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Analysis

Valuing pollination services to agriculture

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ABSTRACT

Crop pollination by animal pollinators is an important ecosystem service for which there is no generally accepted valuation method. Here, we show that two existing valuation methods, previously thought to be unrelated, are each a special case of a more general equation. We then present a new method, termed attributable net income, for valuing insect pollination of crops. The attributable net income method improves upon previous methods in three ways: (1) it subtracts the cost of inputs to crop production from the value of pollination, thereby not attributing the value of these inputs to pollinators; (2) it values only the pollination that would be utilized by the crop plant for fruit production, thereby not valuing pollen deposited in excess of the plants' requirements; and (3) it can attribute value separately to different pollinator taxa, for example to native vs. managed pollinators. We demonstrate all three methods using a data set on watermelon pollination by native bees and honey bees in New Jersey and Pennsylvania, USA. We discuss the reasons why different methods produce disparate values, and why the attributable net income method most accurately reflects the actual ecosystem service that is being valued, marketable fruit production.

1. Introduction

Pollination by animals is an important ecosystem service because crop plants accounting for 35% of global crop-based food production benefit from animal-mediated pollination (Klein et al., 2007). Bees (Hymenoptera: Apiformes) the primary pollinators for most of the crops requiring animal pollination (Delaplane and Mayer, 2000; Free, 1993; Klein et al., 2007). In much of the world, the cornerstone of agricultural pollination is the managed honey bee (*Apis mellifera*). Honey bees, which are native to Europe and Africa but not North America, are maintained in hives which are moved into agricultural areas during crop bloom. Despite the honey bee's effectiveness as a pollinator for many crops, there are risks associated with reliance on a single, managed pollinator species. Managed honey bee stocks in the USA have decreased steadily since the 1940s, and are now at less than half their original numbers (Ellis et al., 2010). Declines since the 1990s are largely due to infestation by a parasitic mite, *Varroa destructor* (NRC, 2007). Since 2006, honey bees in the USA have experienced further die-offs due to Colony Collapse Disorder (Cox-Foster and VanEngelsdorp, 2009), raising further concern about the availability of agricultural pollination.

In contrast to the sole species of honey bee, there are at least 17,000 species of native, wild bees worldwide (Michener, 2007). Many of these species visit crops (Delaplane and Mayer, 2000; Klein et al., 2007), and they contribute substantially to the pollination of such crops as coffee *Coffea spp.* (e.g. (Klein et al., 2003), watermelon *Citrullus lanatus* (Kremen et al., 2002; Winfree et al., 2007), tomato *Solanum lycopersicum* (Greenleaf and Kremen, 2006a), blueberry *Vaccinium spp.* (Cane, 1997; Isaacs and Kirk, 2010), sunflower *Helianthus annuus* (Greenleaf and Kremen, 2006b) and canola *Brassica spp.* (Morandin and Winston, 2005). These native bees provide pollination thus directly benefiting crop production. In addition, they complement in a number of ways the service provided by honey bees: biologically, by enhancing the efficacy of honey bee pollination in some cases (Greenleaf and Kremen, 2006b), and economically, by insuring against pollination shortages. Having accurate estimates of this value could improve land use planning by quantifying the costs and benefits of conserving habitat for pollinators in agricultural systems.

A few studies have attempted to value wild pollinators, while a much larger literature has attempted to value honey bee pollination. For the most part, these valuations have focused on the benefits to producers, calculated as either 1) the cost of alternative pollination sources (Allsopp et al, 2008), or 2) the value of production resulting from bee pollination (Losey and Vaughan, 2006).

The first approach – estimating the cost of using an alternative technology or organism to achieve the same function – is commonly known as the replacement value method. The idea is the same as

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valuation via input or factor substitution (Point, 1994). In the case of native pollinators, this typically involves measuring the amount of managed pollinators (usually honey bees) needed to replace the service (de Groot et al., 2002). In the case of honey bees, this involves measuring the cost of achieving pollination through either another managed pollinator, hand pollination, or pollen dusting (Allsopp et al., 2008).

A second and more widely used approach focuses on the value of crop production attributable to pollination. Production, or yield, is assumed to fall when pollinators decline. The yield reduction is approximated using studies of the dependency of fruit set on the presence of insect pollinators (Klein et al, 2007). The expected fractional yield loss in the absence of pollinators is then multiplied by the market value of production (Morse and Calderone, 2000; Robinson et al, 1989). Studies interested in breaking down the service between honey bees and native bees have estimated the proportion of pollen deposited by respective taxa in crop fields and then used this to appropriate the value between the different pollinators (Allsopp et al., 2008; Losey and Vaughan, 2006). With one notable exception, Olschewski et al. (2006), these studies do not take account of production costs and will be collectively referred to as "production value" approaches.

The replacement value and production value approaches produce widely divergent results, and furthermore garner criticism on theoretical grounds. Allsopp et al. (2008) estimate the value of managed honey bees and all unmanaged pollinators using both approaches; the resulting values calculated for wild pollinators differ by nearly a factor of a 100.[2] This alone is evidence that methodology deserves further attention. But there are conceptual criticisms that additionally call into question the validity of production value approaches. Muth and Thurman (1995) raise two concerns in regards to the production value approach: (1) it ignores the possibility for adjustments on the part of the farmer that could abate the production losses and (2) that it "fails to distinguish between the average contribution [of pollinators] and the marginal contribution" (Muth and Thurman, 1995). These two concerns, coupled with the empirical inconsistency, argue for an improvement to one or both of the methods.

In this paper, we first unify the replacement value and production value approaches conceptually by demonstrating that each is a special case derived from the same general equation. Next, we address the problematic issues raised above through a modification of the production value approach. The choice to focus attention on the production value method is supported by three considerations: it is the most common method employed, the calculations are simple, and it is relatively easy to acquire the necessary data. We illustrate this improved approach, which we term the attributable net income method, using a data set on watermelon *Citrullus lanatus* pollination by native bees and honey bees, and compare the resulting values to those obtained by using the two traditional methods. By native bees, we mean the native, unmanaged bees. Our definition of honey bees includes both managed and feral *Apis mellifera* as it is not possible to separate the two in most data sets.

2. Field study of watermelon - materials and methods

The materials and methods for the field study of watermelon are briefly summarized here and are reported at length elsewhere (Winfree et al., 2007, 2008).

2.1. Study system

The field study was conducted in 2005 at 23 watermelon farms located in central New Jersey and east-central Pennsylvania, USA. The study plant, watermelon, requires insect pollen vectors to produce fruit because it has separate male and female flowers on the same plant (Delaplane and Mayer, 2000). An individual flower is active for only one day, opening at daybreak and closing by early afternoon. In order to be fully pollinated and set a marketable fruit, a female flower needs to receive at least 1400 pollen grains, and fruit production asymptotes when 50% of flowers are fully pollinated (Stanghellini et al., 1997; Stanghellini et al., 1998; Stanghellini et al., 2002; Winfree et al., 2007). Knowledge of these values and in particular the rate of fruit abortion gives greater confidence in our economic estimates which could otherwise be confounded by the relationship between pollination and fruit production (Bos et al., 2007).

Sixty-five percent of the farmers in the study either own or rent hived honey bees for crop pollination purposes. Most honey bees recorded in the study were probably managed bees, because feral honey bees have been rare in the study region since in the 1990s due to mites and other problems (Stanghellini and Raybold, 2004), although they may be rebounding in recent years (Seeley, 2006). Because it is not possible to separate managed and feral bees in the field our estimates of honey bee pollination combine the two. Thus our results will over-estimate the value of pollination from managed honey bees alone.

2.2. Measuring flower visitation rates and pollen deposition

We visited each farm on two different days and measured bee visitation rate to watermelon flowers in units of bee visits flower^{-1} time^{-1}. Visits were recorded separately for honey bees and various types of native bees. Per-visit pollen deposition was measured by bagging unopened female flowers with pollinator-exclusion mesh, and then offering virgin flowers to individual bees foraging on watermelon. After a bee visited a flower, the pollinated stigma was prepared as a microscope slide so that the number of watermelon pollen grains could be counted with a compound microscope (Kremen et al., 2002). Control flowers were left bagged until the end of the field day, and contained few pollen grains (mean = 3 grains, N = 40 stigmas). In the field study of watermelon, we observed a total of 6187 bee visits (2359 by honey bees and 3828 by native bees) and collected 271 counts of per-visit pollen deposition.

2.3. Simulation methods

In order to estimate the contributions of honey bees and native bees separately, we developed a Monte Carlo simulation (Matlab R2006a, The MathWorks, Inc., 2006) of the pollination process. The simulation estimates total pollen deposition by each bee taxon by multiplying the daily number of visits to a watermelon flower by the number of grains deposited per visit, using distributions based on the field data for both variables (Winfree et al., 2007). The estimate is made separately for each of the 23 farms, and means and standard errors (SE) are calculated across farms. Program output is the frequency distribution across flowers for the number of pollen grains deposited on a flower over its lifetime by (a) all native bees combined, and (b) honey bees. Further details of the simulation methods are reported at length elsewhere (Winfree et al., 2007).

Simulation results indicated that across the study system as a whole, native bees provide 62% (5% SE) of the pollen deposited on female watermelon flowers, and honey bees provide 38% (5% SE) (Winfree et al., 2007). These values are used for the parameters ρ_{nb} and ρ_{hb} in our economic calculations, below. We also calculated the fraction of flowers at each farm that were fully pollinated by either native bees alone or honey bees alone by comparing the amount of pollen deposited on flowers at a given farm to the pollination requirements of the plant. The mean of these values taken across farms is used below for the parameters F_{nb} for native bees, and F_{hb} for honey bees. Lastly, we calculated the fraction of farms where the crop is fully pollinated by native bees (91% ± 6% SE) and honey

[2] The authors calculate the value of wild pollinators using the production value ("proportional dependence") as $215.9 million. Although not specifying the value as such, they also calculate the cost of replacing wild pollination with honey bees as $2.6 million (Allsopp et al, 2008).

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bees (78% ± 9% SE). These last values are used in the replacement valuation method below.

3. Economic valuation of pollination: theory and methods

The goal of valuation studies of pollination services is to understand the value that would be lost following the loss of certain pollinators (for example, native wild pollinators, or all pollinators) to a specified area (for example, regionally, nationally, or globally). For want of a logistically- and ethically- appropriate controlled experiment, the loss of pollinators is posed as a hypothetical experiment.

A loss of pollinators could affect production of a pollinator-dependent crop by reducing yield and/or by increasing the growers' costs. When pollinators are lost, fruit set might decline and as a consequence overall yield falls. This is the most intuitive economic consequence. But growers can also adjust inputs to compensate for the loss, thus mitigating or eliminating yield losses, while increasing costs instead.

These two effects both impact producer profits negatively, and adequately describe the value lost from a loss in pollinators on a relatively small scale. However if the pollination loss results in yield reductions on a large enough scale, then the market price of the crop may increase. This third, indirect effect positively impacts growers both within and outside of the affected region. It also negatively impacts consumers at a large scale.

To understand the value of pollination, we thus want to know the aggregate economic effect of a change in the pollination service on these three stakeholders: producers of the crop in the affected region, producers of the crop outside this region, and consumers of the crop. When the market price is unaffected by the hypothetical change in pollination, then the value computation would involve only the first group: assessing the impact on production. But, computing the value of pollination on a large scale, such as for an entire industry or globally, involves assessing not only the impact on production but also the economic consequences of market adjustments resulting from this impact. For this reason, large scale analysis is analytically distinct and considerably more complex than analysis on a small scale. In this study, the (hypothetically) affected region, New Jersey and Pennsylvania, produces less than 2% of the domestic market supply of watermelon, so we can reasonably rule out price effects in our analysis. We therefore focus on yield and cost effects only. We invite interested readers to see Appendix A for a discussion of valuation at large scales, which includes price effects.

3.1. A conceptual framework for pollination value

Consider the production of a pollinator-dependent crop in a region that currently has a certain level of pollination service input, denoted by q. Following McConnell and Bockstael (2005), we consider agricultural profit, π, as the net value to production, or revenue minus cost:

$$\pi = P \cdot Y(q) - C(Y(q), q) \tag{1}$$

where P is crop price, Y is the aggregate yield of the affected region, which is a function of the amount of pollination service, q, to the region, and $C(Y(q), q)$ is the total cost of production, which is a function of both aggregate yield and pollination service to the region. We assume here that price (P) is fixed in accordance with the assumption that the region's yield is small relative to the market supply.

The value of a certain amount of insect pollination (Δq) can then be depicted by using the chain rule to consider the first order changes to net income were this amount of service to be eliminated:

$$\Delta\pi = \left[P \cdot \left(\frac{\Delta Y}{\Delta q}\right) - C_Y \cdot \left(\frac{\Delta Y}{\Delta q}\right) - C_q\right] \Delta q \tag{2}$$

where $\left(\frac{\Delta Y}{\Delta q}\right)$ is the change in yield, if any, resulting from the change in pollination, C_Y is the marginal cost of production – the extra cost for producing one more (or less) unit of yield, and C_q is a marginal cost adjustment, such as the cost of renting more bees to compensate for lost pollination, if any, for the change in pollination, Δq.

From Eq. (2) it can be seen that the value of pollination to production is composed of three components: revenue effects from yield changes, cost adjustments to yield, and cost adjustments to pollination service. For a loss in pollination ($\Delta q < 0$), the value lost to producers is equal to the revenue lost from reduced yield, less the cost savings from reduced yield, plus the additional costs to substitute the lost pollinators.

There are circumstances in which one or more of the three components will be negligible. In particular there are two important cases to consider, which interestingly correspond with the two most prominent valuation methodologies. The first case occurs when pollinator loss is perfectly substituted and thus no yield is lost. In this case, the first two components of Eq. (2) drop out and what's left is $C_q \Delta q$, the cost of the substitution. This is precisely what replacement cost studies estimate. When yield does not remain constant, then replacement cost measures are not fully capturing the adjustments to production (McConnell and Bockstael, 2005). In addition, yield may fall despite substitution, or substitution may not occur if replacing the service is too costly. For instance, measures of replacement cost that exceed the total production value, as Allsopp et al. (2008) find, would never be pursued as farmers would rather lose the entire crop. Substitution is a key component; however it typically cannot be decoupled from yield effects.

The second case would be one in which the farmer does not compensate in any way for the loss in pollinators. If the farmer is able to neither employ substitutive pollination, nor reduce input costs in the face of yield losses – for example in the case of a sudden, unanticipated loss of pollinators after all costs have already been outlaid – then the latter two terms of Eq. (2) would be dropped, leaving simply $P \cdot \left(\frac{\Delta Y}{\Delta q}\right) \cdot \Delta q$, the lost revenue. This is exactly the calculation that production value approaches use. However, if there is any capacity to adjust to the expected loss in pollination by reducing input costs, then the production value approach will over-estimate the value of pollination because it ignores cost adjustments.

3.2. Improving the production value method

The production value method estimates the value of pollination under this latter assumption of no substitutive pollination and complete revenue loss. To estimate the change in yield the production value approach uses the crop's dependency on insect pollination, D, which represents the fractional reduction in fruit set that occurs when insect pollinators are absent (Klein et al, 2007). D is measured as $1 - (f_{pe}/f_p)$, where f_{pe} = fruit set under conditions of pollinator exclusion and f_p = fruit set with insect pollinators present. Then $\left(\frac{\Delta Y}{\Delta q}\right) \cdot \Delta q$, the expected reduction of yield for a ρ% reduction in insect pollinators, is approximated as $-Y \cdot D \cdot \rho$. Substituting this expression in for the lost revenue results in the common equation used in production value approaches (Allsopp et al., 2008; Gallai et al., 2009; Kremen et al., 2007; Losey and Vaughan, 2006; Morse and Calderone, 2000; Robinson et al., 1989):

$$V_{\Delta \text{pollination}} = P \cdot Y \cdot D \cdot \rho \tag{3}$$

The value of all pollination is calculated by replacing ρ with 1. The value of pollination contributed by particular taxa, for example, the value of all pollination from native bees, or from honey bees, is calculated by replacing ρ with ρ_{nb} or ρ_{hb}, which represents the fraction of all pollen grains that are deposited by native bees or honey bees, respectively. When pollination data are not available, ρ_{nb} or ρ_{hb} can be estimated as the fraction of all flower visits provided by each group, which should provide a reasonable proxy in most cases (Vazquez et al, 2005).

A problem we have noticed in the published literature is that the calculation of Eq. (3), is commonly applied in contexts other than the special case for which it is appropriate. First, the calculation is often employed for nation-wide or global analysis (e.g. Gallai et al., 2009; Losey and Vaughan, 2006; Morse and Calderone, 2000; Robinson et al., 1989), in which case the assumption that prices are unaffected is not valid. Secondly, most studies are interested in valuing the pollination service in annual terms. Under these circumstances, the assumption that producers could not adjust their input mix to accommodate the reduced pollination *every year* is flawed, and leads to inflated values for pollination services (Muth and Thurman, 1995). We discuss these issues at greater length in the Discussion and Appendix A.

The production value approach can be amended easily by considering changes to costs. Cost adjustments to yield can be estimated using estimates of yield change and the marginal cost of production. When measures for marginal costs can't be found, they can be approximated using average variable costs. Variable costs, which are defined as the expenses that vary according to output, will fall by approximately the same proportion that quantity declines, D. Using VC to denote total current variable costs, the assumption can be expressed as $\Delta C(Y,q)\approx VC\cdot \Delta Y/Y\approx -VC\cdot D$. This approximation will generally over-estimate the cost adjustment to yield (McConnell and Bockstael, 2005), since some variable costs may not be reduced in proportion to D — for example, if the farmer is not aware of pollination failure until after some costs have been incurred.

We can now use a simple calculation to represent the value depicted in Eq. (2):

$$V_{\Delta pollination}\approx(P\cdot Y-VC)\cdot D\cdot\rho \tag{4}$$

where VC again denotes the total variable cost, and other terms are defined in Eqs. 1 and 3. We term this approach the net income method following Point (1994). We note that Olschewski et al. (2006) used a similar approach by reporting changes in "net revenue." The only distinction between their method and ours is that we include only variable costs in VC, on the assumption that only variable costs will be recouped should pollination fail, whereas Olschewski et al. used total costs.

The second issue that our new valuation method addresses is the calculation of expected yield reductions, and the importance of accurately relating pollen deposition to the expected yield. Most plants have a threshold number of pollen grains that are required to set the maximum-sized fruit; this is referred to as the plant's pollination threshold. Additional pollen deposited beyond this threshold will not increase yield. Pollination thresholds can be exceeded in agricultural, as well as natural, settings. For example, in our field study, pollen deposition exceeded the threshold for watermelon fruit set at all farms (see Fig. B.1).

In the context of over-pollination, the question arises as to which pollinators are residual – that is, superfluous. The answer to this question need not be the same in all contexts. In many cases farmers rent honey bees for their crops, a choice that can be revoked, whereas native pollinators are provided by the ambient ecosystem. This implies that honey bee pollination is more easily removed and thus deemed superfluous. Counterexamples exist, such as when honey bees are feral (supplied by the ambient ecosystem) or come from hives belonging to someone else, the farmer has no control over them. And in some situations, farmers can affect native bee populations by modifying habitat on the farm. In this case, the habitat management decision could be revoked, and native bee pollination considered superfluous. We present the results in both ways to cover all cases.

3.3. Attributable net income method

We derived the parameter values for our study area as follows. We estimated the annual dollar value of watermelon production in New Jersey and Pennsylvania combined ($P\cdot Y$) using the total ha in watermelon production[3] , watermelon production in kg per ha[4], and price per kg[4]. For watermelon D = 1 because $f_{pe}=0$ (Stanghellini et al., 1998); that is, watermelon doesn't produce any fruit under conditions of pollinator exclusion and thus its dependency on pollinators is 100%. We used the output of the simulation to calculate the fraction of all pollen deposition attributable to native bees (ρ_{nb}), along with its SE. The value for honey bee pollination (ρ_{hb}) was estimated similarly.

In a second step, we subtract the costs of variable inputs to production from the total production value. In place of $P\cdot Y$, the total production value, we now use ($P\cdot Y-VC$), where VC is the summed cost of all known variable inputs to production. Crop production budgets provided by extension programs are a good source for average costs per unit yield and this is what we used for our calculations[5]. As an intermediate step, we compare these results, which we term net income, to the other methods.

We then modify the equation to relate the pollination delivered to the pollination needs of the crop, and to partition the resulting value among various taxa of pollinators. First, rather than attributing value to native bees according to the fraction of total pollen that they deposit (ρ_{nb}), the attributable net income method values only the pollen that is needed for fruit production. In other words, it does not value pollen delivered in excess of the pollination requirements of the plant. In this way it directly ties the ecosystem service (pollen deposition by native bees) to the production of value to people (marketable watermelon fruits). Second, the attributable net income method accounts for the presence of other pollinator taxa by optionally considering a given taxon as either the primary pollinator in the system (i.e., all of the pollination it provides up to the plant's pollination threshold is valued) or residual (i.e., the pollination it provides is only valued if the pollination already provided by other pollinator taxa is insufficient).

We demonstrate the attributable net income method by considering native bee pollination first, and valuing honey bee pollination only in addition to native bee pollination. However, the alternate order (honey bee pollination valued first, native bee pollination second) can also be done and those numbers are also presented in the Results.

Eq. (5) values native bee pollination based on the extent to which native bees alone fully pollinate the crop. There are two components to full pollination: at the flower scale, a flower must receive a certain amount of pollen deposited in order to set a marketable fruit; and at the field scale, fruit set will asymptote as the percentage of flowers that are fully pollinated approaches a saturation point. In the case of watermelon, a flower must receive ≥ 1400 conspecific pollen grains in order to set a marketable watermelon fruit, and fruit set asymptotes at the field scale when around 50% of flowers are fully pollinated (see Methods 2.1). These two components can be incorporated into the value function:

$$V_{nb}=(P\cdot Y-VC)\cdot D\cdot min\left(\frac{1}{\alpha}F_{nb},1\right) \tag{5}$$

[3] Based on data recorded by agricultural extension agents in each state: for New Jersey, by M. Henninger of Rutgers University, and for Pennsylvania, by M. Orzolek of Pennsylvania State University (Henninger and Orzolek, pers. com.).

[4] USDA-NASS 2010. Values from 2009 for the neighboring state of Delaware were used because USDA-NASS does not record watermelon production statistics for New Jersey or Pennsylvania.

[5] Source for watermelon production cost budget: University of Delaware Cooperative Extension Vegetable Crop Budgets 2009–20011, available online at http://ag.udel.edu/extension/vegprogram/publications.htm.

Where VC = the summed costs of the producers' variable inputs to watermelon production, α = the asymptotic fruit set proportion at the field scale, i.e. the maximal proportion of flowers that can produce fruit, F_{nb} = the fraction of flowers that are fully pollinated by native bees, i.e., that receive $\geq$ 1400 pollen grains from native bees,[6] and the other parameters are as in Eq. (3).

Honey bee pollination is valued based on the additional pollination honey bees contribute, above the amount contributed by native bees but only up to the pollination threshold:

$$V_{hb} = (P \cdot Y - VC) \cdot D \cdot min\left[\frac{1}{\alpha} F_{hb}, 1 - min\left(\frac{1}{\alpha} F_{nb}, 1\right)\right] \tag{6}$$

Where F_{hb} = the fraction of flowers that are fully pollinated by honey bees and the other parameters are as in Eqs. (3) and (5). As in Eq. (5), the factor of $\frac{1}{\alpha}$ associated with the F_{hb} and F_{nb} terms accounts for the fact that fruit production asymptotes when 50% of flowers are fully pollinated.

All valuations reported in this paper were done using 2009 US dollars. In all of our estimates we were only able to propagate error through the parameters obtained from our own work (ρ_{nb}, ρ_{hb}, F_{nb}, F_{hb}; from Winfree et al, 2007). The parameters obtained from other sources did not include the information necessary to propagate error. Therefore, the standard errors (SE) reported in the Results are under-estimates of the true SE.

3.4. Replacement value method

A replacement value for native bee pollination is what it would cost farmers to rent enough honey bees to replace the pollination currently provided by native bees. We calculated this value by multiplying the area in watermelon production (746 ha)[2] by the industry-wide recommended honey bee stocking rate (4.5 hives ha^{-1}; Delaplane and Mayer, 2000) by the annual rental cost of a honey bee hive in the study area (\$60-\$75 hive^{-1})[7] by the fraction of farms at which native bees alone are fully pollinating the crop (91%). We used the same method to estimate the replacement value of honey bee pollination, substituting the fraction of farms fully pollinated by honey bees (78%) for the fraction fully pollinated by native bees (91%). This replacement value represents what it would cost to replace the pollination services currently provided by honey bees with equivalent services provided by new honey bees.

Our calculation of the replacement value differs from what has been used by other workers, who have not included information about how much pollination bees are currently providing (our coefficients of 0.91 and 0.78 above). For this reason, these previous estimates are too high. Previous estimates value what it would cost to provide complete pollination by honey bees, not what it would cost to replace the pollination provided by native bees.

4. Results

The value of native bee pollination based on the replacement value of renting enough honey bee hives to replace native bees is \$0.21 million year^{-1} (range, \$0.20 - \$0.21 million year^{-1}) and the replacement value of honey bee pollination is \$0.18 million year^{-1} (range, \$0.17 - \$0.18 million year^{-1}); (Fig. B.2). The results are presented as ranges because one of the input variables, the cost of hive rental, is only available as a range.

The production value method provides a higher estimate. The estimated annual production value of watermelon in New Jersey and Pennsylvania combined ($P \cdot Y$), before subtracting the costs of inputs to production, is \$7.64 million year^{-1}. Multiplying this production value by the 62% $\pm$ 5% (SE) of all pollen deposition done by native bees provides an annual value of \$4.74 $\pm$ 0.38 (SE) million for the pollination service provided by native bees. For honey bees, the corresponding value is \$2.90 $\pm$ 0.38 (SE) million year^{-1} (Fig. B.2). After subtracting the costs of variable inputs to production, the estimated annual net income value (Eq. (4)) of watermelon in New Jersey and Pennsylvania combined is \$3.63 million year^{-1}, leading to estimates of \$2.25 0.18 (SE) million for the pollination services provided by native bees and \$1.38 0.18 (SE) million year^{-1} for honey bees (Fig. B.2).

The annual attributable net income value of native bee pollination, when native bees are considered primary pollinators (Eq. (5)), is \$3.40 $\pm$ 0.16 (SE) million year^{-1}. The value of honey bee pollination, when honey bee pollination is valued residually (Eq. (6)), is \$0.24 $\pm$ 0.16 (SE) million year^{-1} (Fig. B.2). When honey bee pollination is valued as primary (Eq. (5)), its value is \$3.07 $\pm$ 0.25 (SE) million year^{-1}. When native bee pollination is valued residually (Eq. (6)), its value is \$0.56 $\pm$ 0.25 (SE) million year^{-1} (Fig.B. 2).

5. Discussion and conclusions

There is a great need for a better understanding of ecosystem services in terms of both their ecology (Kremen and Ostfeld, 2005) and their economic value (Daily et al., 2000; Turner et al., 2003). There are many methods for valuing ecosystem services and each has its limitations (Heal, 2000; Turner et al., 2003). Our goal here is to make these valuation methods more consistent and their assumptions more explicit, using pollination as a model ecosystem service. We first demonstrate that the two main valuation methods currently in use, the replacement value and the production value methods, are special cases of the same general equation (Eq. (2)). We then use a single data set to compare the estimates of producer-side pollination service value obtained with these two widely-used methods, as well as with a third valuation method that we develop here and call the attributable net income method. The attributable net income method modifies the production value to subtract the costs of inputs to production, thereby reducing the extent to which this method overestimates pollination value. It also accounts for the pollination requirements of the plant, and the pollination already provided by other pollinator taxa, thereby better relating the measured service (pollination) to the marketable good (fruit production). The attributable net income method produces valuations that are intermediate between those obtained with the replacement value and the production value approaches. We further discuss the strengths and limitations of these methods, and the relationships among them, below.

The replacement value method assumes that production does not change when pollinators are lost, and values the cost of obtaining replacement pollination services. For native bee pollination this replacement is based on the cost of renting honey bees, since for most crops the given level of pollination from native bees could be obtained equivalently from honey bees. We measured this value using current honey bee rental costs and obtain a relatively small value (Fig. B.2). However, this method assumes that honey bees are indefinitely available as a replacement for native pollinators, whereas an important component of the value of native bees is their ability to compensate, in part, for the potential loss of the honey bee. Current challenges to honey bee health such as Colony Collapse Disorder (VanEngelsdorp et al., 2009) make the assumption of indefinite honey bee availability questionable. Furthermore, the replacement value method excludes potential future price increases in honey bee rental costs, which seem likely given continued honey bee health problems. For example, the cost of renting a single honey bee colony for almond pollination increased from \$35 in the early 1990s to \$150

[6] As for ρ_{nb}, values of F_{nb} come from the data and simulation presented in Winfree et al., 2007.

[7] Range of rental costs for pollinating cucurbit crops in our study region; Tim Schuler, State Apiarist for New Jersey, pers. com. Prices vary by beekeeper and according to the number of hives rented, but no further information that would allow a variance to be calculated is available.

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in 2007 (Johnson, 2007). The same conceptual problems apply when this method is used to calculate the replacement cost for honey bees, i.e., the cost of replacing the existing honey bees with new honey bees.

An alternative way to use the replacement value method, which does not assume the availability of honey bees, would be to calculate the cost of a replacement for both native bees and honey bees, such as hand-pollination by people (Allsopp et al., 2008). This approach produces much higher valuations (Allsopp et al., 2008) but is only possible for the small number of crops that have been pollinated by other means other than bees. No cost estimates for non-bee pollination of watermelon are available.

The production value method makes the opposite assumption from the replacement value method: it assumes that no replacement for the lost pollinators is possible, and values pollination services as the loss in production that would occur subsequent to pollinator loss. This widely-used method (Allsopp et al., 2008; Gallai et al., 2009; Losey and Vaughan, 2006; Morse and Calderone, 2000; Robinson et al., 1989), essentially calculates the proportion of the total value of the crop that depends on pollinators. There are several problems with the production value method which may lead it to its over-estimating the producer welfare value of pollination. The attributable net income method corrects most of these problems.

First, the production value method ignores the possible reduction of other inputs to production that would ensue from a significant loss in production capability (McConnell and Bockstael, 2005). For example, if pollination failed then farmers would not invest further in inputs that vary with yield, such as harvest costs. The production value method disregards these cost savings, thereby over-estimating the value of pollination. This problem can be ameliorated by subtracting the costs of variable inputs production from the value of production, as we do in our net income method. In our case this reduces the value of pollination services by 52% (Fig. B.2), and suggests that many of the previous estimates of pollination value have been too high. Absent the distinction of fixed and variable costs, the subtraction of total costs as done by Olschewski et al. (2006) would still be preferable, thereby attributing the net, not the gross, value of crop production to pollination.

A second problem with the production value method is that the method assumes all the pollen deposited is necessary for fruit set, whereas in reality plants may be getting more pollination than they need (Muth and Thurman, 1995). The attributable net income method solves this problem by valuing only the pollination that is likely to be utilized in fruit production, i.e., the pollen delivered up to the threshold pollination requirements of the plant. The attributable net income method also allows for valuing a given pollinator taxon either independent of, or in addition to, another taxon. In systems such as ours where most farms are over-pollinated, the decision about whether to consider a pollinator taxon as primary or residual can lead to a 6–13 fold difference in its ecosystem service value (Fig. B.2). This highlights the importance of specifying the goal of the valuation - a decision that must be made by stakeholders or users.

A third problem with the production value method is that it does not account for opportunity costs – in this case changes growers could make if pollination became more costly, such as switching to less pollination-dependent crops (Muth and Thurman, 1995; Southwick and Southwick, 1992). These are long-term considerations, however. Both the production value and the attributable net income methods are best interpreted as estimates of values over the short-term.

A fourth problem with the production value method is that it assumes the market price of the output crop is fixed, and would not adjust to the resulting loss in yield. If the area in question is significant – say, at a national scale or even for a large region – the resulting (hypothetical) loss in yield would surely affect the market price and mean the calculation is not accounting for the consequential effects. It is problematic then that this method has been used in contexts where its assumptions are violated. While the attributable net income method presented in the text suffers from the same limitation, we present in Appendix A a generalized attributable net income method and framework for calculating the value of pollination in these larger contexts.

In this paper we have shown that the two commonly used methods for valuing pollination services to agriculture, the replacement value method and the production value method, are special cases of the same general equation. This equation has implicit spatio-temporal assumptions which we clarify here as they have at times been violated in the published literature. We introduce a new method, Attributable Net Income, which overcomes some of the limitations of existing methods. In so doing, it brings the valuation of the regulating service of pollination into better alignment with the provisioning service that provides the final utility to people: crop production. We hope that this work moves the science of ecosystem service valuation one step closer to the level of accountability required for use in the policy arena.

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Appendix A. Generalizing the framework to larger scales

In Section 3.1, we discussed valuing a loss in pollination when the scale of the loss was small enough to not affect the market price of the crop. One of the shortcomings of this framework is that it is not applicable for valuations on the global, national or even regional scales if the output of the area in question represents a sizable portion of the market. In this Appendix, we generalize the model to allow for price effects, and thus provide a more broadly applicable framework.

Our objective here is to articulate the necessary components for this more comprehensive analysis. The layout is as follows: we first depict the total welfare at stake when it comes to a loss in pollination, we then relate the approaches of existing studies within this framework, and end by simplifying the calculation of each component to maximally take advantage of existing data. The approach of this framework is, as in the main text, a first order approximation: a linearized prediction of outcomes based on small changes from the current situation.

A loss of bees is assumed to occur for a specified area, and directly impact the production of a pollinator-dependent crop in this area, which we now denote by a. If both the effect on yield and the area's total production relative to the market are significant, then the market price of the crop may adjust and consequently affect two additional stakeholders apart from the producers in the area: consumers of the output crop, as well as producers of the crop in other areas, the latter of which will be denoted by $\neq a$.

The total social welfare then is the sum of net benefits accruing to the producers of the crop in the area, to producers of the crop outside the area, and to consumers of the crop:

$$SW = \pi_a + \pi_{\neq a} + CS \tag{A.1}$$

where π_a is net income (or profit) of producers in the affected area, $\pi_{\neq a}$ represents the net income to producers in the rest of the market, and CS represents the consumer surplus – the value to consumers – for the output crop.

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We now define each of the three terms in Eq. (A.1). The producer profit of the affected area is very similar to that laid out in Section 3.1, with one important exception:

$$\pi_a = P(Y_a + Y_{\neq a}) \cdot Y_a - C(Y_a, q_a) \tag{A.2}$$

Here, unlike in Eq. (1), the price, P, is now recognized to be a function of the total market production, which is the sum of that produced within the area (Y_a) with that from the rest of the market ($Y_{\neq a}$). But apart from the substitution of P, the equation is otherwise the same as before (now with subscripts a). In a similar fashion, the producer profit of the entire market, less the affected area, is defined as

$$\pi_{\neq a} = P(Y_a + Y_{\neq a}) \cdot Y_{\neq a} - C(Y_{\neq a}, q_{\neq a}) \tag{A.3}$$

For simplicity, we assume the same cost structure, $C(Y,q)$, for both the affected area and out-of-area producers.

The value of the crop to consumers is defined as the consumer surplus and is represented by the area above the price and under the demand curve for the crop:

$$CS(P) = \int_P^{\overline{P}} Q(p)dp \tag{A.4}$$

where $Q(p)$ is market demand at price p, and $\overline{P}$ is the threshold price above which there is no demand.

The loss of insect pollination to the area (Δq_a) can then be valued by considering first order changes, employing prodigious use of the chain rule, to total social welfare (Eq.(A.1)) were this amount of service to be eliminated:

$$\begin{aligned} V_{\Delta pollination} &= \left[\frac{\Delta \pi_a}{\Delta q_a} + \frac{\Delta \pi_{\neq a}}{\Delta q_a} + \frac{\Delta CS}{\Delta q_a}\right]\Delta q_a \\ &= \left[\left(\frac{\Delta P}{\Delta Y_a}\right)\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right)\cdot Y_a + P\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right) - C_Y\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right) - C_q\right]\Delta q_a \\ &\quad + \left[\left(\frac{\Delta P}{\Delta Y_a}\right)\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right)\cdot Y_{\neq a}\right]\Delta q_a \\ &\quad + \left[-(Y_a + Y_{\neq a})\cdot\left(\frac{\Delta P}{\Delta Y_a}\right)\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right)\right]\Delta q_a \end{aligned} \tag{A.5}$$

where $\left(\frac{\Delta Y_a}{\Delta q_a}\right)$ is the change in the area's yield, if any, resulting from the change in pollination, $\left(\frac{\Delta P}{\Delta Y_a}\right)$ is the change in crop price, if any, resulting from the change in yield, and as before C_Y is the marginal cost of production – the extra cost for producing one more (or less) unit of yield, and C_q is cost adjustment, if any, for the change in pollination, Δq_a. Eq. (A.5) is cumbersome, but not overly complex once it is broken down and simplified. The first line is very similar to Eq. (2), with an additional term for the change in price, $\left(\frac{\Delta P}{\Delta Y_a}\right)$. This line represents the value to the area's producers. The second line represents the spillover effects of the area's productivity to producers outside the area. And the last line represents the change in Consumer Surplus.

Eq. (A.5) can be verbally interpreted as follows. A loss in pollination potentially affects the welfare of three groups: affected area's producers (the first line of Eq. A.5), out-of-area producers (the second line), and consumers of the crop (the last line). If the crop price rises, consumer welfare unambiguously declines, out-of-area producers unambiguously gain with higher prices, while affected producers could lose or gain depending on the magnitude of the price effect. The economic effect on producers in the area is equal to the revenue gain from increased price, less the revenue lost from reduced yield, plus the cost savings from reduced yield, less the additional costs to substitute the lost pollinators. While in most cases we would expect producers to lose when a environmental service is stripped away, the potential for price increases to negate this loss is important and must not be disregarded. As will be discussed below, existing studies have estimated measures of impacts on one of these three groups, but what Eq. (A.5) demonstrates is that the appropriate valuation should unite producer and consumer welfare in a single value calculation.

As discussed in Section 3.1, there are certain circumstances in which one or more of the terms will be negligible. In that section we presented two important cases which correspond with the two most common methodologies employed. In the first case, yield losses are averted through input substitution leaving just $C_q\Delta q_a$ (the replacement cost), which is still the case under this framework. The second case was sudden, short run loss precluding any possible cost adjustments. From Eq. (2), this resulted in $P\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right)\cdot\Delta q_a$ (the production value approach). The more complete framework presented here reveals the limitations of that approach. First, we see that ignoring the change in price means that production value calculations overestimate the value to the area's producers (who can benefit from price increases), while ignoring entirely the possible spillover benefits to other producers (who benefit from those same increases while not sustaining yield losses). Second, the production value approach calculation ignores the loss to consumers, which is an important component of the value of pollinators, and provides no guidance as to how that loss compares with the value calculated for producers.

Focusing on that consumer welfare component, a third case is worth considering. This case corresponds with another common methodology, consumer surplus approaches. As it has been framed in existing studies, this analysis focuses on the so-called "long run" (Southwick and Southwick, 1992). The long run assumption is that crop choice is not fixed and entry is free so supply is highly elastic. Even slight changes in price drive large changes in supply: an increase in price drives supply up as more land is enrolled into production, and the converse is true for price decreases. The net result is that price changes very little as increased or decreased production moves the price back towards the long-run equilibrium. Thus, long-run supply is more-or-less flat (i.e. long-run price is fixed), implying zero profit. It should be noted at this point that this long-run assumption of perfect elasticity (an implication of zero profit) is less a reflection of reality as it is a simplifying assumption to focus solely on consumer surplus: with zero profits, the first two terms of Eq. (A.1) vanish and we are left with only the consumer surplus. The marginal impact is then just: $-(Y_a + Y_{\neq a})\cdot\left(\frac{\Delta P}{\Delta Y_a}\right)\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right)$. This is the measure used by Southwick and Southwick (1992) to value pollination services.

Another study has considered consumer surplus losses and is worth an extended discussion. Gallai et al (2009) estimate the global value of pollination using a production value approach in addition to a quantitative consideration of consumer surplus effects. The scale of analysis in that study (a global assessment) certainly implies price effects and so a production value approach alone would not be sufficient. Thus the consideration of consumer surplus is warranted. However, there are three problems with the approach of Gallai et al (2009). The first problem is that costs are not included; thus if producers are able to adjust and/or substitute for the loss in bees, the value calculation will be an over-estimate. The second issue is that the total value of pollination is comprised of the sum of the welfare changes to producers and to that of consumers (see Eq. (A.5)) – thus, while Gallai et al (2009) calculate both, the two should be united in a single calculation. The third issue is a conceptual one. As stated above, the consumer surplus approach of Southwick and Southwick (1992) assumes profit to be negligent, which is an assumption that runs into direct conflict with the production value approach, which measures the effect of pollination loss on profit. Instead, the calculation of consumer surplus need not follow the framework of Southwick and Southwick (1992), which ignores the effects on producers, and can instead simply estimate consumer surplus effects as but one component of the overall calculation, as in

Eq. (A.5). Despite these issues, Gallai et al (2009) make an important step in the right direction by at least considering measures of losses to both producers and consumers.

As the main point of this Appendix is to elucidate efficient and sufficient ways of calculating the value of pollination, we now attempt to simplify Eq. (A.5). The main text focuses on the terms $\left(\frac{\Delta Y_a}{\Delta q_a}\right)$, C_q, and Δq_a, so here we focus on the key additional term in Eq. (A.5) – the change in price, $\left(\frac{\Delta P}{\Delta Y_a}\right)$ – and how to estimate it. The question is: what is the relationship between the area's yield and the market price? This relationship is contained within a parameter commonly estimated in industry analyses: the price elasticity of supply. The price elasticity is denoted ϵ_a, defined as $\epsilon_a = \left(\frac{\Delta Y_a}{\Delta P}\right)\cdot\frac{P}{Y_a}$, and represents the sensitivity of supply to changes in price (specifically, it is the percent change in supply for a 1% change in price). Rearranging this definition, we have the simple representation of the change in price as a result of a change in area yield:

$$\left(\frac{\Delta P}{\Delta Y_a}\right) = \left(\frac{1}{\epsilon_a}\right)\cdot\frac{P}{Y_a}. \tag{A.6}$$

In other words, the price change can be estimated with the current price, the area's yield and an estimate of the price elasticity of supply.

We can then use this equation for the change in price to substitute for $\left(\frac{\Delta P}{\Delta Y_a}\right)$ in Eq. (A.5), exchanging variables for quantities that are more easily measured, and simplifying the value calculation. Using Eq. (A.6), and in some cases grouping terms, the total value of the pollination (Eq. (A.5)) can be simplified to:

$$\begin{aligned} V_{\Delta pollination} = & \left[\left(1+\frac{1}{\epsilon_a}\right)\cdot P\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right) - C_Y\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right) - C_q\right]\Delta q_a \\ & + \left[\left(\frac{1}{\epsilon_a}\right)\cdot P\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right)\cdot\left(\frac{Y_{\neq a}}{Y_a}\right)\right]\Delta q_a \\ & + \left[\left(\frac{1}{\epsilon_a}\right)\cdot P\cdot\left(\frac{\Delta Y_a}{\Delta q_a}\right)\cdot\left(\frac{Y_a + Y_{\neq a}}{Y_a}\right)\right]\Delta q_a. \end{aligned} \tag{A.7}$$

Eq. (A.7) has the same elements as Eq. (A.5), but now it is expressed entirely in variables that can be estimated using current data and information. And to reiterate, this value calculation unites producer and consumer welfare in a singular calculation, and does so without requiring the assumptions that are made in the existing production value and consumer surplus approaches.

The framework presented in this Appendix represents an approximation to the value of pollination at scales large enough to impact supply and the market price. The strength of this framework is that it unites the values for different components (that is, the different stakeholders affected by pollination) within a single calculation, and allows for comparisons between different existing methodologies. The main drawback of this framework, which is common to all current approaches, is that it extrapolates welfare effects based on a limited set of information. The framework utilizes current measures of yield, price, and price elasticity of supply, along with flower-level estimations of crop-pollination dependency, to predict the effect a loss of pollination on aggregate supply and producer and consumer welfare. It does this by considering first-order changes to supply (or in other words, assuming linear supply and demand curves around the equilibrium), which works well for small changes in supply and price. It can be improved by considering second-order effects (that is, non-linear supply and demand curves), or using actual estimates of supply and demand curves and impacts. We invite further work that would make this approach more applicable to large scale analyses.

Appendix B. Figures

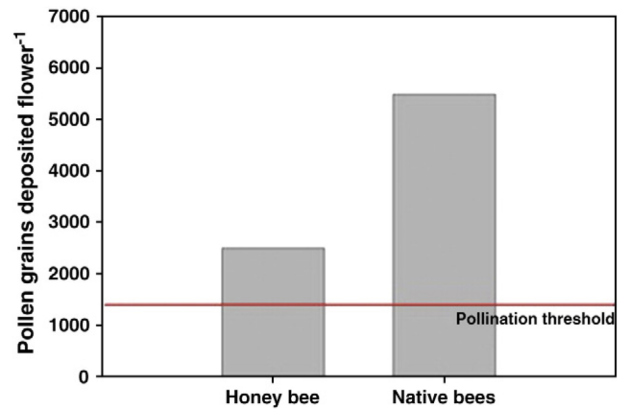

Fig. B.1. Pollen Deposition by Bees.

A graphical representation showing how different valuation methods attribute value to multiple pollinator taxa. In this example using data from one of our study farms, native bees deposit a median of 5427 grains per flower and honey bees deposit a median of 2558 grains per flower, whereas asymptotic fruit set is obtained when the median flower receives only 1400 grains (the pollination threshold, indicated by the red line). The production value method attributes 68% (=5427/7985 grains) of the crop pollination to native bees, and 32% (=2558/7985 grains) to honey bees. In contrast, because each taxon fully pollinates the crop, the attributable net income attributes 100% of the pollination to whichever taxon is valued first, and 0% to the taxon valued second.

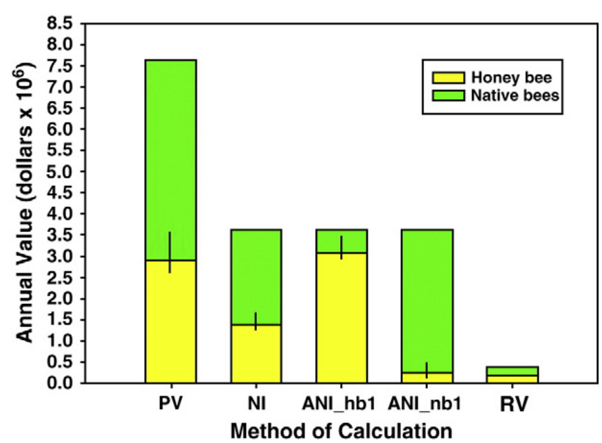

Fig. B.2. Calculating the Value of Pollination.

The annual value of watermelon pollination by honey and native bees in New Jersey and Pennsylvania, as estimated using different valuation methods. PV: Production Value, NI: Net Income, ANI_hb1: Attributable net income, honey bees primary pollinators, ANI_nb1: Attributable net income, native bees primary pollinators, RV: Replacement Value. Depending on which pollinator is deemed primary and which residual, the attributable net income results differ significantly for each taxa, although in sum remain the same as net income.

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