Pressure Function

The predation-pressure function $l_{ikj}(\mathbf{d}_{ik}(\mathbf{u}_i, \mathbf{x}_k))$ is defined as the probability that a barn owl nesting in box k will 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 further from the nest is expected to be less appealing to the owls because longer flights are required. The appeal of the field also depends on the crop grown there, through the size of the 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 chances of pinpointing its prey, as well as its hunting success.

Let $d_{m_i k}(\mathbf{u}_{m_i}, \mathbf{x}_k)$ be the distance between box k and the centroid of land unit m_i within field i. The predation-pressure function for field i, when assigned to crop j, is:

$$(3) \qquad l_{ikj}(\mathbf{d}_{ik}(\mathbf{u}_i, \mathbf{x}_k)) = \sum_{m_i=1}^{M_i} \Pr_j(d_{m_i k}(\mathbf{u}_{m_i}, \mathbf{x}_k))$$

where $\Pr_j(d_{m_i k}(\mathbf{u}_{m_i}, \mathbf{x}_k))$ is a probability density function specific to crop j, which represents the probability of the barn owl nesting in box k to hunt at point m_i.

Estimating $\Pr_j(d_{m_i k}(\mathbf{u}_{m_i}, \mathbf{x}_k))$ requires two datasets. The first represents the barn owl's "actual predation behavior," and includes records of the locations of barn owls while hunting, from 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 reflects the "predation opportunities" of barn owls, and is specifically required to estimate differences in the hunting appeal of different crops. We employed a recursive estimation procedure that involves survival analyses based on radiotelemetry records of barn owls in Sde Eliyahu's fields, the selection of a functional form based on the Akaike Information Criterion (AIC), and estimation of crop-preference parameters. In the online appendix A, we detail the data and the estimation procedure. Here we report the estimation result of the selected gamma probability density function:

$$(4) \qquad \Pr_j(d_{m_i k}) = a_j \frac{0.11 \exp\left[0.16\left(\ln\left(\pi d_{m_i k}^2\right) - 3.25\right) - 0.025 \exp\left[6.35\left(\ln\left(\pi d_{m_i k}^2\right) - 3.25\right)\right]\right]}{2\pi^2 d_{m_i k}^3}$$

where a_j is a crop-preference parameter whose value is presented in table 1 for the 11 land uses. Except for the case of legumes, barn owls seem to prefer trees, probably owing to the advantage provided by perches (Kay et al. 1994).

The estimated predation-pressure function has a few noteworthy implications. First, our evaluation of the contribution of barn owls to agricultural profits is based on alfalfa production. Given that the estimated crop-preference parameters for alfalfa are among the lowest, this crop is not attractive to barn owls, and therefore our focus on alfalfa may considerably underestimate the overall contribution of barn owls to profit. Second, as our evaluations rely heavily on the predation-pressure function, validation is required. In the on-line appendix B, we provide empirical evidence showing that (a) the calculated predation pressures can explain the hunting patterns of barn owls in alfalfa fields as found in the radiotelemetry survey, and (b) endogeneity due to reverse causality is unlikely, meaning that larger alfalfa yields do not stimulate predation pressure. Finally, the predation-pressure function is also used

Table 1. Estimates of Crop-Preference Parameters

Land Use	α_j (t value)	R^2	F-statistic
Fallow	0.69 (3.16)***	0.40	9.96
Alfalfa, year 1	0.39 (2.54)**	0.30	6.46
Alfalfa, year 2+	0.29 (2.51)**	0.30	6.29
Corn	0.12 (1.95)***	0.20	3.80
Legumes	2.08 (4.66)***	0.59	21.74
Wheat	0.79 (3.12)***	0.39	9.75
Vegetables	0.42 (2.49)**	0.29	6.22
Citrus	1.26 (2.76)**	0.34	7.63
Dates	2.64 (5.71)***	0.69	32.65
Olives	1.89 (1.90)*	0.19	3.61
Residential areas	0.88 (4.91)***	0.62	24.11

Note: * denotes significance at a 10% level, ** denotes significance at a 5% level, and *** denotes significance at a 1% level.

to validate our assumption that the box locations ($\mathbf{x}$) do not affect the optimal assignment of fields to crops ($\boldsymbol{\delta}^*$).[3]

The Box-Selection Function

From the farmer's point of view, the profitability associated with installing and maintaining a nesting box depends primarily on the probability of the box being in use. The proximity of the box to attractive hunting areas has a potentially important impact on the probability of the box being occupied. Hence, the location of each box is likely to be a key determinant of its occupancy rate, and in turn a key determinant of the efficacy of rodent control by barn owls overall.

Barn owls reselect their nesting places once a year, at the onset of the breeding season. Previous studies have indicated the dependence of nesting rate in boxes on their physical features and geographical attributes (Charter et al. 2010). In this study, we estimate an occupancy probability function in which the impacts of the boxes' proximity to certain crops and to other boxes are incorporated based on the estimated predation-pressure function.

The average occupancy rate for the 58 boxes over the 10-year 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 groups. The first group includes time-invariant features of the boxes themselves, including dummy variables for three entrance directions and a dummy for boxes located in the shade. The second group of variables represents the environment of each box. We hypothesize that boxes located closer to land uses that provide better hunting conditions are more attractive for nesting. Variables in this group represent the predation pressure exerted by barn owls nesting in a box on rodents in the aforementioned 11 land uses (see table 1), conditional on its being occupied. The predation pressure was computed for each box k, land-use j, and year t, $t = 1, \ldots, 10$, by:

$$(5) \qquad L_{kjt} = \sum_{i=1}^{I} \delta_{ijt} l_{ikj}(\mathbf{d}_{ik}(\mathbf{u}_i, \mathbf{x}_k))$$

using the parameters estimated for the predation-pressure function $l_{ikj}(\mathbf{d}_{ik}(\mathbf{u}_i, \mathbf{x}_k))$. The predation pressure represents the probability (or fraction of time) that a barn owl nesting in box k will hunt in the fields assigned to crop j. Note that the pressures computed for Sde Eliyahu's residential area and for perennial plantation fields are time-invariant, since $\delta_{ijt} = \delta_{ij}$ for all $t = 1, \ldots, 10$. In addition, to control for potential territorial effects in nest selection, 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 (4) to the distance from box k to every other box, and averaging across boxes. For all of the variables in this

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[3] We estimated a multinomial logit model of the probability that fields are assigned to non-perennial crops, in which the calculated cumulative predation pressure exercised by all of the boxes on the fields constitutes the explanatory variable; the corresponding coefficients were found to be statistically insignificant for all crops.

group (i.e., the predation pressures on the 11 land uses and the engagement probability), second-degree polynomials are included to allow for non-linear effects.

It is worth noting that yields in the fields surrounding the nest might affect the nesting rate, and controlling for this effect could introduce endogeneity into our analysis. However, this is not relevant for the specific case of alfalfa, since box occupancy is generally established before the first alfalfa harvest.

The third group of variables includes time-specific variables—annual rainfall at Sde Eliyahu, the number of years since the box was installed, year fixed effects, and the total number of nesting boxes throughout Israel to control for potential impacts on the barn owl population. In addition, since boxes occupied in previous years may signal favorable nesting conditions, we included a lagged dependent variable that indicates whether the box was occupied in the previous year. This entails estimating a dynamic probit model, with unobserved box heterogeneity. Following Wooldridge (2005), we internalize into the model the correlation between the initial dependent variable (denoted g_{k0}) and the unobserved heterogeneity (η_k) using a linear function: $\eta_k = \theta_0 + \theta_1 g_{k0} + \mathbf{z}_k \boldsymbol{\theta}_2 + \phi_k$, where $\mathbf{z}_k = (\mathbf{z}_{k1}, \ldots, \mathbf{z}_{k10})$ is the row vector of all explanatory variables in all time periods, θ_0, θ_1, and θ_2 are coefficients, and $\phi_k | (g_{k0}, \mathbf{z}_k) \sim N(0, \sigma_\phi^2)$. This yields a dynamic probit model with response probability:

$$(6) \qquad \Pr(g_{kr} = 1) = \Phi(\mathbf{z}_{kt}\boldsymbol{\psi} + \zeta g_{k,t-1} + \theta_0 + \theta_1 g_{k0} + \mathbf{z}_k \boldsymbol{\theta}_2 + \phi_k)$$

where g_{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 non-perennial crops, which are the time-variant variables. The stepAIC procedure (Venables and Ripley 2002) was employed to select the set of variables to be retained in the model based on the AIC. Table 2 reports the estimation results.

Only one variable from the group of time-invariant features of the boxes was retained by the stepAIC procedure: the shade conditions.[4] As could be expected in hot environments, shaded boxes are significantly more attractive. The agricultural environment also appears to play an important role in nesting box occupancy. The coefficients of alfalfa and wheat, which are known to be favored by rodents, are positive. That is, larger predation pressure on these crops (i.e., a reduction in the distance between the box and the fields where these crops are grown, which in turn increases the probability that the barn owl nesting in the box will hunt in these fields) increases the probability of the box being occupied. However, this finding is inconsistent with the predation habits (table 1), implying that hunting patterns might not always be accounted for in the nest-selection stage. Note that the variable measuring the predation pressure on alfalfa fields in their first production year was eliminated by the stepAIC procedure; this indicates a possible learning process in which barn owls gradually recognize the alfalfa fields, or come to understand their appeal. Proximity to date palms also increases nesting probability,[5] possibly due to the preference for perches as prowl points and the abundance of rodents in date plantations, particularly rats.[6] 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 aversion to human presence, light, and noise. We hypothesize that the distance between neighboring nests will reflect an attraction-repulsion balance, converging to some favorable intermediate distance.[7] This hypothesis is reinforced by the opposite signs of the coefficients of the engagement-probability and engagement-probability-squared variables, which indicate

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[4] The dummy variable indicating the east-facing side of the box entrance was retained in the second-best model of the stepAIC procedure, which has a relative likelihood that is 7% lower than the first best (Burnham and Anderson 2002).

[5] The marginal effects of the crops' predation-pressure variables with statistically significant non-linear effects (pressures on dates and residential areas) are found to be monotonic throughout the whole sample range of these variables.

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

[7] Barn owls exhibit type B territorial behavior patterns (*sensu* Taylor 1994), where the area of breeding activity (the nest) is defended, but the hunting area is not. This implies that the territorial effect will be limited, and even reversed, if distances between boxes become large enough, and barn owls may tend to avoid nesting in boxes that are too isolated.

Table 2. Estimation Results for the Dynamic Probit Nesting Function

Variable	Sample Mean (St. Dev.)	Coefficient (Z value)	Marginal Probability Effect (t value)[a]
Occupancy (g_{kt}, dependent variable)	0.4293 (0.4954)	–	
Shaded conditions (dummy)	0.2414 (0.4283)	0.582 (2.74)***	0.239 (2.47)**
Pressure on alfalfa, year 2+ (Probability)	0.0302 (0.0499)	2.452 (1.84)*	1.009 (1.84)*
Pressure on wheat (Probability)	0.1014 (0.0933)	1.696 (1.83)*	0.698 (1.67)
Pressure on dates (Probability)	0.0407 (0.0651)	11.42 (2.20)**	3.074 (1.70)*
Pressure on dates squared	0.0059 (0.0127)	−48.61 (2.09)**	
Pressure on residential areas (Probability)	0.0105 (0.0150)	−87.48 (3.16)***	−24.95 (1.93)*
Pressure on residential areas squared	0.0003 (0.0008)	1,278 (3.04)***	
Engagement probability (Probability)	0.1232 (0.0683)	7.759 (2.04)**	0.211 (0.38)
Engagement probability squared	0.0198 (0.0246)	−29.40 (2.62)***	
Annual rainfall (cm/year)	24.780 (7.973)	0.047 (3.48)***	0.019 (4.11)***
2003 (dummy)	0.1000 (0.3003)	−0.501 (1.57)	−0.206 (1.83)*
2004 (dummy)	0.1000 (0.3003)	0.653 (3.26)***	0.269 (2.81)***
Occupied in previous year ($g_{k,t-1}$) (dummy)	0.3931 (0.4889)	0.793 (6.31)***	0.327 (5.36)***
Occupied in 1998 (g_{k0}) (dummy)	0.1379 (0.3451)	0.535 (2.77)***	0.220 (3.02)***
Sum of pressures on variant crops in 2002 (Probability)	0.3148 (0.1879)	−8.496 (1.42)	−3.497 (1.04)
Sum of pressures on variant crops in 2004 (Probability)	0.3223 (0.1873)	11.55 (1.60)	4.755 (1.25)
Sum of pressures on variant crops in 2007 (Probability)	0.3100 (0.1906)	−4.987 (1.67)*	−2.053 (1.37)
Constant		−1.725 (4.24)***	
σ_ϕ		3.49×10^{-4}	
$\sigma_\phi^2(1+\sigma_\phi^2)^{-1}$		1.22×10^{-7}	
Observations	580		
Log likelihood	−306.5		
AIC	649.1		
Pseudo R^2	0.23		

Notes: * denotes significance at a 10% level, ** denotes significance at a 5% level, and *** denotes significance at a 1% level.

[a] The marginal effects were evaluated for the mean values of the explanatory variables. Standard errors of the marginal effect statistics were calculated by bootstrap procedure.

the existence of a distance between boxes at which occupancy rate is maximized. By employing the estimated probability density function (equation 4), we found that, *ceteris paribus*, an average distance of 410 m between a box and all other boxes maximizes the box's occupancy probability. For comparison, the actual average distance between a box and all other boxes in the study area was approximately 1 km. In other words, increasing the density of the 58 boxes might increase their occupancy rates.

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

Occupancy in the previous year (the lagged dependent variable $g_{k,t-1}$) has a significant positive effect, indicating the potential importance of signals that might be maintained in the boxes between years.[8] There is also a strong correlation between the unobserved heterogeneity (η_k) and the initial value of the dependent variable (occupied in 1998, g_{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. Employing a log-likelihood test, the hypothesis $\sigma^2_\phi\left(1+\sigma^2_\phi\right)^{-1}=0$ was not rejected, implying that the panel probit estimator does not significantly differ from the pooled probit estimator.

The Alfalfa-Production Function

Alfalfa is routinely grown at Sde Eliyahu. Each year, on average, 42 of the total 540 ha of agricultural land at Kibbutz Sde Eliyahu are allocated to alfalfa. Our data encompass a panel of 429 alfalfa harvests in 21 fields from 1999–2008. An alfalfa field is cultivated and sown during the autumn of the first production year, remains untreated during the rainy winter season, and is then harvested up to 11 times during the dry seasons from April to September for a few years—usually not more than 4 sequential ones due to yield reduction. The fields are fertilized once every autumn, and irrigated twice following each harvest. The irrigation dose per harvest is determined according to the growing period only, and is therefore exogenous.[9] Most fields are irrigated by sprinklers, and some by a moving platform, which enables treatment against rodents by flood irrigation. Rodent control in all fields is based on barn owls and other factors, including other predators, natural flooding of canals during the winter, and agronomic activities such as plowing, control of other pests, and routine sanitation of field margins and waterways. Nevertheless, as reflected by the high proportion of rodents in the barn owls' diet (Charter et al. 2009), a large rodent population is present in Sde Eliyahu's fields.

To estimate the alfalfa-production function, we adopt the model developed by Saha, Shumway, and Havenner (1997):

$$y=H\left[\mathbf{W},G\left(\mathbf{X},\mathbf{Q}\right)\right] \tag{7}$$

where y is the quantity produced, $\mathbf{W}$ is a vector of direct production inputs, $\mathbf{X}$ denotes a vector of damage-control agents, $G(\cdot)$ is the abatement function, and $\mathbf{Q}\subseteq\mathbf{W}$ is a subset of the inputs in $\mathbf{W}$ that, in addition to their direct impact, also indirectly affect the yield through interactions with damage-control agents. For example, irrigation may directly increase yields and at the same time change the rodent population, thereby altering the effectiveness of rodent control by barn owls. Saha, Shumway, and Havenner (1997) suggested the empirical specification:

$$y=Y\left(\mathbf{W},\boldsymbol{\beta}\right)\cdot G\left(\mathbf{X},\mathbf{Q},\boldsymbol{\omega},e\right)\cdot\exp(\varepsilon) \tag{8}$$

wherein

$$G(\mathbf{X},\mathbf{Q},\boldsymbol{\omega},e)=\exp\left[-A(\mathbf{X},\mathbf{Q},\boldsymbol{\omega})e\right] \tag{9}$$

is the abatement function, $Y(\cdot)$ and $A(\cdot)$ are continuous and differentiable functions, $\boldsymbol{\beta}$ and $\boldsymbol{\omega}$ are vectors of parameters, and e and ε are error terms. By assuming $e\sim N(\mu,1)$, $\varepsilon\sim N(0,1)$ and $\mathrm{cov}(e,\varepsilon)\equiv\rho$, one obtains the heteroscedastic error term $\varepsilon-A(\cdot)e$. Hence:

$$\ln y\sim N\left[\ln Y(\cdot)-\mu A(\cdot),B(\cdot)\right] \tag{10}$$

where $B(\cdot)\equiv 1+A(\cdot)^2-2A(\cdot)\rho$. These tractable assumptions allow an exact formulation of the expectation of output and its variance:

$$E(y)\equiv\bar{y}=Y(\cdot)\cdot\exp\left[\frac{B(\cdot)}{2}-\mu A(\cdot)\right] \tag{11}$$

$$V(y)=\bar{y}^2\cdot\{\exp[B(\cdot)]-1\}. \tag{12}$$

Following Saha, Shumway, and Havenner (1997), we assume a linear specification for $A(\cdot)$:

$$A(\mathbf{X},\mathbf{Q},\boldsymbol{\omega})=\omega_0+\boldsymbol{\omega}_X\mathbf{X}+\boldsymbol{\omega}_Q\mathbf{Q} \tag{13}$$

and a Cobb-Douglas functional form for $Y(\cdot)$:

$$Y(\mathbf{W},\boldsymbol{\beta})=\prod_{\varsigma}W_\varsigma^{\beta_\varsigma}\cdot\exp(\boldsymbol{\beta}_D\mathbf{W}_D) \tag{14}$$

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[8] While mature barn owls tend to stay year-round within a certain region, in our sample they rarely returned to the same nesting box in a subsequent year.

[9] Rainfall events during the harvest seasons are rare, and the irrigation dose of each harvest corresponds to the months of its growing period: 140 mm/harvest in April, May and September, 160 mm/harvest in June, and 180 mm/harvest in July and August.

where β_ς is the coefficient of the continuous variable W_ς, $\mathbf{W}_D$ is a set of dummy variables, and $\boldsymbol{\beta}_D$ is their corresponding vector of coefficients.

Our dependent variable is y_{i1th}, the weight (in ton/ha) of alfalfa harvested from field i during harvest number h in year t, where $j = 1$ denotes alfalfa production. The set of damage-control variables in $\mathbf{X}$ includes only the effect of the barn owls, represented by the cumulative predation pressure exercised by the occupied nesting boxes in the alfalfa fields. For some field i that is assigned to alfalfa $(j = 1)$ in year t, this cumulative pressure represents the probability that a barn owl nesting in some box k will hunt in this field, summed across all of the occupied boxes in Sde Eliyahu in that year. In view of equation (1), the cumulative probability is calculated for each field i, which is assigned to alfalfa in year t by:

$$(15) \qquad r_{i1t} = \sum_{k=1}^{K} \xi_{kt} l_{ik1}\left(\mathbf{d}_{ik}\left(\mathbf{u}_i, \mathbf{x}_k\right)\right)$$

where ξ_{kt} is an indicator variable receiving a value of 1 if box k is occupied in year t, and 0 otherwise. The per-hectare cumulative predation pressure of the field is included in $\mathbf{X}$, as well as its square, to control for a potential non-linear effect.

The vector $\mathbf{Q}$ incorporates all of the other explanatory variables, encompassing the vectors $\mathbf{q}$, $\mathbf{v}$, and $\mathbf{b}_1$ in equation (2). These variables include rainfall (mm/year), irrigation (mm/harvest), field size (ha), time since the previous harvest (days), average temperature during the period from the preceding harvest, and a set of dummy variables indicating the availability of flood irrigation in the field, the assignment of the field to organic production, the production year (1999 to 2008), the field (21 fields), the serial year of production in the field (ranging from 1 to 4), and the serial harvest number (ranging from 1 to 11). We assume that all of these explanatory variables are included in $\mathbf{Q}$ (i.e., $\mathbf{Q} = \mathbf{W}$) for two reasons: first, fields under conventional production obtain similar treatments against pests and herbs before the harvesting period. That is, other than barn owl predation pressure, there is no variability across these alfalfa fields with respect to damage-control variables. Organic production entails the avoidance of not only pesticides, but also fertilization; therefore, the dummy variable indicating organic production cannot be excluded from $\mathbf{W}$. The second reason for our assumption stems from the size of our set of explanatory variables, which is too large relative to the sample size to detach variables from $\mathbf{W}$ into a $\mathbf{Q}$ subgroup based on a separability pretest (see Saha, Shumway, and Havenner 1997).

The parameters $\boldsymbol{\omega}$, $\boldsymbol{\beta}$, μ, and ρ were estimated by maximizing the log-likelihood function (LLF):

$$(16) \qquad \begin{aligned} LLF(\boldsymbol{\omega}, \boldsymbol{\beta}, \mu, \rho) &= -\frac{1}{2} \sum_i \sum_t \sum_h \Bigg\{ \ln B_{i1th}(\cdot) \\ &\quad + \frac{\left[\ln y_{i1th}(\cdot) - \ln Y_{i1th}(\cdot) + \mu A_{i1th}(\cdot)\right]^2}{B_{i1th(\cdot)}} \Bigg\} \end{aligned}$$

using a non-linear maximization technique. The hypothesis that the error term $\varepsilon - A(\cdot)e$ is normally distributed was not rejected (P-value $= 0.22$). Table 3 reports the sample means and standard deviations of the variables, the estimated coefficients of the functions $Y(\cdot)$ and $A(\cdot)$, and the marginal effects of the variables on production mean and variance.

The formulation in equation (9) implies that the effect of each variable in $A(\cdot)$ on damage abetment is opposite in sign to its estimated coefficient. The marginal effect of the predation pressure is positive, implying that barn owls abate damage (i.e., the production of an alfalfa field increases with the probability that barn owls will hunt in that field, where the increase is channeled by the damage-abatement element of the production function). This finding provides evidence for a real contribution of the barn owls to agricultural productivity. The contribution of the predation pressure exhibits a diminishing return to scale, as the coefficients of predation pressure and predation-pressure squared have opposite signs. However, since the coefficient of the squared variable is not statistically significant, we cannot reject convex responses of abatement to predation-pressure increases.[10]

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[10] Nevertheless, even a concave response of the output to a change in the level of damage control can stem from various characteristics of the damage-abatement process; therefore, as shown by Fox and Weersink (1995), we cannot make any deductions from these findings on the nature of the impact of barn owls on rodents, or on the relations between rodent populations and yields.

Table 3. Estimation Results for the Production and Damage-Control Functions

		Coefficient (Z value)		Marginal Effect (t value)[a]	
Variable[b]	Sample Mean (St. Dev.)	Production, $Y(\cdot)$	Damage Control, $A(\cdot)$	Mean E(y)	Variance $V(y)$
Production (dependent variable, ton/harvest-ha)	1.910 (0.643)				
Predation pressure (Prob./ha)	0.028 (0.038)		−0.735 (2.66)***	123.4 (5.64)***	42.266 (3.15)***
Predation pressure squared	2.24×10^{-4} (4.55×10^{-4})		23.49 (1.54)		
Flood irrigation (dummy)	0.443 (0.497)	−1.022 (1.95)*	-5.873×10^{-3} (1.96)*	−0.472 (0.43)	−0.051 (0.05)
Irrigation (mm/harvest)	139.1 (52.31)	−0.017 (3.17)***	-2.602×10^{-6} (0.36)	−0.003 (1.16)	-9.314×10^{-4} (2.60)**
Organic (dummy)	0.387 (0.488)	−0.591 (3.00)***	-4.183×10^{-3} (2.89)***	−0.062 (0.08)	0.143 (0.31)
Growing period (day/harvest)	22.26 (10.51)	0.026 (3.65)***	1.815×10^{-4} (4.70)***	−0.011 (0.50)	-3.75×10^{-3} (0.76)
Temperature (°C)	31.52 (4.522)	0.105 (0.68)	1.959×10^{-5} (0.16)	0.014 (0.68)	4.87×10^{-3} (1.08)
Precipitation (mm/year)	248.9 (65.60)	0.059 (0.90)	4.585×10^{-5} (0.08)	−0.01 (0.58)	-3.31×10^{-3} (1.87)*
Field size (ha)	10.37 (4.305)	0.257 (2.09)**	3.082×10^{-4} (1.89)*	3.01×10^{-4} (0.59)	1.02×10^{-5} (0.98)
Year no. 2 (dummy)	0.445 (0.498)	0.630 (6.82)***	4.591×10^{-3} (8.93)***	0.103 (0.10)	0.110 (0.41)
Year no. 3 (dummy)	0.138 (0.345)	−0.267 (2.75)***	-7.861×10^{-4} (1.12)	−0.284 (0.39)	−0.022 (0.09)
Year no. 4 (dummy)	0.019 (0.135)	0.206 (0.98)	2.482×10^{-3} (1.55)	−0.146 (0.16)	0.157 (0.13)
Harvest no. 2 (dummy)	0.131 (0.337)	0.940 (2.79)***	4.009×10^{-3} (2.28)**	1.084 (0.45)	1.204 (0.29)
Harvest no. 3 (dummy)	0.131 (0.337)	0.782 (2.31)**	2.484×10^{-3} (1.34)	1.080 (0.45)	0.549 (0.26)
Harvest no. 4 (dummy)	0.126 (0.332)	0.563 (1.55)	1.116×10^{-3} (0.49)	0.919 (0.42)	0.210 (0.15)
Harvest no. 5 (dummy)	0.119 (0.324)	0.640 (1.63)	4.019×10^{-3} (1.78)*	0.372 (0.21)	0.690 (0.15)
Harvest no. 6 (dummy)	0.110 (0.313)	0.606 (1.45)	4.442×10^{-3} (1.87)*	0.219 (0.13)	0.739 (0.10)
Harvest no. 7 (dummy)	0.100 (0.301)	0.433 (1.07)	3.510×10^{-3} (1.45)	0.058 (0.04)	0.385 (0.16)
Harvest no. 8 (dummy)	0.086 (0.281)	0.188 (0.49)	2.458×10^{-3} (1.11)	−0.182 (0.17)	0.121 (0.13)
Harvest no. 9 (dummy)	0.054 (0.226)	0.217 (0.56)	2.472×10^{-3} (1.14)	−0.133 (0.12)	0.148 (0.07)
Harvest no. 10 (dummy)	0.012 (0.107)	0.359 (0.76)	5.636×10^{-3} (2.31)**	−0.346 (0.40)	0.785 (0.20)
Constant (ton/harvest-ha)			−0.024 (0.38)		
μ			1.276 (6.40)***		
ρ			−0.956 (134.8)***		
Observations	429				
Log likelihood	25.75				
Pseudo R^2	0.26				

Notes: * denotes significance at a 10% level, ** denotes significance at a 5% level, and *** denotes significance at a 1% level.

[a] The marginal effects were evaluated for the mean values of the explanatory variables. Standard errors of the marginal effect statistics were calculated by bootstrap procedure. The effects of dummy variables are the difference in the mean and variance under substitution of 0 and 1 in all observations at all bootstrap replications.

[b] Dummies for years and fields are not shown.

Note that our estimation of the effect of barn owls on alfalfa output is based on the position of the occupied nesting boxes in relation to the alfalfa fields. The box locations, however, might be non-random. That is, Sde Eliyahu farmers may have intentionally located the boxes closer to fields with higher alfalfa yields. To examine this possibility, we estimated the model again, this time with the predation pressure in equation (15) calculated as if all boxes are occupied (i.e., $\xi_{kt}=1$ for all $k=1,\ldots,K$). This resulted in a lower value for the log-likelihood function ($LLF=12.38$), and statistically insignificant coefficients for the predation pressure and its square. We therefore reject the hypothesis that the positive impact of barn owls on the output of alfalfa fields can be attributed to the locations of the boxes rather than to the locations of the occupied boxes only.

Returning to table 3, the effects of all other explanatory variables that appear in both $Y(\cdot)$ and $A(\cdot)$ on production and damage abatement are opposite in sign. Thus, these effects seem to offset each other such that the marginal effects on mean output are all statistically insignificant. With respect to the variance of output, only the marginal effects of irrigation and rainfall are statistically significant, and both reduce yield volatility.

Flood irrigation has a direct negative effect on alfalfa yield. This irrigation method is less efficient than sprinkling, since much floodwater is lost through deep-percolation flows. However, flood irrigation affects abatement positively. While we cannot reject the hypothesis of zero marginal effect of irrigation on mean alfalfa output, the coefficient of irrigation in $Y(\cdot)$ indicates a negative marginal product. This can be explained by the irrigation doses (see endnote 9), which, according to the evaporation in the Beit She'an Valley during the months of alfalfa growth (IMS 2013), are more than 25% higher than the recommended doses (Tzukerman 2004). Over-irrigation can result in reduced alfalfa yield (Donovan and Meek 1983; Mueller, Frate, and Campbell-Mathews 2007), and is more likely to occur under conditions of non-uniform infiltration (Feinerman, Letey, and Vaux 1983), saline irrigation water that requires excess irrigation for salt leaching and low water prices, as is the case in the Beit She'an Valley. As expected, organic production tends to yield lower output than conventional production. However, it also stimulates abatement, possibly owing to the avoidance of fertilization, which in turn discourages weed growth. A longer period between harvests increases output, but decreases abatement, probably due to the longer time afforded for the establishment of populations of damaging agents. This may also explain the lower abatement level in the second year of production compared to the first year (the effects are opposite in sign to the coefficients). Productivity is higher in the second and third harvests compared to all other harvests. Larger fields are more productive, but abatement is lower, indicating a negative interaction between field size and the barn owls' effect.[11] That is, as boxes are usually located at the margins of the field, the effect of barn owls on rodents in the interior areas of the field is lower, and further decreases with increasing field size.

To test the sensitivity of our results to the functional form specification adopted from Saha, Shumway, and Havenner (1997), we estimated a linear production function using the same set of explanatory variables, in which all variables were treated as productive inputs. The estimation results (online appendix C), with respect to the signs and significance levels of the coefficients of barn owl predation pressure and its square, are almost the same as those reported in table 3. The two specifications yield almost identical estimates of the predation pressure's marginal effect. This finding reinforces previous results by Carrasco-Tauber and Moffitt (1992) and Lansink and Carpentier (2001), which contradict Lichtenberg and Zilberman's (1986) hypothesis that damage-abatement specifications lead to lower estimates of the marginal effect of abatement inputs. On the other hand, the linear specification yields marginal effects with higher significance levels for almost all of the other explanatory variables.

Simulations

With the estimated functions of predation pressure, box selection and alfalfa production, and additional price and cost data,[12]

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[11] The nature of the interaction between some two variables X and Q in the abatement process, calculated by $\partial^2 G/\partial X \partial Q$, can be qualitatively represented by the sign of the product of their coefficients, $\omega_X \omega_Q$.

[12] Barn owls affect revenues by changing per-hectare productivity, and they entail fixed per-hectare costs associated with

we are in a position to plug these elements into equation (2) to evaluate the profitability of biological rodent control by barn owls. Four scenarios are compared. Scenario 1 represents the observed situation, in which the 58 nesting boxes are in their current locations throughout the fields of Sde Eliyahu. In scenario 2, we simulate alfalfa production in the absence of all nesting boxes, such that rodents are controlled only by the aforementioned agronomic and natural factors. In scenario 3, we run an algorithm that searches for the vector of optimal locations of the 58 nesting boxes, $\mathbf{x}^*$, which maximizes the expected profits of the alfalfa fields. The alfalfa revenues in this scenario are calculated by:

$$(17) \quad R = p_1 \sum_{i=1}^{I} \delta_{i1} E[y(\mathbf{W}_i, \mathbf{X}_i)]$$

where δ_{i1} stands for the probability of field i being assigned to alfalfa production, as computed based on our sample, and $E[y(\mathbf{W}_i, \mathbf{X}_i)]$ is the field's output expectation as in equation (11). Scenario 4 is similar to scenario 3, but instead of expected revenues, the function to be maximized under $\mathbf{x}^*$ incorporates the certainty-equivalent revenues:

$$(18) \quad CE = p_1 \sum_{i=1}^{I} \delta_{i1} \left\{ E[y(\mathbf{W}_i, \mathbf{X}_i)] - \Theta \frac{V[y(\mathbf{W}_i, \mathbf{X}_i)]}{2E[y(\mathbf{W}_i, \mathbf{X}_i)]} \right\}$$

where $V[y(\mathbf{W}_i, \mathbf{X}_i)]$ is the output's variance expressed by equation (12), and Θ is the Arrow-Pratt measure of relative risk aversion, which was evaluated by Bar-Shira, Just, and Zilberman (1997) to be 0.611 for farmers in Israel. As barn owls increase both the production expectation and the variance (see table 3), the certainty-equivalent revenue captures their counter effects on the production and risk premium.

The objective of scenarios 3 and 4 is to get an idea of how much higher the profits of Sde Eliyahu's alfalfa fields could be if the 58 boxes were originally located so as to maximize those profits. These scenarios, however, are associated with the challenge of solving a complicated non-linear spatial optimization problem, and are based on extrapolations of our estimated functions. Therefore, simplifications and constraints are needed to obtain practical and computable results.

Our estimation of the alfalfa production function $H_{i1}(r_{i1}(\mathbf{u}, \mathbf{x}, \boldsymbol{\delta}, \mathbf{a}, \mathbf{h}), \mathbf{v}_i, \mathbf{b}_1)$ implies that alfalfa outputs would considerably increase with cumulative predation pressure (table 3). The estimated predation-pressure function $l_{ikj}(\mathbf{d}_{ik}(\mathbf{u}_i, \mathbf{x}_k))$ tells us that the cumulative pressure on alfalfa fields will increase convexly as the distance between those fields and occupied nesting boxes decreases. The proximity of nesting boxes to alfalfa fields may also increase their occupancy rate, as can be learned from the estimated nesting selection function $s_k(\mathbf{u}, \mathbf{x}, \boldsymbol{\delta}, \mathbf{a}_k, \mathbf{h}_k)$ in table 2. Integrating these three effects implies that profits would be maximized if as many nesting boxes as possible were to be located as close as feasible to the alfalfa fields. A counteracting factor is the occupancy rate, which decreases when boxes become too close to each other. Nesting rates may also be restricted by the impact of the boxes' distances from other land uses, such as date trees. However, while our model captures these opposing forces, the reliability of our predictions is expected to diminish as we extrapolate further. For instance, nesting rates may be limited by unobserved variables such as overall barn owl population in the relevant area, or competition with other predators such as jackals, kestrels, and wildcats, which may affect the barn owls' hunting success. In addition, the location of the boxes should account for operational farming practices, such as the movement of cultivation machinery. These considerations can be taken into account in the model by introducing constraints. The two optimization scenarios incorporate two additional constraints: (*a*) all of the boxes are restricted to being located at the borders of the fields, at least 100 m apart, and (*b*) the per-hectare alfalfa production in every field is restricted to no more than 25 ton/year, which is 25% higher

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the installation and maintenance of nesting boxes. The output price is $264/ton, as reported by the Israel 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 an installation cost of $250, a 10-year lifetime, with one renovation at a cost of $60 and 0.1 working days per year for monitoring and cleaning. Attributing the costs of all 58 nesting boxes to the 42 ha allocated to alfalfa in Sde Eliyahu in an average year, we get a cost of $69/ha per year.

Figure 1. Optimal (scenarios 3 and 4) versus current (scenario 1) distribution of nesting boxes in relation to alfalfa crop-rotation fields

than the typical alfalfa productivity reported by IMARD (2010). In addition, to facilitate computation, our optimization algorithm considers 1,500 predefined potential points (located at the borders of all of Sde Eliyahu's fields, 100 m apart), and searches among them for the optimal location of one box at a time. This is a stepwise procedure in which the first box is located at the optimal point given that it is the only one in the area; the second box is optimally located given the location of the first box, and so on.[13]

Apparently, scenarios 3 and 4 both yield a similar solution for $\mathbf{x}^*$. Figure 1 shows current versus optimal nesting box distributions relative to the fields with positive probabilities of being assigned to alfalfa throughout crop rotations.

The simulation results are summarized in table 4.

Scenario 2 constitutes a benchmark for the calculation of the contribution of barn owls' rodent control to production and profit under the other three scenarios. The yield expectation under scenario 2 is computed by the use of equation (11), while substituting $r_{i1} = 0$ for all $i = 1, \dots, I$ into equation (15) and holding all other variables at their time-average levels. The alfalfa output attributable to the presence of the 58 nesting boxes in their current locations equals the difference between the expected productions under scenarios 1 and 2. This calculation results in a contribution of 1.35 ton/ha per year, which constitutes 9.4% of the observed production expectation of 14.38 ton/ha per year. The associated profit contribution amounts to \$235.8/ha per year. The calculated profit contribution based on the certainty-equivalent profits is slightly higher (\$245.0/ha per year); this is because the increase in the production expectation exceeds that of the variance. Thus, rodent control by barn owls is found to be profitable.[14] As noted, these are likely

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[13] Finding the optimal solution would require computing the value of the objective functions for each of the $2.3 \times 10^{105} [= 1500!/(58! \cdot 1442!)]$ combinations of 58 boxes placed in 1,500 locations. While our algorithm applies only 85,347 $[= (1501 \times 1500 - 1443 \times 1442)/2]$ computations, and therefore may not hit upon the optimal location, it is computationally feasible, and believed to be satisfactory for evaluating the extent to which profits of alfalfa fields could be increased.

[14] The profitability of alfalfa production is rather small, and may even be negative in certain years, so that an increase of 9.4% in production can make a significant difference in terms of profits. Based on production studies published by extension specialists at UC Davis (2008), Texas AgriLife Extension Service (2011), and the University of Wisconsin (2011), an output increase of 9.4% implies profit increases of 31%, 67%, and 107%, respectively. A similar study published by Iowa State University (2011) found

Table 4. Rodent-Control Scenarios

Description	Scenario 1 The 58 Nesting Boxes Are in Their Current Locations	Scenario 2 The 58 Nesting Boxes Are Eliminated	Scenarios 3 & 4 The 58 Nesting Boxes Are Located So as to Maximize Alfalfa Expected Profits and Certainty-Equivalent Profits
Average distance between box and all other boxes (km)	1.00	–	1.61
Average occupancy rate of boxes	0.46	–	0.61
Average pressure on alfalfa fields (Probability/ha)	4.54×10^{-5}	0.00	1.35×10^{-4}
Average alfalfa production expectation (ton/ha per year)	14.38	13.03	17.07
Average standard deviation of production (ton/ha per year)	8.11	7.63	9.29
Average certainty equivalent production (ton/ha per year)	13.17	11.78	15.68
Profit increase compared to Scenario 2 ($/ha per year):			
Expected profits	235.8	0.00	845.2
Certainty-equivalent profits	245.0	0.00	812.9

to be underestimates of the contribution of barn owls to overall profitability, since we completely ignore the potential contribution of the nesting boxes to the yields of other crops, most of which are more attractive for barn owl hunting than alfalfa (see table 1).

Compared with the current box locations (scenario 1), boxes in scenarios 3 and 4 are located around the fields with high probabilities of being assigned to alfalfa (figure 1), and the average nesting rate is considerably higher than the observed nesting rate (table 4). Consequently, the average per-hectare predation pressure on alfalfa fields is an order of magnitude higher; thus, the portion of the production associated with the presence of barn owls increases from 9.4% to more than 23%, and the computed contribution of the barn owls to alfalfa profits is 3.3 times of that under the observed situation. These results highlight the considerable impact of the locations of nesting boxes on alfalfa profits. In a broader perspective, our case study of rodent control using barn owls illustrates the importance of the spatial distribution of sources of agro-biological agents (e.g., honeybee apiaries) as a farming-management tool.

The question arises of how robust these evaluations are to functional form specifications. We examine this question with respect to the production function by simulating scenarios 1, 2, and 3 using the aforementioned linear specification. Apparently, unlike the marginal effect, the linear production function yields evaluations of barn owls' contributions to outputs and profits that are higher under both the observed and optimal locations of the boxes (online appendix C). This finding indicates that the evaluation obtained using the functional form of damage abatement is rather conservative.

As indicated by scenarios 3 and 4, if alfalfa is assumed to be the only crop whose profit can be increased by barn owl activity, the current spatial distribution of nesting boxes at Sde Eliyahu is not optimal; the returns on some of the boxes may not even cover their installation and maintenance costs. To examine this issue further, we applied

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net losses in alfalfa production, yet an output increase of 9.4% could have reduced the losses by 22%. Similarly, a study provided by IMARD (2010) also found net losses in alfalfa production in Israel, and here a 9.4% yield increase could reduce losses by 50%.

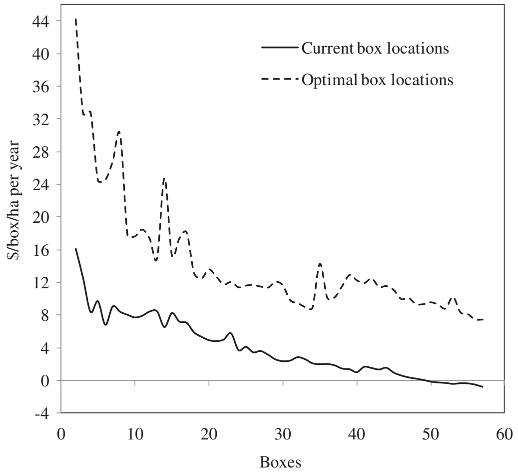

Figure 2. Marginal profits of the number of boxes under current and optimized locations

our stepwise optimization algorithm to the 58 observed locations of the boxes. This enabled us to compute the marginal profit of each additional nesting box, as presented in figure 2. A similar curve is presented for the optimal box locations, as selected by the optimization algorithm under scenarios 3 and 4.[15] As suspected, in their current locations, 10 of the nesting boxes do not cover their costs. Nevertheless, as already noted, the array of boxes as a whole is still profitable. While the marginal profit curve under scenarios 3 and 4 fluctuates noticeably and exhibits a decreasing trend, all of the boxes are profitable.

Conclusions

Our empirical application has two policy implications. First, the results indicate that rodent control by barn owls is profitable from a farming point of view. Thus, under a hypothetical case in which rodenticides are absolutely prohibited, aside from informing farmers about the potential profitability of the method and developing guidance and training programs, additional governmental intervention to promote adoption of the method (e.g., by policy instruments such as subsidies) is unnecessary.[16] However, more active governmental intervention may be warranted if rodenticides are allowed, or in areas where farmers own small agricultural plots where spillover effects of the barn owl damage-abatement services may lead to free riding and thus to the placement of a suboptimal number of nesting boxes. Second, despite the fact that we cannot directly compare the profitability of rodent control by barn owls to that of rodent control by rodenticides, our analysis evaluates profit contributions that are both significant and can be considered underestimates of the overall returns stemming from barn owl damage control. Thus, if policy-makers such as those in Israel (IMARD 2011) are looking to reduce the considerable environmental damage caused by rodenticides (e.g., Yom-Tov and Mendelssohn 1988; Zurita et al. 2007), our findings provide strong arguments for more severely restricting the regulatory conditions under which rodenticides are permitted.

This study leaves a good deal of room for future research. For example, data on the various ecological, zoological, and economical components of the barn owl system can be collected at a finer resolution to elucidate the costs and benefits of control by barn owls versus alternative actions. The barn owls' contribution to profit may be assessed with respect to more crops, which would enable the computation of a more realistic optimal spatial distribution of boxes, including a determination of the optimal number of boxes. The profitability of the method should also be compared to that of rodenticides. Finally, our application evaluates contributions to farmers' profits only; designing rodent-control policies based on a wider social perspective would require valuations of the environmental damage abated through the avoidance of rodenticide use, the benefits associated with preserving barn owls, and the impacts of barn owls on other endangered species.

The spatial economic model developed in this study is applicable to other agrobiological systems, particularly those associated with point-source spatial impacts. Examples

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[15] The curves exhibit non-monotonic patterns due to the spatial interrelations among the boxes; each additional box can affect the occupancy probability of the boxes located earlier by the stepwise optimization algorithm, and thus yield a larger marginal profitability compared to the previous box.

[16] In recent years, the method has been rapidly adopted by Israeli farmers, partly owing to the governmental training activities and financial support for the installation, maintenance, and monitoring of nesting boxes (IMEP 2009; Motro et al. 2010).

include the selection of locations for honeybee apiaries, which influence pollination services and honey production (Manning and Wallis 2005), the management of patches of non-crop habitats to enhance natural pest control (Bianchi, Booij, and Tscharntke 2006), and the positions of cattle watering points, which affect the spatial variation of vegetation in rangelands and thus meat production (Ludwig et al. 1999). Nevertheless, extensions are required to further expand the applicability of the model, particularly to cases in which various movement processes, such as dispersal and wandering, are important (Nathan et al. 2008), for example in the release of lady beetles (Baker et al. 2003) and sterile flies (Enkerlin 2007). Introducing the time dimension might also enable capturing external stochastic spatiotemporal effects (Harper and Zilberman 1989), the dynamics of predator-prey systems (Rafikov, Balthazar, and von Bremen 2008), and long-term adaptation and resistance development in pests (Hueth and Regev 1974).

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