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Partitioning private and external benefits of crop pollination services

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Abstract

1. Ecosystem services (ES) provide a range of benefits to people, but landowners that produce ES are often separate from those receiving benefits. As a result, landowners bear the costs of managing ecosystems, but often share the benefits with others. Accounting for these private and external costs and benefits would improve the effectiveness of payments for ES management.
2. We develop a spatially explicit ES modelling approach to evaluate the alignment of private and external benefits resulting from habitat enhancement for pollinators. After testing the model on synthetic landscapes, we applied it to Yolo County, California, using information on crop type, value per acre and dependence on pollination. Detailed data on parcel ownership allowed us to distinguish private and external costs and benefits of enhancing habitat on any parcel.
3. We found that around 13% of the landowners would generate private benefits that exceed private costs, 47% would generate external benefits greater than private costs, and the remaining 40% would generate neither private nor external benefits greater than private costs. Landowners generating private net benefits had larger fields, more valuable crops and more pollinator-dependent crops than the other owners.
4. These results reveal mis-alignments between private and external incentives. Just over half of the Yolo County landowners' pollinator enhancements would produce external benefits, but only 25% of these would have private incentives to do so. We estimated that enhancements by those acting privately could increase the private net present value of crops by $495,309 and provide a total external benefit of $1,193,345. The remaining 47% of landowners' enhancements generated $1,409,247 in additional net external benefits.
5. Accounting for heterogeneity in enhancement benefits due to ownership and crop characteristics allows one to distinguish contexts where enhancements should be managed by groups as a common-pool resource or by individuals. Rather than fund a PES program to pay for enhancements, effort could be directed towards communicating with landowners about potential private benefits and facilitating common-pool resource management. Overall, this analysis reveals

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the importance of partitioning private and external benefits of actions designed to provide ES.

KEYWORDS
agriculture, bees, common-pool resources, ecological economics, ecosystem services, PES, pollination

1 | INTRODUCTION

There is increasing recognition and evidence that humans receive a variety of benefits from ecosystems, that is, ecosystem services (ES; Daily, 1997). As institutions, organizations and governments move to integrate the supply of ES into land use planning and policy decisions (Rosenthal et al., 2015), there is critical need to more clearly account for spatial heterogeneity in this supply. Tools that provide information on ecosystem service production and valuation, such as InVEST (Sharp et al., 2018), have facilitated development of policies designed to increase the supply of the service and a landscape's overall economic value (Nelson et al., 2008; Polasky et al., 2008). However, these types of analyses typically ignore specific beneficiaries, focusing on the total benefits to a region.

One important issue complicating the science and management of ES is that people and landscapes that produce ES are often separate from those receiving the resulting benefits (Mitchell et al., 2015; Polasky, Lewis, Plantinga, & Nelson, 2014). Unfortunately, ES assessments and the policies designed to capture their benefits rarely are explicit about the beneficiaries of ES and who benefits and pays the costs as ecosystems change (Mandle, Tallis, Sotomayor, & Vogl, 2015). In other words, ES involve economic externalities, such that the consequences of actions taken by one individual have costs and benefits to others, that is, external to the individual taking the action. For example, land management by upstream farmers can improve or degrade water quality and availability to downstream urban centres (Grima, Singh, Smetschka, & Ringhofer, 2016). By more accurately measuring the externalities and attributing the distribution of costs and benefits to include them, one can design payment schemes or incentive programmes that lead to improved outcomes for all affected participants in a landscape (Lewis & Polasky, 2018; Polasky et al., 2014).

Economists have long been aware of these externalities. Meade (1952) conceptualized externalities drawing on the benefits an apple grower provides to a commercial beekeeper through the provision of floral resources that influence honey production. Although Meade laid out the initial theory, few studies since then have quantified the socio-ecological dynamics that define the flow of benefits from one individual to another. As a result, most ecosystem service-based policies are designed to cover only private costs (opportunity and transaction) of landowners providing services, because external benefits have not been enumerated (Engel, 2016).

Payment for ecosystem service programs (PES) typically arrange for suppliers of a service to be compensated by those who receive that service (Zanella, Schleyer, & Speelman, 2014), thus ‘internalizing’ the externality for suppliers. For example, the US Department of Agriculture's conservation reserve program (CRP) is a PES that attempts to account for external benefits by paying farmers to remove erodible land from agricultural production to protect or enhance water quality. Instead of compensating farmers for the marginal social value of the ES provided, however, CRP makes rental payments only to offset opportunity cost resulting from reduced crop area and production. A few studies have shown that total public benefits of the CRP program in terms of nutrient and sediment reduction can far outweigh the rental fees (private benefits) provided by those programs (Johnson et al., 2016; Keeler et al., 2016). On the other hand, farmers themselves do not only incur costs of restorations. They receive some private benefits from the program; for example, soil conservation that maintains soil fertility on the farm itself. The CRP program and others like it are therefore undervaluing farmer actions by failing to fully partition the components of public benefits, that is, the private and external benefits.

Better quantifying the distribution of costs and benefits across beneficiaries would improve the effectiveness and efficiency of land use decisions and policies by identifying which of three potential contexts occur: (a) Private benefits of a given management practice (e.g. soil conservation) are greater than private costs. (b) Private costs are greater than private benefits but are less than external benefits. (c) Neither external nor private benefits alone outweigh costs. Designing efficient PES therefore depends on understanding the relationship between private benefits, for example, soil fertility for landowners, the external benefits, for example, water quality for downstream cities and the private costs of supplying an ecosystem service, which are typically borne by the landowner.

Crop pollination is a great example of a valuable common-pool resource (Ostrom, 2000) that provides both private and external benefits. Animal pollination benefits ~70% of major global crops (Klein et al., 2007), with the majority of that pollination service provided by bees. Managed honey bees are often used for pollination, but their supply is becoming increasingly uncertain (Aizen & Harder, 2009). As a result, incorporating native, wild bees in pollination management have become more common (Garratt, Brown, Hartfield, Hart, & Potts, 2018; Isaacs et al., 2017). Often, pollinator habitats are enhanced near farms to augment the supply of bees, and the resulting increased pollination has been shown to improve yields (Blaauw & Isaacs, 2012). Importantly, many bee species forage 100–1,000 m from nest sites, so enhancements have the potential to provide external benefits to neighbours as well. The relative benefits to the land-owner and their neighbours likely depend on several factors as follows: locations and sizes of crop fields and enhancements (Williams, Isaacs, Lonsdorf, Winfree, & Ricketts, 2019), crop values and dependences on pollinators (Klein et al., 2007) and the overall abundance of bees in the surrounding landscape (Ricketts & Lonsdorf, 2013).

Here we develop a spatially explicit ES modelling approach to quantify both private and external benefits and costs of land use change on crop pollination services in a real landscape. Cong, Smith, Olsson, and Brady (2014) used an agent-based model to simulate differences between farm-scale and landscape-scale management of a pollinator-dependent crop. They used the simulations in a virtual landscape to identify potential tensions arising from what is best for individual farmers versus what is best at the landscape scale. They concluded an incentive-based system that could work to support common-pool resource management but would require accurate information on the distribution of benefits, but stated that it is highly unlikely for farmers to possess such knowledge. Our work builds off of Cong et al.'s simulation study and extends work by Ricketts and Lonsdorf (2013), who focused on aggregated benefits for an entire landscape, to account for specific costs and benefits for each individual landowner. Recognizing that common-pool resources like wild pollination services cannot be managed well without proper knowledge of their distribution with respect to ownership boundaries (Ostrom, Chang, Pennington, & Tarko, 2012), we address the following questions:

1. How well do private benefits align with external benefits of establishing floral enhancements across the landscape? How do landscape context, field size, crop value and its dependence on pollinators affect this alignment?
2. Where would enhancements be beneficial privately versus externally?

To answer these questions, we use landownership information to partition external from private benefits. We address the first question using a virtual landscape where we can precisely control landscape context, ownership, field size and crop dependence on pollinators. We then address the second question with a real landscape using publicly available data from Yolo County, California, USA, an area that produces a variety of pollinator-dependent crops with many owners. We use insights from our controlled analysis of the virtual landscape to understand results from the real landscape.

2 | METHODS

2.1 | Pollination model

Because the model has been published and described elsewhere we provide a brief description here, but see Lonsdorf et al. (2009), Lonsdorf et al. (2011) for full description and Kennedy et al. (2013) for a meta-analysis of its validation with empirical data. The model first determines an index of pollinator supply (0–1) coming from each map unit. Then the model uses the pattern of supply to estimate the potential abundance of pollinators that could visit a crop from each supply unit in the landscape. Bees require nesting and forage resources and the model assumes that the suitability of these resources varies among different land cover types, such the model first rescales each land cover from 0 to 1 to represent quality of nesting or quantity of floral resources respectively. The supply of bees is highest when the quality of nest site i, N_j, is high (e.g. 1) and the forage quantity of each of the n surrounding sites j, F_j, is also high such that the supply of bees from nest site i, S_i, is:

$$S_i = N_i \frac{\sum_{j=1}^{n} F_j e^{-D_{ij}/\alpha}}{\sum_{j=1}^{n} e^{-D_{ij}/\alpha}}, \quad (1)$$

where α represents the average distance a bee will fly to forage and D_{ij} represents the distance between nest site i and floral resources on site j. The resulting supply index ranges from 0 to 1 and is meant to represent the relative fitness of bees at nest site i.

The next step of the model estimates the total visitation from bees as they leave each nest site i to visit crop parcel j. The model makes several assumptions in predicting relative visitation rate, such that it should: (a) increase with increasing supply of bees coming from nest site i, (b) decrease with increasing distance between nest site i and crop parcel j and (c) decrease exponentially with increasing distance such that total pollinator visitation to each crop parcel j the surrounding n sites in the landscape, ρ_j, is:

$$\rho_j = \frac{\sum_{i=1}^{n} S_i e^{-D_{ij}/\alpha}}{\sum_{i=1}^{n} e^{-D_{ij}/\alpha}}, \quad (2)$$

Here we model a single 'proto-bee' to represent the community of pollinators rather than model a single species and separate models for each crop. We used floral and nesting value estimates from Koh et al. (2016; Table S2), average across flora seasons and nesting guilds, respectively, and used 670 m as the estimate for α, following Ricketts et al. (2008).

The model assumes that as the pollinator visitation index on crop parcel i, ρ_i, increases, the expected crop yield, y_i, increases. The model also allows for the dependence of the crop yield on pollination services, d_c, to differ among crop species or cultivars. The model predicts the relative yield of crop parcel i, y_i, as a function of the pollinators visiting parcel i, ρ_i:

$$y_i = d_c \left(1 + k_c\right) \frac{\rho_i}{\rho_i + k_c} + (1 - d_c), \quad (3)$$

where d_c is a value between 0 and 1 represents the proportion of yield that crop species or cultivar c depends on animal pollination (e.g. d_c is 0 for corn). The parameter, k_c is a half-saturation constant representing the visitation needed to meet 50% yield and is specific to each crop type or cultivar c. As k_c decreases towards 0, nearly 100% yield can be achieved with few pollinator visits. Overall, the function assumes diminishing returns with increasing visitations such that rate of increase in yield slows with increasing visitation. The term, $1 + k_c$, ensures that the yield function is scaled from 0 to 1.

The net present value of pollination for parcel i, V_i, is the product of the maximum value per unit area for crop c, ψ_c, and the relative yield from the equation above, y_i, summed over time t with value each year declining as a function of discount rate δ:

$$V_i = \sum_{t=0}^{T} \frac{\psi_c y_i}{1+\delta^t}. \tag{4}$$

Rather than choose a specific length of time or discount rate, we evaluated 12 scenarios to determine whether our results were sensitive to these values. Restorations often require some management after 5 years and enrolment in CRP is based on a 10-year agreement, so we analysed a combination of three time frames (5, 10 years and an infinite time horizon) with four discount rates (3%, 5%, 7% and 10%). We use the lowest three discount rates to represent a range of social discount rates that are consistent with some recent assessments (Kweun, Wheeler, & Gifford, 2018; Nordhaus, 2017), while the highest discount rate provides an upper bound to allow for a potentially higher private discount rate. Here we report the net present value for an intermediate combination of time frame and discount rate (10 years with 5% discount) and report all other values in the supplemental material.

2.2 | Quantifying and partitioning benefits

2.2.1 | Total benefits

We apply the marginal value approach Ricketts and Lonsdorf (2013) laid out to estimate the total benefits resulting from the addition of a pollinator enhancement. We define map unit i's potential benefit as the change in value that results from land cover change at that site less the cost of the enhancement. We simply use the model to calculate the difference in this value resulting from any land cover change. The total benefits of an enhancement of unit i provided by landowner k, TB_{ik}, is thus:

$$\mathrm{TB}_{ik} = \sum_{j=1}^{N} V_j\,(i = \text{Enhanced}) - \sum_{j=1}^{N} V_j\,(i = \text{Current}) - \varphi_{ik}, \tag{5}$$

where V_j is the net present value of parcel j and φ_{ik} is the cost of pollination enhancement paid by owner k on unit i. This first summation term represents the total expected crop value from all N parcels in the landscape after an enhancement and the second summation is the total value prior to the enhancement. We assume that enhancements would bloom within a year of planting (reasonable for California) and that a farmer incurs the enhancement cost only once, so the first two terms are sensitive to the assumptions of discount rate while the enhancement cost is not. Opportunity costs resulting from an enhancement replacing crop production is intrinsic to the model. When an enhancement replaces a crop, the yield will have to increase on the rest of the field for the private benefit to be positive.

2.2.2 | Private benefits

Private benefits represent the subset of total benefits that are provided to the landowner who provided the enhancement. We assume that the landowner incurs all the costs of the enhancement such that the private benefits to owner k of an enhancement of unit i, PB_{ik}, is:

$$\mathrm{PB}_{ik} = \sum_{j=1}^{N} x_{jk} V_j\,(i = \text{Enhanced}) - \sum_{j=1}^{N} x_{jk} V_j\,(i = \text{Current}) - \varphi_{ik}, \tag{6}$$

where x_{jk} is a variable indicating ownership and is equal to 1 if the pixel j is part of owner k's farm and 0 otherwise.

2.2.3 | External benefits

External benefits are the portion of total benefits that are not considered private. Here these are the benefits provided by owner k, who pays for the pollination enhancement, to all parcel j's by someone other than:

$$\mathrm{EB}_{ik} = \sum_{j=1}^{N} \left(1 - x_{jk}\right) V_j(i = \text{Enhanced}) - \sum_{j=1}^{N} (1 - x_{jk}) V_j(i = \text{Current}). \tag{7}$$

2.3 | Applying modelling framework to virtual and real landscapes

2.3.1 | Virtual landscape

We used a virtual landscape to explore how field size, the proportion of a field being enhanced and the crop's dependence on wild bees affect the magnitude and structure of benefits in silica. The virtual landscape consists of a 6 km × 6 km area made up of two cover types: (a) bee habitat, which provides suitable nesting and floral resources for bees ($N = 1$ and $F = 1$) and (b) crops that provide minimal nesting or floral resources for bees. We selected a parcel as close to the centre of all parcels to have the enhancement. We used the pollination model described above to calculate the crop value on each pixel. We overlaid a simple gridded ownership map within the landscape roughly 1.5 km from the edge to avoid any edge effects such that the size of the landscape where ownership was assigned was 3 km × 3 km or 9 km^2 (Figure 1).

We used this simple landscape to control the proportion of crop and bee habitat in the landscape, the parcel size, crop value (ψ_c) and the dependence of the crop on bee pollination (d_c) and then explicitly aggregate benefits and costs for each owner. Under different scenarios, we first simulated the value of crops for each owner. We then selected a single owner near the middle of the landscape, simulated a restoration of bee habitat and recalculated the crop value of all pixels, and determined the resulting benefits and costs to each owner as well as the private and external benefits (Figure 1).

We repeated the above process under different contexts generated by varying pollinator habitat quality in the landscape,

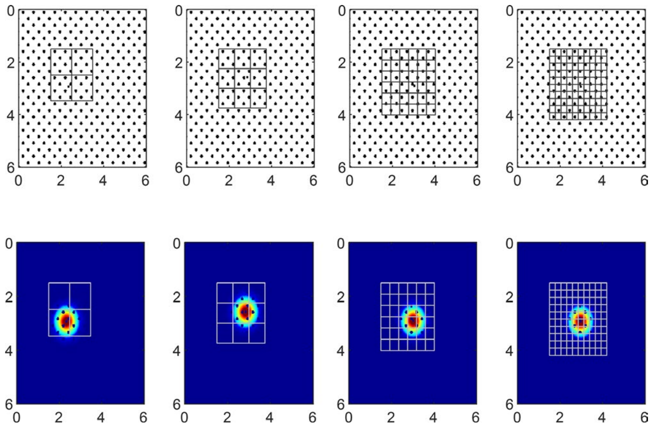

FIGURE 1 Ownership scenarios used in virtual analysis. Each panel represents the 6 km × 6 km landscape with inner lines representing boundaries of landownership parcels within it. Each panel in the top row depicts an identical pattern of land cover where the white areas represent a pollinator-dependent crop and the dark patches represent natural habitat that is ideal for pollinators. We varied the ownership patterns from a few large parcels to many small parcels. The bottom row of panels represents the change in crop value in the landscape arising from a single enhancement placed on the middle edge of one parcel (blue is no change and red indicates relatively large increase)

parcel size, crop value and crop dependence on pollination. We selected contexts to represent a range of observed values in Yolo County, California. We used nine field sizes by splitting the 9 km^2 into fields of equal size with 2–10 parcels on a side (4–100 parcels) resulting in fields that ranged in size from 225 to 9 ha. We evaluated 10 scenarios of pollinator dependence (i.e. from 5% to 95% with increments of 10%), three levels of crop price (i.e. $5,000, $10,000 and $15,000 per acre) and three levels of habitat context by varying the overall percentages of crop habitat and pollinator habitat (i.e. 95% crop with 5% pollinator habitat, 85–15 and 75–25 respectively). For each combination of field size and dependence on pollination we calculated the total, private and external benefits for each landowner resulting from the action of a single landowner. We used Matlab (The MathWorks, Inc., Natick, MA, USA) for simulation and analysis of the virtual landscape.

2.3.2 | Case study: Yolo County

Yolo County, California, USA, is located in the northern part of California's central valley and contains a variety of agricultural crops, including many that are dependent on bee pollination. The underlying pollination service model has been shown to be a relatively good predictor of pollinator abundance and pollen deposition in the county (Lonsdorf et al., 2009), and there is a gradient of wild bee habitat quality. Crop parcels vary in size from a few acres to a few hundred acres.

To estimate the value of crops resulting from wild pollination, we combined the USDA's crop data layer (CDL; USDA-NASS, 2014) with publicly available tax parcel data and crop information in Yolo County for 2014 (Yolo County California, 2014). The parcel data from Yolo County describes 342 different cover types for crops, far more than is described by the USDA's CDL, so we collapsed these types into those found in the CDL. Table S1 provides information on how we reclassified the Yolo County data into the CDL. We followed methods described by Koh et al. (2016) to translate the cover types into floral and nesting values needed to calculate the pollinator visitation index. We used reported harvested crop values for California from the 2014–2015 California Agricultural Statistics Review (2015) to estimate crop values (see Table S2 for full parameter estimates for each cover type). We assume that production costs are not sensitive to the changes in yield such that the net benefits calculated from changes in pollination services are due to changes in pollinator supply. The county parcel data delineated specific crops and identified the owner of each parcel via a unique owner ID, and these data allow us to aggregate each parcel's value by owner so that we can partition benefits into external and private components. Figure S1 illustrates example input layers for the analysis.

To determine the potential private and external benefits for each parcel, we applied the marginal value framework (Ricketts & Lonsdorf, 2013) and used costs of creating a floral and nesting-rich enhancement from Williams et al. (2019) which estimated it to be $4,446 per hectare in Yolo County. Williams et al. provide full detail for the components of those costs. We assumed for simplicity that the enhancement cost was not a function of crop type. We first evaluated the value of the current Yolo landscape and attributed crop value to each of the landowners. Then, we systematically converted a single 0.81 ha cell (equal to one 90 m × 90 m pixel) from its current land cover into ideal habitat for pollinators and recalculated the crop value for the entire landscape and for each owner. We identified the location of an enhancement that provided the greatest increase in value to the owner. For example, if there were three cells owned by the same landowner where private benefits were greater than cost (~$3,600), we chose the site that had the greatest private benefit as the site of an enhancement. We compared the value before and after this habitat enhancement for each landowner which allowed us to determine the total, private and external benefits of the enhancement.

3 | RESULTS

3.1 | Alignment of private and external benefits

Private net benefits (benefits—costs) are typically negative (Figure 2), indicating that the private costs of enhancements borne by landowners often exceed the private benefits. External net benefits, in contrast, are always positive (Figure 2), because neighbours bear no enhancement costs. Overall total net benefits (the sum of private and external) are relatively equally divided between positive and negative values (Figure 2).

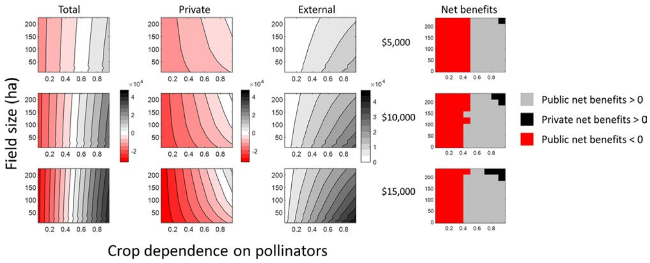

FIGURE 2 Effects of ownership and crop context on total, private and external benefits. Results of virtual analysis analysing effects of crop dependence on pollinators (*x*-axis), field size (*y*-axis) and the value of the crop (panel row) on total benefits (first panel column), private benefits (second panel column), external benefits (third panel column). The last column separates contexts where private (black) or public (red) benefits are greater than costs from contexts where costs are greater than benefits (grey). For the panels representing total, private and external benefits, the filled contour plots are coloured red to black representing negative to positive benefits of the enhancement. External benefits are always positive. For the last column of panels, black indicates that private net benefits are above zero, red indicates that external benefits exceed private costs and grey indicates that the costs outweigh the benefits

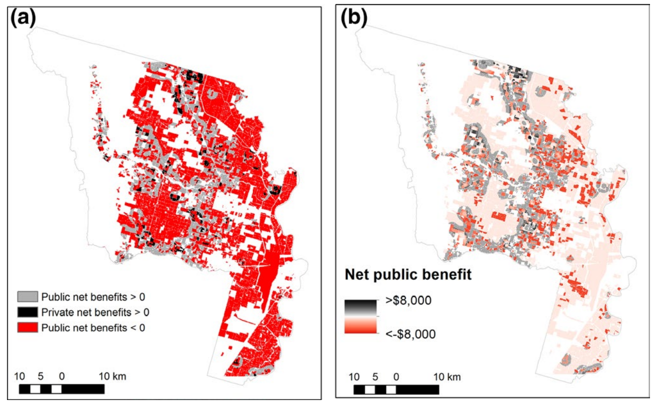

FIGURE 3 Maps illustrating whether private or total net benefits are positive (A) and illustrating total net benefits of enhancements in Yolo County, California (B). Panel A partitions locations of positive benefits into those where private benefits are positive (black) and those where private benefits are negative but total benefits are positive overall (red). In panel B, total net benefits represent the value of adding an enhancement minus the opportunity and enhancement costs independent of land ownership. Black to gray represent positive benefits while pink to red colors represent net loss

Total, private and external benefits all vary as a function of crop value and crop's dependence on pollination, but private and external benefits depend on parcel size while total benefits do not (Figure 2). Private and external benefits increase as crop value increases and as the crop's dependence on pollinators increases. Private and external benefits respond inversely to field size, however, with private benefits increasing with increasing field size while external benefits decrease.

Given the contexts explored and assumptions of the models, areas where private benefits were greater than costs (Figure 2, last column in black) occurred only at the largest field sizes and with crops that were highly dependent on pollinators. Contexts in which external benefits were greater (red), however, occurred as long as crop dependence on pollinators was 45%–55% depending on the value of the crop.

3.2 | Identifying enhancements with highest return on investment

We found that our results were not sensitive to the choice of discount rate or the time frame. We report net present value of 10-year period and 5% discount and provide the full results in Table S3. Of the 574 landowners evaluated in Yolo County, 73 had at least one location on their parcels where an enhancement would produce private benefits that were greater than private costs (Figure 3a, black), an additional 268 landowners had locations where total benefits were greater than the private costs (Figure 3a, grey) while the total benefits were less than private costs for the remaining owners (Figure 3a, red). Figure 3b illustrates the pattern of total net benefits for each potential location independent of landownership. Note that highest net total benefits (black in Figure 3b) are not always predicted to have positive net private benefits (black in Figure 3a). This would indicate that those landowners have a relatively small field (Figure 2 fourth column of panels).

Similar to virtual landscapes, Yolo County parcels with positive private net benefits were on average larger, had crops with higher dependence on pollination and had crops of higher value, compared to parcels where private net benefits were negative (Table 1). In locations where private or total benefits were greater than costs, the opportunity cost (value of the crop the enhancement replaced) was also much lower than parcels where private net benefits were negative. Parcels where the external benefits outweighed private costs were found in smaller parcels, with relatively large variation in crop dependence on pollination and crop value.

3.3 | Potential benefits from enhancements with private versus total incentives

If owners of all 73 parcels with positive private net benefits invested in enhancements, they would create a private net present value of $495,309 and provide a total net benefit of $1,193,346 in Yolo County. These benefits would result from roughly 50 enhanced hectares and would thus provide total net present value of just over $20,000 per hectare enhanced.

If owners of the additional 268 parcels with positive total net benefits invested in enhancements, they would collectively incur a net loss of $1,046,544 but lead to an increase in external net present value of $2,455,792 so total net benefit of over $1,400,000.

TABLE 1 Average characteristics of farms for which private or total benefits exceed costs of pollinator enhancements in Yolo County, California. Opportunity costs, private and total benefits are net present value based on 5% discount rate over a 10-year timeframe

Benefit > cost?	Number of owners	Field size (ha)	Dep. on bee (d_c)	Crop value	Opportunity cost	Private benefits	Total benefits
No	233	244	0.18	$3,452	$14,865	−$8,954	$2,776
Private	73	867	0.72	$11,266	$1,019	$6,785	$9,562
Total	268	141	0.10	$2,207	$1,098	−$3,905	$9,163

These total net benefits would result from roughly 181 additional enhanced hectares, resulting in a total net present value of nearly $6,500 per hectare.

4 | DISCUSSION

Who benefits from restoring pollinator habitats on farms—the landowner, the neighbours or both? Using spatial models in both virtual and real landscapes, we find that with this mobile ecosystem service that there is often a misalignment between external and private benefits. In our analysis of Yolo County, we found that it is often the collection of one's neighbours that benefits rather than an individual; total benefits were often positive, but private benefits rarely are. Pollinator enhancements by 50% of the landowners would provide positive total net benefits, but only 20% of these landowners would benefit themselves by doing so, that is, 10% of landowners overall. Some form of payment is needed for the rest. Overall, this analysis reveals the importance of including patterns of landownership and partitioning private and external benefits of actions designed to provide ES.

By accounting for heterogeneity in benefits due to size of property, value of the crop and its dependence on pollination, we provide an analytical framework for how costs and benefits are distributed among landowners, information that is essential for distinguishing when resources are managed by a group from those managed by individuals (Engel, 2016). In our simulations, landowners receive positive net benefits from enhancements if they own relatively large farms and grow valuable crops that depend highly on pollinators (Figure 2; Table 1). Under these conditions, landowners are able to ‘capture’ pollination services provided by the enhancements and are thus unlikely to need incentives. In contrast, we found that farmer-led cooperative efforts would be particularly important where the size of ownership is small and both the crop's dependence on pollination and the value of those crops are relatively high. With these heuristics, the efficiency and impact of incentive programs could be improved by understanding when and where each management approach is appropriate.

When landowners are projected to have positive private net benefits of enhancements, financial incentives are not necessary and effort could instead be focused on providing them information regarding the benefits of enhancements. Our results from Yolo County indicate that this context occurs for 10% of landowners who tend to have larger farmers with relatively valuable crops that have higher dependence on external pollination. Indeed, our analysis suggests these landowners could increase the net present value of their crop by an average of $6,785 *without* external incentives (Table 1; Figure 3a), while increasing the external net present value by an average of $9,562 (and collectively over $698,000).

Why do not farmers invest in enhancements given these projected benefits? It may be that farmers simply do not know of the potential benefits. Our in silica analysis, like several in situ studies (Blaauw & Isaacs, 2014; Castle, Grass, & Westphal, 2019; Kremen, M'Gonigle, & Ponisio, 2018), suggests that the value of an enhancement can be as valuable privately as many crops. Yet California, the state with largest demand for pollinators, currently has zero acres enrolled in the CRP, a program that would pay farmers when our results suggest there are cases where no payments are needed. The payments, however, are less than the value of the crop so farmers may perceive only that the opportunity cost is greater than any benefit. In a recent survey of Michigan blueberry farmers, however, Garbach and Morgan (2017) observed that the adoption of different bee management practices was positively correlated with farmer perceptions on the benefits of the practices and with the level of interactions with USDA's National Resource Conservation Service which would provide information on the benefits of enhancements. Thus, simply providing information to specific farmers could help increase the adoption of beneficial enhancements.

When private net benefits are negative yet total benefits of an enhancement are positive, common-pool resource management, rather than individual-based PES, may be more appropriate (Engel, 2016). Our analysis of Yolo County indicates that this occurs for 40% of landowners where farms that grow less valuable or less dependent crops, or farms that are small relative to the foraging ranges of bees. We observed that restoration would collectively reduce their private net present value by more than $1,000,000 but could provide an estimated net present value of more than $2,400,000 in external benefits to all other farmers. In several such cases, these enhancements were located on parcels without any crops at all. The insight here is that parcels with low opportunity costs, that is, low-value crops that also provide poor habitat for pollinators, may provide pollination services more cost effectively than enhancing habitats on neighbouring farms with high value crops. Thus, cooperative management of landscapes to improve efficiency of pollination services is essential.

Current incentive programs (e.g. CRP, EQIP) typically account only for opportunity costs of lost acreage and thus ignore private benefits of improved yields on remaining crops or external benefits to neighbours (Engel, 2016). The CRP has a specific cover practice designed to support pollinators, but the incentives again are designed only to cover the costs to farmers instead of the potential benefits to farmers and their neighbours. Specifically, our analysis provides explicit information on who benefits from action such that a group of neighbouring farmers may be more effective by setting payments based not on willingness of the landowner to accept, but instead on the collective external benefits of restored habitats and the expected yield increases for the participating landowner and neighbours (Engel, 2016).

Rather than use public funds to pay for enhancements, effort could be directed towards improving the information needed to build effective local cooperation. A centralized official in the area could provide two roles—knowledge provider and facilitator. On parcels where private net benefits are positive (i.e. black areas in Figure 3a), this official could inform landowners of likely positive private net benefits from enhancements, and act as a facilitator to help farmers engage cooperatively to identify effective placement of enhancements that provide net benefits to all parties (Cong et al., 2014; Ito, Feuer, Kitano, & Komiyama, 2018). Koh et al.'s (2016) national pollinator analysis, which identified US counties with relatively high demand for pollination but relatively low supply of wild bees, could be used for further identifying where to target these engagement efforts.

While our analysis provides detailed information on the flow of benefits from one landowner to another, it is important to recognize the caveats of our assumptions and discuss opportunities for improving the work. Our yield equation does not include the influence of managed honeybees. Ideally, knowledge of how the integrated management of pollination using both managed and wild bees (Isaacs et al., 2017) predicts yield could be used to guide management. The placement of hives could then also be viewed as a common-pool resource problem, but few studies exist relating that managed hive density to crop yield (but see Cunningham, Fournier, Neave, & Le Feuvre, 2016). This uncertainty provides a great opportunity for research to continue to monitor the benefits of enhancements and other nearby natural areas to crop parcels and to use this data to improve models like the one presented here.

The insights and conclusions gained from our work on pollination services applies to any ES with spatial flow from areas of supply to beneficiaries, such as water purification, flood control and pest control (Bommarco, Kleijn, & Potts, 2013; de Vries & Hanley, 2016; Zhang, Ricketts, Kremen, Carney, & Swinton, 2007). As we have shown here for pollination, spatial assessments that account for ownership can help to identify owners who can supply the greatest external benefits from ES. Ultimately, applying our growing understanding of the distribution of private and public benefits of ES should facilitate more cost-effective policies that better maintain the ES that support economies and livelihoods world-wide.

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CONFLICT OF INTEREST

The authors have no conflicts of interest.

AUTHORS' CONTRIBUTIONS

E.V.L., I.K. and T.R. conceived the ideas and designed methodology; E.V.L. collected and compiled the data needed for the analysis; E.V.L. and I.K. analysed the data; E.V.L. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Matlab code and data used to run analyses can be found at https://figshare.com/projects/Partitioning_private_and_external_benefits_of_crop_pollination_services/85031 (Lonsdorf, 2020a,b).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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