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Pest Control and Pollination Cost–Benefit Analysis of Hedgerow Restoration in a Simplified Agricultural Landscape

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Abstract

Field edge habitat in homogeneous agricultural landscapes can serve multiple purposes including enhanced biodiversity, water quality protection, and habitat for beneficial insects, such as native bees and natural enemies. Despite this ecosystem service value, adoption of field border plantings, such as hedgerows, on large-scale mono-cropped farms is minimal. With profits primarily driving agricultural production, a major challenge affecting hedgerow plantings is linked to establishment costs and the lack of clear economic benefits on the restoration investment. Our study documented that hedgerows are economically viable to growers by enhancing beneficial insects and natural pest control and pollination on farms. With pest control alone, our model shows that it would take 16 yr to break even from insecticide savings on the US$4,000 cost of a typical 300-m hedgerow field edge planting. By adding in pollination benefits by native bees, where honey bees (*Apis mellifera* L.) may be limiting, the return time is reduced to 7 yr. USDA cost share programs allow for a quicker return on a hedgerow investment. Our study shows that over time, small-scale restoration can be profitable, helping to overcome the barrier of cost associated with field edge habitat restoration on farms.

Key words: hedgerow, pest control, pollination, economics

Simplified agricultural landscapes are highly productive, but have low biodiversity due to the large-scale monoculture cropping systems having limited surrounding natural habitat. This lack of natural habitat leads to a loss of ecosystem service benefits such as water filtration, natural pest control, and pollination. Potentially, this deficit also causes costly water quality impairments, greater pesticide use, and a higher demand for a limited supply of managed honey bee hives for pollination on farms (Zhang et al. 2007, Rusch et al. 2016). As a result, there is wide-spread concern that simplified agricultural systems are not sustainable (Tilman 1999, Millennium Ecosystem Assessment [MEA] 2005, Hobbs 2007, Jonsson et al. 2015).

Farmers are the primary land-use decision makers for agricultural landscapes, and their land-use practices are mostly based on direct economic returns rather than environmental and social concerns such as biodiversity enhancement and ecosystem service benefits (Jackson et al. 2007, Pascual and Perrings 2007). Resultantly, there has been poor adoption of agri-environment and biodiversity enhancement incentives by landowners and farmers (Burton et al. 2008, Griffiths et al. 2008, Brodt et al. 2009, Carvalheiro et al. 2011). To overcome this barrier and increase the likelihood that farmers will adopt on farm conservation practices, direct economic benefits of habitat plantings need to be shown (Pascual and Perrings 2007).

Research shows that biodiversity and other ecosystem services can contribute to economic benefits to farming systems, particularly in pollination and pest control, that are quantifiable (Morandin and Winston 2006, Dale and Polasky 2007, Chaplin-Kramer et al. 2011, Winfree et al. 2011, Blaauw and Isaacs 2014, Morandin et al. 2014). However, studies on the impact of restoration projects on crop yield and profit are rare, and there are no studies that integrate multiple economic benefits of pest control and pollination in cropping systems (Griffiths et al. 2008, Garibaldi et al. 2014). With economic benefits differing between ecosystems, crops, and type of habitat planted, this information is needed to help growers make informed decisions on costs and direct economic returns of specific restoration practices to minimize risks on their investments.

Our study focused on restored California native, perennial plantings on field crop edges (herein referred to as hedgerows) in California's Sacramento Valley. We assessed the combined economic benefits of pest control and pollination ecosystem services in adjacent crops, at sites with and without hedgerows on field edges. We included the cost of installation of a standard hedgerow planting in this region, benefits from the potential reduction in pesticide

applications from natural pest suppression, and potential crop seed set increases from native bee enhancement due to farm-habitat restoration practices. These economic estimates were used to determine the net benefit of hedgerow plantings over time and how long it would take for the farmer to make a return on the investment.

Materials and Methods

The impact of field edge management on annual pollination and pest control services in adjacent crops was studied through a comparison of four hedgerow sites and four conventionally managed sites from 2009 to 2011. The study was in Yolo County, CA, an intensively farmed area with large-scale monoculture orchards and rotational field crops such as processing tomatoes and seed crops. The conventionally managed edges (herein referred to as controls) were mowed, disced, or sprayed with herbicides, but always had some residual vegetation with weeds germinating following the different management practices. The control edges represent the most common type of field edge in our study area, and during the cropping season, they generally are full of vegetation composed of mainly of nonnative grasses and nonnative flowering herbaceous plants. The hedgerows were planted about 10 yr prior to the study and consisted of mature California native, perennial shrubs and grasses including California buckwheat (*Eriogonum fasciculatum foliolosum*), California lilac (*Ceanothus griseus*), California coffeeberry (*Rhamnus californica tomentella*), Coyote brush (*Baccharis pilularis*), Elderberry (*Sambucus nigra*), and Toyon (*Heteromeles arbutifolia*) (Morandin et al. 2014). Each hedgerow field site was paired with a control site 1–3 km away, promoting independence of pollinator, pest, and natural enemy communities among sites, while maintaining treatments in similar landscapes and spanning the entire study area in all project years.

Hedgerow and control edges were ~300–350 m long (or if longer, we used 350 m) that bordered 16 ha to 32 ha processing tomato fields each year. We choose tomatoes as our adjacent crop because they are one of the most common, high-value crops in the region (Yolo County Crop Report 2014), permitting us to obtain sufficient replication of mature hedgerows adjacent to the same crop each year. To control for differences in field management practices, paired hedgerow and control fields were managed primarily by the same farmer. The processing tomato crops were conventionally managed, with the exception of one organic farm, and all sites were monitored and treated with insecticides for pest control when needed.

Pest control studies were conducted in 2009 and 2010 and reported in Morandin et al. (2014). Pollination studies were conducted on sentinel canola (*Brassica rapa* L. v. Eclipse) plants placed in tomato fields in 2010 and 2011. This methodology was used because processing tomatoes do not need pollinators for fruit set and we could not find fields of pollinator-dependent crops adjacent to a sufficient number of hedgerows. Canola was selected because this plant increases fruit set in response to pollinator visits, shows minimal self-pollination, and is easy to work with for pollination studies (Morandin and Winston 2006).

Hedgerow Cost

The one-time fixed cost of installing a hedgerow and maintaining it for the first three years was estimated by Long and Anderson (2010) using data from the establishment of the same hedgerows examined in this study. Their cost estimate was based on a 305-m-long hedgerow with a single row of shrubs, forbs, and perennial grasses planted along a field crop edge. The estimate included materials and labor for site design, field preparation, plants, weed control, irrigation, and vertebrate pest control. The total cost estimate for establishment of a hedgerow including labor was US$3,847, which we rounded up to US$4,000 for our model. Some of the hedgerows in our study were part of the Environmental Quality Incentives Program (EQIP), a United States Department of Agriculture (USDA) federal government cost share program, which usually covers 50% of habitat establishment costs (http://www.nrcs.usda.gov/wps/portal/nrcs/main/wi/programs/financial/eqip/). We therefore included models that account for a 50% establishment cost reduction to the grower. The establishment cost for the conventionally managed field edge was considered to be zero.

Long and Anderson (2010) noted minimal additional upkeep costs for hedgerows beyond the first three years of establishment that included mowing and herbicide use for weed control. As conventionally managed control field edges require similar yearly maintenance, in calculating differences between costs and benefits of the two edge types, we did not include a yearly upkeep cost in our model. We did not include crop losses due to a reduction in crop acreage as in our study area, hedgerows are planted on field edges and do not take land out of production. In addition, hedgerows of shrubs and grasses generally do not get big enough to cause adjacent crop losses due to competition for resources, so there was no need to include potential losses from factors such as shading.

Valuation of Pest Control Services

In 2009 and 2010 growing seasons, we monitored key pest species of processing tomatoes using University of California Integrated Pest Management guidelines (http://www.ipm.ucdavis.edu/PMG/C783/m783yi01.html). Pests included potato aphids (*Macrosiphum euphorbiae* (Thomas)), stink bugs (*Euschistus conspersus* (Uhler) and *Thyanta pallidovirens* (Stål)), tomato fruitworm (*Helicoverpa zea* (Boddie)), western flower thrips (*Frankliniella occidentalis* (Pergande)), and armyworms (*Spodoptera* spp.). Three times each season, from tomato bloom until shortly before harvest, we examined populations of pests, pest damage on leaves, and their economic control threshold levels. During the second and third crop assessments, we also quantified damage to fruit and pests on fruit. We conducted assessments at 10, 100, and 200 m along two transects into fields from field edges for a total of six sample locations in each field.

To estimate the economic benefit of hedgerows for natural pest control, we evaluated the difference between pest control costs with and without hedgerows in the proportion of fields that reached threshold pest or damage levels requiring control by insecticides as follows:

$$P_{PC} = \sum_{S=1}^{n} (W_S - H_S) C_S \quad (1)$$

Where P_{PC} is the average profit increase, in dollars, attributed to having a hedgerow adjacent to the field, W_S is the proportion of fields with conventionally managed edges, and H_S is the proportion of fields with hedgerow plantings that had pest populations or damage for species S at or above the recommended treatment threshold. C_S is the average cost for insect pest control for a typical processing tomato field in our study area, for pest species S (Miyao et al. 2008). In our model, revenues were considered the same between fields,

with growers having set contracts and prices paid per ton of tomatoes by the industry.

Valuation of Pollination Services

Measurements of pollination limitation (herein referred to as seed deficit) can be used to estimate profits resulting from differences in ambient pollinator populations among sites (Morandin and Winston 2006). To determine the impact of field edge management on crop pollination, we calculated proportional seed set deficit due to pollen limitation at four hedgerow and four control sites in 2010 and 2011 using sentinel canola plants in adjacent tomato fields. This approach isolated the effect of pollinators on seed yield by field edge treatment, which otherwise would vary due to factors such as crop type and field management practices.

We used 32 potted canola plants per site, in clusters of four placed along the two transects, as described in the pest control services section, at 0, 10, 100, and 200 m into the field for both hedgerow and control sites. We manually cross-pollinated two–three flowers on each plant to achieve maximum pollination and left three–four flowers on each plant open for pollination from ambient pollinator populations (Morandin and Winston 2006). In 2010, canola plants were placed in tomato fields for 5 h, and we conducted one, 4-min pollinator observation on each cluster of plants. In 2011, plants were in fields for 2.5 d and we conducted four, 4-min observations on each cluster (two on each of 2 d). During visual observations, we recorded all flower visitors that touched the reproductive parts (anther and stigma) of any mature flower in the cluster. The different types of flower visitors were recorded in citizen scientist monitoring (CSM) categories described in Kremen et al. (2011).

To measure pollination limitation, seed deficit was calculated at each location (location was defined as one set of four plants at each distance into each field) as the mean number of seeds per fruit from manually cross-pollinated fruit minus mean seeds per fruit from open-pollinated flowers, divided by full potential seed set at each location. Full potential seed set at each location was the mean of either seeds from manually cross-pollinated or open-pollinated flowers, whichever was greater (maximum seed set at that location). A greater difference in seed number between open and manually pollinated flowers indicated a greater degree of pollen limitation. If open-pollinated flowers resulted in pods with at least the number of seeds as fruit from manually cross-pollinated flowers, a zero pollination deficit was recorded, as a negative proportional seed deficit value is not meaningful.

Because native bees are the most important unmanaged crop pollinator (Klein et al. 2007, Garibaldi et al. 2013), and can be enhanced in adjacent fields by the presence of farm habitat restoration (Morandin and Kremen 2013, Garibaldi et al. 2014), we first calculated pollination differentials with all floral visitors. We then calculated pollination deficit differences due only to differences in native bee abundance, removing the contribution of honey bees and syrphid flies to discern the impact of native bee pollinators between our hedgerow and control field edge management practices. Bees considered native in our study, may not all have been native. In a previous study in the same region (Morandin and Kremen 2013) where we identified bees to species, ~2% of the non*Apis* bees were nonnative, naturalized species. In this study, the percent of nonnative, naturalized species in our native bee category likely was similarly low, and we therefore use the term native bee throughout.

In 2010, canola plants were in fields for only 5 h. By contrast, in 2011, plants were in fields for the life of the flower, allowing us to measure visitor abundance and seed deficit when most flowers were fully pollinated. To calculate the relationship between observed pollinator visitation and pollination deficit, we used the 2010 and 2011 data. We determined the relationship between floral visitor abundance and seed deficit using nonlinear regression of proportional seed deficit (bound at zero) on total number of pollinators observed at each location.

Using the estimated total floral visitor abundance and the relationship between visitor abundance and seed deficit (nonlinear regression), we then calculated an estimated seed deficit for the 2010 data, if the plants had been left out for the total flower life. We calculated regressions between the number of flower visitors observed in the first 4-min observation in 2011 to the total observed in 2011, over all four 4-min observations (one regression for each of the six CSM categories, at each site type) and used the regression equations to calculate estimated total floral visitor abundance, from each CSM category, for the 2010 data.

In order to observe the contribution of seed set from native bee pollinators, independent of honey bees and syrphid flies, we first determined pollination efficiency of each pollinator group. Contribution to seed set from one visit of each floral visitor group was experimentally determined in 2012 using methods outlined in Kremen et al. (2002). We set out potted canola (*B. rapa* v. Eclipse) plants at sites known to have high bee abundance and diversity. The evening prior to bringing plants out to the site, flower buds that were ready to open the next day were bagged with mesh bags. At the site the next day, observers removed bags on two–three flowers at a time, and observed these flowers until a pollinator had contacted the reproductive parts of the flower. Immediately after the pollinator left the flower, the flower pedicel was marked with acrylic paint in a color unique to that pollinator group (CSM group), and the baggie was carefully placed over the flower so that the flower was disrupted as little as possible and no parts of the baggie touched the flower. Plants were left undisturbed (other than periodic watering) for 2 d, so as to not move plants while experimental flowers were still in bloom. Approximately 20 d later, pods were harvested and seeds counted.

We compared these seed set values and if any were significantly different from average seed set, we used these seed set values to weigh relative contribution of each group when we removed a group from the pollinator deficit model. Because seed set contribution of each group did not differ ($F_{5,288} = 0.11$, $P = 0.99$), we did not include a pollinator efficiency in the model. We factored out estimated contribution of honey bees and syrphid flies to seed set at each location by subtracting their observed (2011 data) or estimated (2010 data) visits.

We used R Core (Team 2013) and lme4 (Bates et al. 2012) to perform a linear mixed effects analysis of the relationship between proportional seed deficit (arcsine-square-root transformed) and field type (control or hedgerow). Field type and distance were entered as fixed effects, and site and year as random effects. *P*-values were obtained by likelihood ratio tests of the full model with field treatment (hedgerow or control edge) against the model without field treatment. Proportional differences in seeds were used rather than absolute differences in seed number between open and manually pollinated flowers because maximal seed set may have varied among fields due to factors other than pollination, such as differences in microclimate and field conditions. If mean proportional seed deficit (calculated using 1. all floral visitors and 2. only native bees) was significantly different between site types, we then calculated the difference between the mean proportional increase in seed set (*PI*) due

to the presence of a hedgerow, as average PI at control sites minus PI at hedgerow sites. We expected hedgerow sites to have lower proportional seed deficit values than control sites, leading to $PI > 0$.

Assuming costs were held constant between the two treatments, we translated PI into profit change per unit area:

$$P_P = MV \times Y \times PI \quad (2)$$

Where P_p is the estimated change in profit ($) with a 305-m hedgerow, resulting from a change in seed set, MV is the market value per ton of the crop, and Y is the average yield per unit area (tons).

Economic Cost–Benefit Model Synthesis for Pest Control and Pollination

Using the insecticide treatment reduction and pollination increase data, we created a cost–benefit model for a hedgerow installation bordering two typical, 16-ha crop fields (one on each side). We have observed that it takes ~3 yr before plants are mature with floral resources, and therefore, net benefits were calculated starting at $Y > 3$. Estimated economic benefit to growers for establishing hedgerows, for each year (Y) after the third year of establishment was calculated as:

$$B_Y = \left\{ \sum_{Y=4}^{Y} \left[\frac{(P_P + P_{PC})}{1.05^Y} \right] \right\} - C \quad (3)$$

Where B_Y is the estimated net economic benefit in dollars per field at Y years, starting at $Y = 4$, from the time of initial restoration, P_p is the mean profit increase resulting from differential pollination deficit, between control and hedgerow sites, P_{PC} is the average profit change attributed to having a restored hedgerow adjacent to the field for pest control, and C is the cost of establishing and maintaining a 305-m hedgerow for the first three years. We took into account the time value of money (i.e., that money available now is worth more than the same amount in the future), and the uncertainty of future returns by applying a discount rate of 5%, such that profit each year was divided by 1.05^Y.

Results

Valuation of Pest Control Services

In 2009, one tomato field in the control group was treated for aphids. In 2010, three control fields and one hedgerow field reached the threshold for aphid treatment in our assessments. In total therefore, four of the eight control tomato fields and one of the eight hedgerow tomato fields reached thresholds and were treated for aphids. Using an average cost of one treatment for aphids of US$43.24/ha (Miyao et al. 2008), it would cost ~US$692 to treat a 16-ha field for aphids. With 4/8 or half of control fields needing treatment, that equals an average cost of US$346 per control field. When only 1/8 hedgerow fields require treatment for aphids, average costs for aphid control on hedgerow fields is US$86, 75% less per field than control fields. Although we sampled 200 m into fields from hedgerows, we calculated potential savings to a 16-ha field (400 by 400 m^2), as there was no decline in pest suppression of aphids up to the distance we measured (200 m from hedgerows; Morandin et al. 2014).

Few pests, other than aphids, were observed in our tomato fields at economic treatment threshold levels in the years of this study. Some fields were treated with sulfur for tomato russet mites (*Aculops lycopersici* (Massee)); however, we did not include this in our model because these mites are not effectively controlled by natural enemies and therefore their populations would not be impacted by the presence of hedgerows (University of California Integrated Pest Management [UC IPM] 2013).

Valuation of Pollination Services

The number of replicated pollinator visits for the canola pollination efficiency study was between 31 and 83 for all groups except the CSM group, "small dark bees" which only had 12 replicate visits. Pollination efficiency of each group, based on seed set from one visit from an individual of that group (number in brackets is average seeds per pod from one visit), was honey bees (3.0), syrphid flies (3.1), striped sweat bees (3.0), tiny dark bees (2.6), small dark bees (2.8), and hairy legged bees (2.9), with no significant differences between any group ($F_{5,288} = 0.11$, $P = 0.99$; Table 1).

In the studies with sentinel canola plants in the crop fields, there was no difference in total abundance of visitors on *B. rapa* flowers between hedgerow and control sites (Fig. 1). However, there was a greater abundance of native bees observed on *B. rapa* plants at hedgerow than control sites ($F_{1,14} = 26.06$, $P = 0.0002$). Because overall floral visitor abundance was not different between field types, we did not see differences in seed set between fields with and without hedgerows. We used the relationship between floral visitors and seed set to estimate seed set differences due to differences in native bee abundance differences. The best-fit relationship between observed floral

Table 1. Mean seeds per pod (±SE) from one floral visit by each pollinator group on canola, *B. rapa*

Pollinator group[a]	Average seeds per pod from one floral visit (±SE)	No. of replicates
Honey bees	3.0 ± 0.39	60
Syrphid flies	3.1 ± 0.43	54
Striped sweat bees	3.0 ± 0.41	54
Tiny dark bees	2.6 ± 0.28	83
Small dark bees	2.8 ± 0.82	12
Hairy legged bees	2.9 ± 0.52	31

Pollinator efficiency was not significantly different among groups, $P = 0.99$.

[a] The different types of flower visitors were recorded in CSM categories described in Kremen et al. (2011).

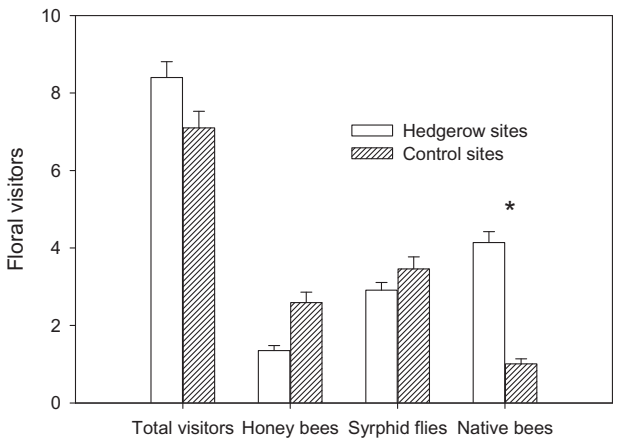

Fig. 1. Mean floral visitors (+SE) observed during 4-min visual observations on *B. rapa* sentinel canola plants in processing tomato fields adjacent to hedgerows or control (conventionally managed) field edges. Stars above a pair of bars indicate a difference in abundance for that group between treatments ($P < 0.05$).

visitors and seed deficit was an exponential decay equation: $y = 0.45\exp(-0.128x)$ ($R^2_{adj} = 0.42$, $F_{1,118} = 77.1$, $P < 0.0001$; Fig. 2).

Crop yields vary widely based on agronomic conditions; however, we used an average yield of 1,200 kg/ha and the 2011–2012 average value of canola seed at US$600/ton (US$0.60/kg) to calculate an average value from canola production of US$720 per hectare (http://www.canolacouncil.org/markets-stats/statistics/). Input costs for non-GM canola were ~US$300/ha resulting in a net profit of ~US$420/ha.

When we removed the estimated seed set resulting from honey bee and syrphid fly visits, field treatment (hedgerow or control edge) affected proportional seed deficit ($\chi^{2(1)} = 10.5$, $P = 0.001$). Using the mean values for seed deficit considering only native bees ($PI = 0.21$), there was a $21 \pm 4.9\%$ (standard error) seed increase at hedgerow sites due to enhanced native bee populations. Therefore, if a hedgerow were present, greater pollination from enhanced native pollinator populations would increase yields 21% to 1,452 kg/ha and a net profit of US$571/ha, which represents a US$151 profit increase, per hectare, over no hedgerows. As in Morandin and Winston (2006), we acknowledge that harvest and transport costs could increase slightly with greater yield; however, this likely would be a small amount and we do not factor it in.

Using the above values, profit from a 16-ha canola field with a conventional edge would be US$6,720. With the pollination increase from native bee enhancement by hedgerows (in an area with no managed honey bees or other effective pollinators), profit would be increased on a field by US$151/ha (from US$420/ha to US$571/ha, or 36% increase) resulting in a profit increase of US$2,416 per 16-ha field.

Overall profit therefore, from the combined benefits of increased pollination and fewer pest control treatments over time will help offset the costs of a 305-m hedgerow plantings as shown in Fig. 3. Scenario 1 shows the benefits from reduction in insecticide treatments alone each year (either no pollinator-dependent crops in the rotation or managed honey bees in the system provide all pollination needs). Scenario 2 is identical to scenario 1 but includes a 50% USDA EQIP cost share program. Scenario 3 depicts benefits from reduction in insecticide treatments each year and enhanced pollination in a pollinator-dependent crop every 3 yr. Like Scenario 2, Scenario 4 is identical to Scenario 3, but includes a 50% USDA EQIP cost share program.

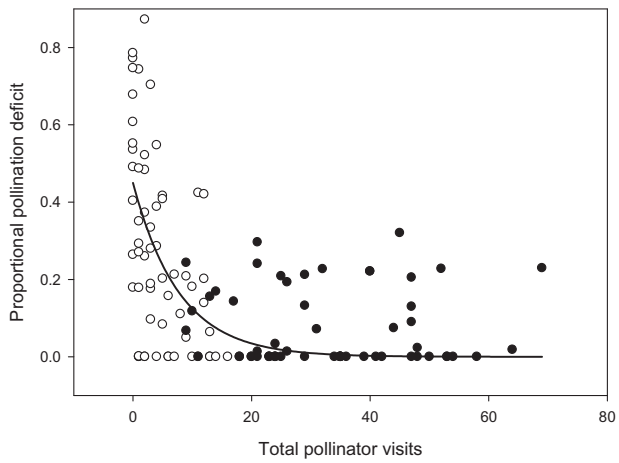

Fig. 2. Relationship between pollination deficit (maximal seed set minus open seed set, divided by maximal seed set at each grouping of four canola plants) and the observed abundance of floral visitors (honey bees, native bees, and syrphid flies) on *B. rapa* at four fields with hedgerows and four fields with conventionally managed edges (control) in each of two years, 2010 (open circles) and 2011 (closed circles).

Discussion

All of our hedgerows or control edges had crops on either side of them, usually with both fields owned by the same grower, and therefore we modeled benefits to two, 16-ha fields on either side of the hedgerow. Due to crop rotations, we modeled a situation in which the adjacent crops would benefit from natural pest control services and a reduction in insecticide use every year (at the rate calculated for a processing tomato field although the benefit could be greater or less depending on the actual crop present). The enhanced profit from native bee enhancement would only be realized if pollination was deficient prior to native hedgerow installation, unlikely if managed honey bees or other pollinators such as syrphid flies were abundant in the area and efficient pollinators of the crop (such as in our case where there were abundant managed honey bees and syrphid flies, both efficient pollinators of *B. rapa*). Therefore, Scenarios 1–2 (Fig. 3) account for hedgerow installation cost return from reduced pest control costs only, and assume either crops that do not benefit from pollination or a situation where pollination is saturated already from wild and or managed pollinators.

However, as has often been shown to be the case in simplified agricultural landscapes, pollination is a limiting factor to seed set (Kremen et al. 2002, Long and Morandin 2011, Klein et al. 2012), and seed set is increased in the presence of enhanced native bee populations (Klein et al. 2003, Kremen et al. 2004, Morandin and Winston 2006). In addition, with current uncertainty in managed honey bee supply, it is important to understand input of native bees and ways to

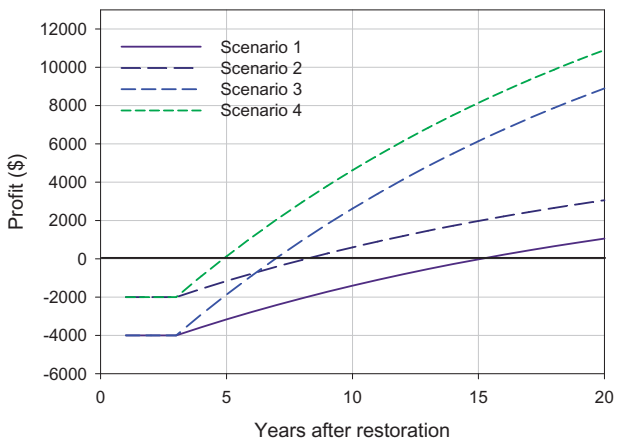

Fig. 3. Discounted profit (US$ 1.05% discounted rate per annum) from installation of a 305-m hedgerow of native California flowering plants on a field crop edge, calculated from the cost of installation and potential cost savings incurred from hedgerows from reduction in insecticide application and pollination benefits from natural enemies and pollinators. Scenario 1: benefits from reduction in insecticide treatments alone each year (either no pollinator-dependent crops in the rotation or managed honey bees in the system provide all pollination needs). Scenario 2: same as Scenario 1 but with a 50% USDA EQIP cost share program. Scenario 3: benefits from reduction in insecticide treatments each year and enhanced pollination in a pollinator-dependent crop every 3 yr. Scenario 4: same as Scenario 3 but with a 50% USDA EQIP cost share program. We do not show a potential for cost benefit from reducing the number of honey bee hives needed for pollination. However, a grower could also gain from the enhancement of native bees if they needed to rent fewer honey bee hives. Hedgerows were planted on field borders, so there was no loss in crop production. (Online figure in color.)

enhance their populations and pollination contribution to add resilience in cropping systems (Garibaldi et al. 2011, Winfree 2013, M'Gonigle et al. 2015). This information is vital because recent overwintering losses of managed honey bee colonies in many parts of the world (vanEngelsdorp et al. 2009, Neumann and Carreck 2010) and a 300% increase in the proportion of crops requiring pollination (Aizen and Harder 2009) has resulted in uncertainty as to whether managed honey bees can meet future global crop pollination requirements. Furthermore, a recent data synthesis found that crop yields around the world are responsive to increases in native pollinator visitation rates but not to increases in honey bee visitation rates (Garibaldi et al. 2013). Syrphid flies were also efficient pollinators of the canola plants in our study, but we did not include them in our cost–benefit model because their numbers are highly variable from year to year in California, so cannot be relied on for crop pollination (N. M. Williams, personal communication). In addition, abundances in fields are not affected by the presence of hedgerows (Morandin and Kremen 2013). Their somewhat greater abundance in control fields than in fields adjacent to hedgerows in our study was likely due to greater aphid abundance in control fields (Morandin et al. 2014).

In Scenarios 3–4, we show economic benefit of hedgerows if crop rotations include pollinator-dependent crops and managed honey bees in the system do not provide all pollination needs. We factored in the pollination benefit only once every third year, to account for crop rotation of nonpollinator-dependent crops two out of three years, by reducing the pollination enhancement benefit by 1/3rd each year on both sides of the hedgerow. Although not significant, visual inspection of a boxplot of the interaction between distance and treatment on seed deficit showed a slight increase in seed deficit at hedgerow sites at the 100 and 200 m distances (still significantly lower than at control sites that had constant seed deficit at all distances). To keep our cost return estimates conservative, we therefore only applied the pollination benefit to the first 200 m of the field (8 ha).

We did not include potential reduction in cost of honey bee hive rental in our profit equations for the scenarios where managed honey bees are abundant in the landscape because of the inability from our data to make accurate predictions in the amount of reduction in hive rental that would be possible from enhancement of native bees with hedgerow restoration. However, hive rental reduction could greatly increase profit from hedgerows.

Cost return, using a 5% discount rate per year, to the grower in this case would take about 16 yr if the grower paid for the full amount of the hedgerow with only the savings that we observed from reduced insecticide application (Fig. 3). However, with a 50% cost share such as EQIP, a grower would break even in costs and return at ~9 yr postinstallation, less than the age of the hedgerows in this study. Thus, in situations where pollinator-dependent crops are not within the rotation, based on insecticide application savings calculated for processing tomato, growers likely will recuperate their initial investment in hedgerow restoration, especially when a cost-share program is used. When we modeled a situation in which we exclude pollinators other than native bees, simulating an environment with no managed pollinators or efficient pollinators other than native bees, cost return times decrease substantially to 5 yr and 7 yr (with and without cost-share programs, respectively).

This cost–benefit model is a starting point for valuing the economic benefit of multiple ecosystem services resulting from on-farm restoration in highly simplified agricultural landscapes. The value could be an over or under estimate for multiple reasons. These values could be underestimates of benefits of hedgerows to growers because costs can be comprehensively estimated, while total benefits are multifaceted and comprehensive estimation is beyond the scope of any one study (Olson and Wackers 2007). Specifically, we have not valued the impact of natural enemies on multiple pests in tomatoes. For example, we conducted a sentinel stink bug egg parasitism experiment in order to assess differences in parasitism between control and hedgerow sites (Morandin et al. 2014). We found greater parasitism up to 100 m into hedgerow sites than control sites. However, from this experiment, it was not possible to extrapolate to direct economic impact and cost savings from reduced pesticide use because stink bug levels remained below economic treatment thresholds during the years of this study. Also, there is the potential that enhancement of native bee populations may reduce the need for honey bee hive rental, a possible important savings with high rental costs and supply uncertain due to honey bee health issues. Further, some crops, in some areas, may benefit more from pollination enhancement by native bees and pest control than the crops and location that we used to create this model. And finally, other ecosystem services potentially provided by hedgerows, such as water quality enhancement through filtration of sediments and other pollutants, are not part of this study.

Our economic analysis could also be an overestimate in agroecosystems with crops where pest control protocols are preemptive rather than dictated by pest levels in individual fields, such as when insecticides are applied prophylactically as in neonicotinoid seed treatments (Douglas and Tooker 2015). This problem could be mitigated if more growers and pest advisers used IPM protocols and pest threshold levels when making pesticide use decisions on crops. Overestimates may also occur in agroecosystems with few crops that require or benefit from pollination services or have their pollination needs met with managed honey bees.

We may also be overestimating the pollination impacts by using sentinel canola plants and scaling up to whole field crop systems. In using sentinel canola plants within a pollinator independent tomato crop, the canola may have concentrated available pollinators, which could lead to overestimation of the pollination service when scaled up to the field scale. The same number of pollinators, spread over a much larger field of canola, might have a much smaller effect on pollination. In addition, manual pollination can result in a greater number of seed and seed size, requiring a greater allocation of plant resources, resulting in an overestimate of pollination limitation (Zimmerman and Pyke 1988, Knight et al. 2006). However, Morandin and Winston (2005) found there was no decline in seeds per fruit in open-pollinated canola (*B. rapa* and *B. napus*) compared with manually cross-pollinated flowers, so we do not believe this was the case for our study.

Our research demonstrated that small-scale restorations can be cost effective, and provide profit to land owners in simplified agricultural landscapes. Using this, or similar models, data on pollination and pest control service enhancement from hedgerow or other habitat augmentation on multiple crops can be used to calculate cost return times and profit in a variety of situations for growers. In addition, other ecosystem service benefits could be added to these cost–return calculations. While the data derived from our study area in Yolo County, CA, show revenue after 5 to 16 yr, the cost–benefit model can vary depending on local conditions, including farm management and crop rotations (Sardiñas and Kremen 2015). As a result, more long-term monitoring of crop yield, pollination levels, and pest populations on farms with and without hedgerows are needed. This model is a starting point for evaluating multiple ecosystem service benefits and economic return of within

farm habitat enhancement to help minimize risks of investments. It can be applied to any agroecosystem where pest, natural enemy, and pollinator abundances are impacted by farmland habitat restoration.

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