

Optimal Management Of An Ecosystem Service Over Space

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Abstract

Many crops rely on services provided by neighboring ecosystems and specifically those harboring beneficial insects, such as for integrated pest control or pollination. These wild insect populations originate principally from public lands, while their dispersal and utilization are affected by land use decisions on individual farms. With a central planning authority to choose restoration both at the source and on the farmland, the question becomes – when is investment in the ecosystem service optimal, and where should habitat restoration be targeted? This paper presents a framework to determine optimal resource allocation over space for pollination – both from managed species (such as the honey bee), and from native, wild species (such as the bumble bee) – of pollinator-dependent crops. The optimal solution is then compared to the outcome when land management is distributed among many farmers who cannot internalize the spatial externalities, which results in sub-optimal restoration.

Introduction

Pollination by bees is a crucial function in many terrestrial ecosystems and an important contribution to many crops that require or benefit from bee pollinators. Crop production relies chiefly on the domesticated honey bee (*Apis mellifera*) to pollinate the cultivars, but wild bees in the natural environment also provide a significant part of the service (Kremen et al. [2002]). The natural environments that offer habitat (shelter, nesting grounds and food resources) for these bees provide an economic service to the nearby agricultural lands with pollinator-dependent crops. This ecosystem service is an important case study, not only because there is relatively strong ecological knowledge of the service and economic information on its value, but also as it can enlighten policies that are addressing the increasing instability in honey bee populations.

In designing a payment scheme to enhance the ecosystem service, the chief problem is in determining where to focus restoration strategies and where demand – and therefore where potential funding resources would come from – are located.

In this paper we develop a model for evaluating the allocation of biological resources on a spatially heterogeneous landscape. Native bees, emanating from natural habitats, pollinate nearby crops to a significant extent, in some cases in such abundance that farmers need not rent the domesticated honey bee (Kremen et al. [2002]). This positive externality is differentiated significantly and rather exclusively based on the proximity to natural and semi-natural habitat (Kremen et al. [2004], Klein et al. [2007]). Protecting and enhancing the natural service can be achieved through restoration strategies both off-farm – by providing large “source” areas through land conservation or restoration of upland habitat – as well as on-farm – by reducing insecticide use, providing nesting sites and planting or allowing floral resources (Kremen et al. [2002]).

In many respects, this problem mirrors that of pollution or pest control

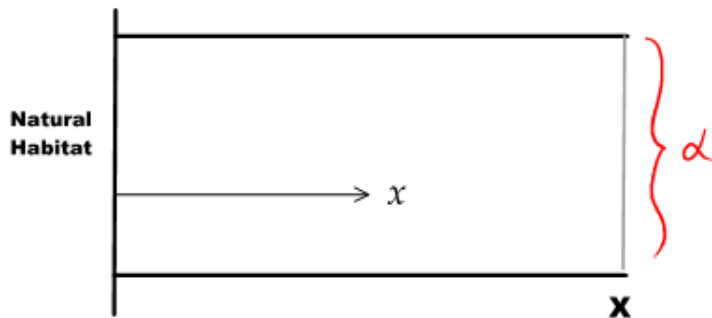
problems in which there is a directional (positive or negative) externality, flowing from a source and affecting a particular nearby crop (Brown et al. [2002]). For such a pest control case, Brown et al employ an optimal control framework over a spatial dimension, addressing the tradeoff between source control (in that case, eliminating particular vegetation in a riparian ecosystem) and on-site mitigation through a “buffer crop zone”. Similar studies of a unidirectional externality have demonstrated that such mitigation strategies cannot be viewed as substitutes (Chakravorty et al. [1995]).

The optimal source and distribution “control” of native bees is conditioned on the ecological viability of the area for specific bee habitats and their respective foraging ranges. The framework can be expanded to consider multiple natural habitat hot-spots and multiple land use patterns. In the end, we have both a conceptual and empirically testable hypothesis as to why some landscapes would find it optimal to manage for the ecosystem service provided by native bees while others would focus on developing the honey bee pollination system.

The modeling framework

Consider an agricultural landscape with a neighboring “natural” area. We define the natural area as a long-standing, uncultivated area composing habitat suitable for native bee populations, which includes preserved and unpreserved forest and grasslands. The important assumption regarding this habitat is that it is managed by a public entity interested in natural pollination of nearby farms. In order to maintain the simplest possible setting, we assume land is identical in all respects except the availability of native bees, which can be defined along a distance gradient from the natural habitat boundary. Land is located over a continuum of distance x from the habitat boundary, with maximum distance X , the length of the agricultural landscape. Let α be the uniform width of the agricultural landscape. See Figure 1.

Fig. 1: Diagram of Landscape



For simplicity, we assume there is a single crop grown on the landscape and this crop depends on insect pollination. All insect pollinator-dependent crops can be pollinated from a numerous variety of native bee species, and most can be pollinated by the managed honey bee. Thus, except for a few crops, a crop's pollination can be acquired through any sufficient combination of honey and native bees.

To model the pollination service generated by the natural habitat, we will consider the wild bee population as a stock variable dependent on location. We use $W(x)$ to denote the density – that is, the number flying around over a unit of space – of wild bees at location x . We reduce the multitude – thousands, in fact – of different pollinator species to a consideration of one conglomerate population – the *meta-bee*. In reality, the different species nest in different locations – some exclusively in the natural habitat, some on farms no matter how intensified (Kremen et al. [2004]). Each bee has a maximal foraging range. $W(x)$ represents, in a sense, a summation of each of these bee distributions at each location, which results in a population concentrated greatest in natural habitat (where there are the greatest abundance of nesting grounds and floral resources), and diminishing with distance.

Let the amount of native bees available at the natural habitat boundary be W_0 , which is determined endogenously by a social planner. The net cost

of generating the source population of native pollinators $g(W_0)$ represents the capital expenditures and opportunity costs of maintaining the quantity and quality of natural habitat sufficient to support the population size, net of additional benefits that such habitat generates. The native bees forage over the cropland according to a simple population flow dynamic: a fraction of native bees stop foraging beyond distance x . This fraction is denoted $s(x)$, with $s(x) \geq 0$. Then

$$\dot{W}(x) = -s(x)W(x), \quad (1)$$

where a dot over the variable W indicates the operator d/dx . Condition (1) implies that for $W_0 > 0$, $W(x) > 0 \forall x$ and $\dot{W}(x) \leq 0$, so the residual spread of native bees over cropland decreases away from the natural habitat source.

The availability of wild bees on the agricultural landscape can be enhanced by maintaining ample nesting and forage resources. A number of pilot programs have begun assessing empirically how effective restoration strategies on farm sites (e.g. planting row- and border-crops, keeping debris for nesting grounds, etc.) are in improving native bee abundances.¹

So we suppose the stop function $s(x)$ depends on $r(x)$, defined as the investment in habitat restoration per unit surface area of the cropland. The variable represents the sum of annualized investment cost and the cost of protection and maintenance. Note that r is a function of x and can therefore vary with location. If no investment is made in improving pollinator habitat on cropland, i.e., $r(x) = 0$, then the fraction of bees that stop foraging beyond distance x , $s(x)$ equals the base transition rate s_0 , $s_0 \in [0, 1]$, and the population flow follows an exponential decay curve. A positive value of $r(x)$ (e.g., planting bee-benefiting vegetation or logs for nest sites) induces more bees to forage beyond location x thus causing the stop function $s(x)$ to

¹ In addition to native pollinators, these practices may also enhance/attract pest populations (both deleterious and beneficial) and may involve a reduction in cultivated acreage. In this paper, we will ignore such secondary effects.

be less than s_0 .

Let the reduction in the transition rate obtained by investing $r(x)$ be given by $m(r(x))$. We then obtain

$$s(x) = s_0 - m(r(x)). \quad (2)$$

Assume $m(\cdot)$ to be an increasing, twice continuously differentiable function with decreasing returns to scale in r , $m(\cdot) \in [0, s_0)$, $m(0) = 0$, $m'(\cdot) > 0$, $m''(\cdot) < 0$, $\lim_{r \rightarrow \infty} m(r) = s_0$. The limit indicates the transition rate can only be driven to zero.

It is important to note at this point that this restoration on agricultural land generates exclusively a spatial externality: improving nesting resources at location x does not increase the stock of native bees at location x , but rather increases the fraction of the stock of wild bees that continue foraging beyond location x . The positive externality benefits farm locations “downstream”. Thus, unless a farmer operating on a small scale can capture these rents, he will never choose to invest in restoration. In contrast, if the landscape is managed by a single farmer or social planner, then the spatial externality is internalized in the decision.

Farmers make private investment in pollination by renting honey bees from beekeepers. Honey bee hives are rented and placed on the farms to pollinate the crop as well. Let $h(x)$ be the density of honey bees – a continuous control variable – chosen for location x . Total available supply of honey bees for the landscape is set at N_0 . Thus,

$$\int_0^X h(x) \alpha dx \leq N_0 \quad (3)$$

The stock N_0 is chosen with cost $C(N_0)$. Yield is determined by the total amount of pollination, $\phi(x)$, which is the combined service of honey and wild bees at location x . We assume that pollination affects productivity through

a fixed asset effect represented by $f(\phi(x))$, where $f(\cdot)$ is twice continuously differentiable, with $f'(\cdot) > 0$, $f''(\cdot) < 0$. To simplify matters, we assume the total amount of pollination service can be expressed as a weighted sum of pollinator densities:

$$\phi(x) = h(x) + \beta W(x), \quad (4)$$

where β represents an equivalence factor to translate wild bee densities into equivalent honey bee stocking densities.

We proceed the investigation with two models – one where a single farm manager operates the entire landscape, and one where a continuum of firms are located over the landscape. We assume these firms to be identical in all respects except location. The key distinguishing feature between these two regimes is that in the first case, the spatial externality is internalized in the decision making process, while in the latter case actions at a location cannot capture benefits to downstream firms.

The modeling framework

Optimal resource allocation in a one-farm regime

The single farmer then maximizes profit over the region, choosing inputs, as well as the initial stocks of wild and honey bees:

$$\max_{h,r,W,N_0} \int_0^X \left[pf(h(x) + \beta W(x)) \alpha - r(x) \right] dx - g(W_0) - C(N_0)$$

$$s.t. \quad \dot{W}(x) = -[s_0 - m(r(x))]W(x) \quad (5)$$

$$W(0) = W_0 \quad (6)$$

$$\int_0^x h(x)\alpha dx \leq N_0 \quad (7)$$

$$h(x) \geq 0 \quad (8)$$

$$r(x) \geq 0 \quad (9)$$

The Hamiltonian for this problem is

$$\mathcal{H} = [pf(h + \beta W) - \lambda h]\alpha - r - \mu [s_0 - m(r)] W$$

where λ is the shadow cost of honey bee use, and μ is the co-state variable associated with W . The marginal impact of restoration at location x on the Hamiltonian is given by

$$\frac{\partial \mathcal{H}}{\partial r} = -1 + \mu m'(r)W \quad (10)$$

If this expression is negative, so that the marginal user benefit per dollar spent on restoration are less than one, then there will be no investment in restoration at location x . The interior solution is pursued when the marginal benefit per dollar of restoration is equated to one.

Now consider the marginal impact of honey bee rental on the Hamiltonian

$$\frac{\partial \mathcal{H}}{\partial h} = [pf'(h + \beta W) - \lambda]\alpha \quad (11)$$

If this expression is negative so that the marginal value of honey bee pollination is less than the shadow price, then no honey bees will be rented. Honey

bees will be rented with the value of marginal product and the shadow price of honey bees are equated.

The co-state variable follows the dynamic

$$\dot{\mu} = -\frac{\partial \mathcal{H}}{\partial W} = -pf'(h + \beta W)\alpha\beta + \mu [s_0 - m(r)] \quad (12)$$

Using μ_0 to denote the value $\mu(0)$, the transversality condition requires

$$\mu_0 = g'(W_0) \quad (13)$$

which makes sense, since $\mu(x)$ is the value to the rest of the landscape (locations beyond x) of having one more unit of wild bee stock at point x , so the marginal value of having one more unit of wild bee stock at the habitat boundary, μ_0 , is equal to the marginal cost of generating this extra unit, $g'(\cdot)$.

The final first order condition relates to the choice of honey bee stock:

$$\lambda = C'(N_0). \quad (14)$$

Since the shadow price of honey bee usage is the value of having one more unit of honey bee stock, at the margin this must equal the marginal cost of acquiring this unit. This marginal cost can be construed as the supply function function of honey bees, or simply the price on the spot market for honey bees, which remains consistent with the interpretation that λ is the rental rate of honey bees.

Characterizing the Optimal Paths

To solve this problem, we first look at the optimal allocation of honey

bees over the landscape. The binding stock constraint reflects the scarcity of honey bee hives, and importantly, generates the shadow price of honey bees endogenously. At this juncture we are assuming the supply function of honey bees $C(N_0)$ is given. The farmer employs honey bees provided the value of marginal product exceeds the shadow price. Of course, with a sufficient availability of wild bees, this may not hold for land close to the natural habitat. We define the point $x_1 \in [0, X]$ within which crops rely exclusively on wild bees and at distances beyond x_1 , honey bees hives are rented. Then for $x > x_1$, a positive value in the control $\hat{h}(x) > 0$ satisfies (11) with equality, and the shadow price is determined,

$$\lambda = pf'(\hat{h}(x) + \beta W(x)). \quad (15)$$

Note that the shadow price λ does not depend on location – the price of honey bees is uniform on the landscape. Differentiating (15) with respect to x and substituting back in 2 we find

$$\dot{h} = -\frac{pf''(h + \beta W)}{pf''(h + \beta W)}\beta(-sW) = \beta sW > 0, \quad (16)$$

which implies optimal honey bee allocation increases with distance from the habitat boundary. This makes sense since honey bees are naturally substituting for the diminishing supply of wild bees.

To investigate optimal restoration we proceed by assuming that for some x , (10) is satisfied with equality – that is, there is an interior solution for r , which we denote $\hat{r}(x)$. We can rewrite (10) to form the following equation for the co-state variable

$$\mu = \frac{1}{m'(r)W}, \quad (17)$$

which ensures that $\mu > 0$. Differentiating (10) with respect to x , and substi-

tuting in (17), we know that along an optimal path of restoration investment,

$$\dot{r} = pf'(h + \beta W)\alpha\beta \frac{m'(r)^2}{m''(r)} < 0. \quad (18)$$

The only non-positive element of the RHS is $m''(r) < 0$, so it must be that for $\hat{r}(x) > 0$, restoration projects decrease with distance from habitat source. This implies optimal farmland restoration would focus greater effort on land closer to natural habitat. This makes intuitive sense since land closer to the natural habitat boundary have more native bees with which to spread over the landscape; reducing the rate of spatial decay has a larger impact with a larger population. Land far from the natural habitat, with scant wild bees, might likely not find positive net benefits for farmland restoration. We define the point $x_2 \in [0, X]$ beyond which restoration investment is no longer optimal.

Optimal resource allocation in a many-small-farm regime

We now consider the case where the downstream benefits of restoration are ignored and farm managers take wild bees as fixed. The problem is solved then in a two-stage maximization approach (Brown et al. [2002]). At each location x , firms choose inputs ($h(x)$) given the availability of wild bees ($W(x)$), and an exogenously determined honey bee rental rate (λ^c):

$$\max_h pf(h + \beta W(x)) - \lambda^c h$$

which yields a solution $\hat{h}^c(\lambda^c, W(x))$. which clearly has the properties of (16). A social planner then chooses honey bee stock (N_0) and wild bee stock in

the habitat (W_0) to maximize

$$\max_{W_0, N_0} \int_0^X \left[pf \left(\hat{h}^c(\lambda^c, W(x)) + \beta W(x) \right) \alpha \right] dx - g(W_0) - C(N_0)$$

$$s.t. \quad \dot{W}(x) = -s_0 W(x) \tag{19}$$

$$W(0) = W_0 \tag{20}$$

$$\int_0^X \hat{h}^c(\lambda^c, W(x)) \alpha dx \leq N_0 \tag{21}$$

$$\hat{h}^c(x) \geq 0 \tag{22}$$

The first order conditions (11) and (12) (with the substitution s_0 for s) along with the transversality condition (13) are necessary for a maximum to this problem as well.

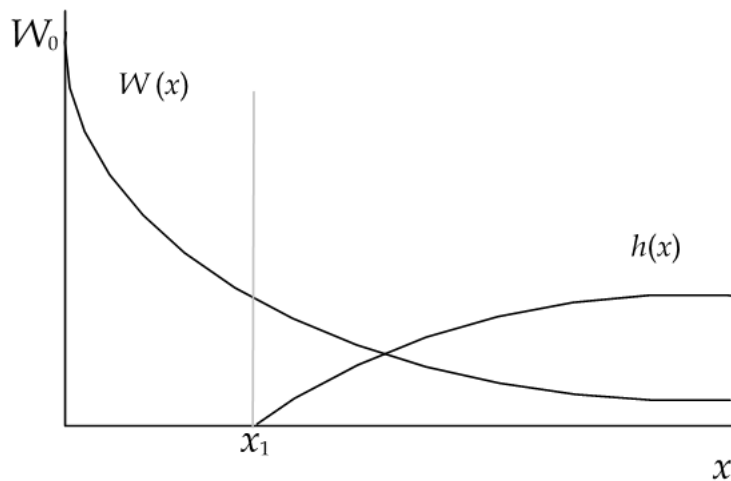
Characterizing the Optimal Paths

This problem is more tractable. Since no actions are taken to influence the spread of wild bees, their distribution can be determined based on its initial population stock at the natural habitat boundary. We can solve the first order differential equation (1) by the method of separation of variables and using the initial condition $W(0) = W_0$, we have wild bee density

$$W(x) = W_0 e^{-s_0 x} \tag{23}$$

The outcome can then be solved numerically with specific parameter values and the optimal paths graphed as in Figure 2.

Fig. 2: Example Solution Path: Model 2



Comparing outcomes

Using the conditions above and comparative statics on the variables, we have the following relationships:

$$W_0^* > W_0^c \quad (24)$$

$$x_1^* > x_1^c \quad (25)$$

$$x_2^* > x_2^c = 0 \quad (26)$$

where superscripts (*) and (c) denote regimes 1 and 2, respectively. Diagrammatically, we summarize the findings in Figure 3.

Conditions (24) and (26) say that under a holistically managed landscape regime in which the spatial benefits of habitat restoration on farmland are captured, there is greater investment in restoration – both at the source and on the farmland. These implicate condition (25), which says a larger portion of the landscape relies solely on wild bees.

We can also think about these results in terms of social investment in

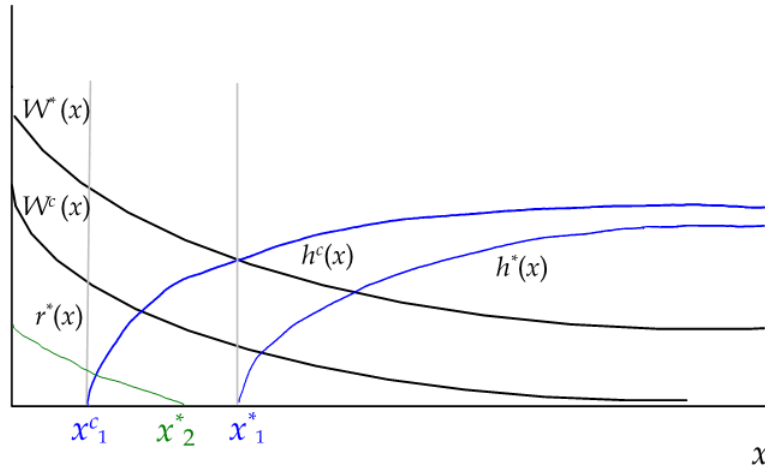


Figure 3: Optimal allocation of wild bees, honey bees and restoration investment under one-farm regime (*) and many-small-farm regime (c).

pollination resources: when the spatial externalities of habitat restoration can be internalized, the native bees are more highly valued and thus there is more investment in their stock. This extra investment of course comes at the expense of bringing more honey bees to the landscape.

Equations (24-26) inform the welfare implications of the two regimes. With restoration at both the source and on the farms, more land benefits from having surplus pollination from wild bees and less land must rent honey bees. Thus the region of land $[x_1^c, x_1^*]$ benefits in terms of yield increase and input cost savings. Land close the habitat ($x < x_1^c$) have even greater abundances of wild bees and thus may experience increased yields. Land far enough from the habitat that they must be renting honey bees regardless are unlikely to be affected one way or the other under either scenario.

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