The economic insurance value of wild pollinators in almond orchards in California

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Biodiversity can provide an economic insurance value against the uncertain provision of ecosystem services for risk-averse economic agents. For uncertain pollination services, we determine the risk premium and the economic insurance value of wild pollinators in almond orchards for a risk-averse farmer. For this, we describe pollination services as a distribution, which can be analysed by statistical methods. Thus, we determine the mean, standard deviation, coefficient of variation and skewness of the distribution. Further, we develop an ecological-economic model to determine the risk premium and insurance value of wild pollinators in general, and apply this model to empirical data on flower visits of honeybees (*Apis mellifera*) and wild pollinators such as several wild bee species (e.g., *Andrena* spp., *Osmia* spp.) and other wild insect pollinator species to almond trees in California. Results show that wild pollinating species can both increase or decrease the riskiness of a pollination distribution. That is, it is dependent on the measure for variance (standard deviation or coefficient of variation) that is evaluated. Thus, wild pollinators can or cannot have an insurance value depending on the risk-preferences of the economic agent.

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1 Introduction

Pollination is an important regulating ecosystem service provided by various insects, bats and also several managed pollinator species e.g. the European honey bee (Pejchar et al. 2009). Many of the pollinator-dependent crops rely on pollination services by the European honey bee. However, wild pollinator species (e.g. wild bee species and hover flies) are known to be effective pollinators, too, that may also forage under more inclement weather conditions than the honey bee (Garibaldi et al. 2013). As pollination services are dependent on various exogenous and uncertain factors, the provision of pollination services are uncertain and farmers relying on these services face a risk.

The value of biodiversity to ecosystems and to ecosystem services is well studied from an ecological point of view. It is useful, however, to actually evaluate biodiversity in monetary terms, that is, in this study, what is biodiversity's contribution to pollination worth? Various studies already determine the monetary evaluation of the insect pollination services using different methods. For example, several studies use the annual production value, the annual production value multiplied by the insect dependence factor, the hive rental cost or the replacement value to determine the economic value of pollination due to honey bees or wild insect pollinators (Allsopp et al. 2008, Morse et al. 2000, Burgett et al. 2004, Losey et al. 2006). Gallai et al. (2009) use a more complex approach and determine the contribution of insect pollination to the world agricultural output economic value and also include the vulnerability of the global agriculture due to a possible pollinator decline. To date, the economic approaches to determine the value of pollination services due to honey bees or wild insect pollinators lack the integration of both relevant insights from ecology as well as insights from economics (Bos et al. 2007). For example, most studies do not integrate significant and relevant economic insights regarding human behaviour such as risk-aversion and the property of being utility-maximizing in times of uncertainty. Additionally, most studies focus only on the economic value and do not take into account other values such as the economic insurance value, which has already been observed from an ecological point of view (Winfree et al. 2007).

Here, we focus on the economic insurance value of wild pollinators and take into account both knowledge from ecology as well as knowledge on human behaviour, that is, accounting for humans to tend to be risk-averse and utility-maximizing in times of uncertainty (Holt et al. 2002, Olbrich et al. 2011). Therefore, we use an interdisciplinary approach here to

1. analyse pollination service distributions and resulting farm income distributions by statistical methods,
2. develop an ecological-economic model to determine the risk premium and the economic insurance value, and
3. apply that model to empirical data about species-specific flower visits and fruit set in almond trees in California to quantify the risk premium and the economic insurance value of wild pollinators in almond orchards. We assume a risk-averse farmer who strives to maximize their expected utility.

2 Methods

We present an overview of the case study and the assumptions we made for developing the ecological-economic model which we used to analyse the statistical numbers, namely, the expected income, standard deviation, coefficient of variation and skewness of the pollination/income distributions and the economic values, namely, risk premium and insurance value of wild pollinators to an ecosystem manager (e.g. a farmer). Additionally, we explain the different data sets to which the ecological-economic model is applied to determine our values of interest, including data about the flower visitors and observation frequencies, the fruit set, the almond weight and the almond market price and the risk-aversion.

2.1 Case Study

We assume an almond orchard farmer who grows almond crops, which are dependent on the ecosystem service of pollination provided by honey bees and wild pollinators.

Therefore, the farmer's harvest is related to the amount of pollination services, and thus, his income is related to these services, too, because they sell the almonds on the market.

Most of the almond cultivars (*Prunus dulcis*) are self-incompatible (Jackson et al. 1991), which means that one almond cultivar requires the pollen from another compatible almond cultivar to be pollinated successfully (Hill et al. 1985). The main way this pollen is transferred is by pollinating animal species such as the European honey bee, wild bee species (e.g. *Andrena* spp., *Osmia* spp., *Bombus* spp.) and other wild pollinators (e.g. hoverflies (Syrphidae) and houseflies (*Musca* spp.)).

The European honey bee is an important managed pollinator, so for almond pollination the honey bee is commonly introduced to orchards (Kremen et al. 2002, Jackson et al. 1991). Most honey bees show flower constancy; that is, they forage only in one flower species, resulting in a higher probability of successful pollination for that plant (Free 1963). However, they do not forage under harsh weather conditions, which is one factor leading to the uncertainty of pollination by honey bees (Corbet et al. 1993, Kevan et al. 1983). Wild pollinating animals such as wild bee species and hover flies are known to forage also under inclement weather conditions (Vicens et al. 2000, Kevan et al. 1983). Thus, it is possible that wild pollinators can compensate partly for a possible underprovision of pollination services due to, e.g., harsh weather conditions, and can provide an economic insurance value.

In our case study, we applied the ecological-economic model to empirical data about the visitation frequencies of different pollinating species, that forage in almond orchards in California, and we apply the model to data about the fruit set in these orchards, and data about the almond weight. Each data set was provided by Klein et al. (2012).

Klein et al. (2012) collected the data about the visitation frequencies of pollinator species and the fruit set in 23 almond orchards in Colusa and Yolo Counties in the Sacramento Valley in Northern California (38º42' to 38º57'N and 121º57' to 122º14'W). In order to investigate the effect of different habitat surroundings on flower visitation frequencies of pollinators, they selected eight organic and ten conventional orchards with different habitat surroundings. Half of the orchards were surrounded by <5% natural or semi-natural habitat and half by >30% natural or semi-natural habitat in a 1 km radius (hereafter referred to as natural habitat) (Klein et al. 2012). Klein et al. (2012) also selected five conventional orchards with a low percentage of surrounding natural habitat, but which had an adjacent strip of semi-natural vegetation (10-25 m wide). The strips were along one side of the orchard and consisted of scrubby riparian habitats. The distance between orchards was 1 km at minimum with a mean inter-site distance of 3 km. The organic orchards were certified according to the California Organic Food Act (1990) and did not use any insecticide or herbicide (Klein et al. 2012). That is, there are five different management scenarios we investigate, entailed by the different surrounding habitats:

a) organic orchards, with a low percentage of surrounding natural habitat
b) organic orchards, with a high percentage of surrounding natural habitat
c) conventional orchards, with a low percentage of surrounding natural habitat
d) conventional orchards, with a high percentage of surrounding natural habitat
e) conventional orchards, with an adjacent strip of semi-natural vegetation along one side of the orchard.

Additionally, Klein et al. (2012) counted the visitation frequencies and thus, the pollination services of different pollinating species for each site. Regarding to this data, we grouped the different pollinator species as

- honey bee group (h),
- wild bee species group (w), or
- other species group (o).

In the honey bee group only the European honey bee was included, in the wild bee species each pollinating species belonging to the Apoidea was included, apart from the honey bee. As other species we included all other pollinators observed in the almond orchards. Further, we investigated the following combinations of biodiversity because only these combinations can bee observed in ecosystems (Klein et al. 2012):

- honey bee group and other species group together (*ho*)
- honey bee group, other species group and wild bee species group together (*how*).

Considering only the wild pollinators, we take the other species group and the wild bee species group into account and combine them as a theoretical group (*ow*).

Klein et al. (2012) also estimated the number of flowers on each tree and documented the number of flowers they observed per time period, so we were able to create a relative measure for scaling up the data about observation frequencies to one almond tree. We assembled the observations from each of the sites for a given management scenario and scaled them up to one almond tree and one almond season. Thus, we obtained a distribution of the pollination services in each management scenario. Klein et al. (2012) also provided data about the fruit set (the proportion of the flowers that developed successfully to a fruit) for each site, so we calculated a mean of expected almonds for each scenario. Thus, we determined the farmer's income because we knew the estimated number of flowers per tree for each site. Additionally, we converted the distribution of pollination services into a distribution of income per management scenario.

We predict different values across those scenarios for the expected income, risk premium and insurance value because wild pollinators (*wo*) are known to be more abundant in orchards with a high percentage of surrounding natural habitat (Klein et al. 2012).

2.2 Ecological-Economic Model

We used a variation of the model developed by Baumgärtner (2007) and Baumgärtner et al. (2014) to determine the expected income, the risk premium and the insurance value of pollinator diversity.
We consider an economic agent who is an almond orchard farmer. As discussed in the introduction, his almond harvest is related to the provision of pollination services by honey bees and wild pollinators. With an increase in pollinator species diversity, the probability for an increase in pollination services increases, too. Further, the probability of a flower being pollinated increases with an increase in the amount of pollination

services provided by the pollinators, and thus, the fruit set would also be expected to increase. We determine the expected number of almonds of the fruit set and the average number of flowers per almond tree. Moreover, the data provides the mean almond weight. With these information and with the market price for the almonds we determine the farmer's expected income.

Additionally, we know the probability distribution of flower visitation frequencies by the different pollinator groups. Here, we assume, that the visitation frequencies represent the pollination services by these visiting species. This allows us to determine the number of almonds which will result in large part of these flower visits by the different pollinator groups. And further, we can convert the given distribution of pollination services into an income distribution for the farmer in relation to the pollinator groups and management scenarios. With this income distribution, we can calculate the expected income of the farmer. Further, we calculate the standard deviations, the coefficients of variation and the skewness of these income distributions to investigate each income distribution in relation to the expected income from that distribution.

Consider s as the amount of pollination (ecosystem service). As the ecosystem service depends on the level of biodiversity (v), the pollination depends on the level of the diversity of pollinators. The level of biodiversity v is captured by our different pollinator groups. We consider honey bees only; honey bees and pollinators from the other species group, and the combination of the honey bees, other species group and wild bee species group. Therefore, v can be

- v_h for biodiversity represented by the honey bee group only,
- v_o for biodiversity represented by the other species group only,
- v_w for biodiversity represented by the wild bee species group only.

Additionally, v can also be combined pollinator groups:

- v_{ho} for biodiversity represented by the honey bee and the other species group combined,

- v_{how} for biodiversity represented by the honey bee, the other species group and the wild bee species group combined.

Pollination is risky, so s is a random variable, described by a probability density function:

$$f_v(s) \tag{1}$$

with

$$\int_0^\infty f_v(s)ds = 1. \tag{2}$$

The ecosystem manager's net income y is given by:

$$y = p \cdot s, \tag{3}$$

where p is a factor which includes the average number of developing almonds due to one pollination service (s) and the market price for these almonds. As pollination is a random variable, income y is also a random variable. The ecosystem manager chooses, then, a level of biodiversity (v) and, thus, a particular distribution of their income y. This can be seen as an income lottery (Crocker et al. 2001). The ecosystem manager, who manages the orchards, is assumed to be risk-averse and to want to maximize their expected utility. Their expected utility is given by the von Neumann-Morgenstern expected utility function. It reflects the ecosystem manager's preferences over their uncertain income y:

$$U = \mathcal{E}_v[u[y]]. \tag{4}$$

$\mathcal{E}$ is the expectancy operator. $u(y)$ is a Bernoulli utility function, which is increasing ($u' > 0$) and strictly concave ($u'' < 0$). That is, the farmer is non-satiated and risk-averse. We assume that $u(y)$ is a constant relative risk aversion utility function:

$$u(y) = \frac{y^{1-\rho} - 1}{1 - \rho}, \tag{5}$$

where $\rho > 0$ measures the degree of risk-aversion of the farmer (Arrow 1965, Pratt 1964). With the probability density function given by Equation 2, the ecosystem manager's von

Neumann-Morgenstern expected utility function is then

$$U = \int_0^\infty \frac{(p \cdot s)^{1-\rho} - 1}{1 - \rho} f_v(s) ds. \tag{6}$$

2.2.1 Statistical Methods

We use here statistical numbers to describe and characterize the income distributions of the farmers. We analyze the mean (expected income), standard deviation, coefficient of variation and skewness of the income distributions. The expected income of the farmer is available because the probability density function of the pollination services can be converted into an income probability density function. Thus, with this function we can determine the expected income, which is dependent on the variance of the income:

$$\mathcal{E}_v[y] = \int_0^\infty y \cdot f_v(s) ds. \tag{7}$$

The variance of the income is the extent to which the possible incomes differ from the expected income. It is typically measured by the standard deviation (SD), which we calculate for each income distribution by using

$$SD_v[y] = \sqrt{\int_0^\infty (y - \mathcal{E}_v[y])^2 \cdot f_v(s) ds}. \tag{8}$$

In addition, we determined the coefficient of variation, which also gives a measure for the variance, unlike the standard deviation relates the variance to the mean value. It is defined as the ratio of the standard deviation to the mean:

$$CV_v[y] = \frac{SD_v[y]}{\mathcal{E}_v[y]}. \tag{9}$$

A higher variance from the expected income is related to a higher risk, and thus, the risk premium should be greater for a risk-averse farmer. Further, we calculate the skewness of the income distribution which is given by:

$$g_v[y] = \sqrt{n}\frac{\sum_{i=1}^{n}(y_i - \mathcal{E}_v[y])^3}{(\sum_{i=1}^{n}(y_i - \mathcal{E}_v[y])^2)^{3/2}} \tag{10}$$

The skewness is a measure for the asymetry of a distribution. It relates to upside (right-skewed distributions) or downside (left-skewed distributions) risks.

2.2.2 Measures of economic value

Here, we determine the economic values of interest, namely the risk premium, certainty equivalent (CE) and insurance value. The risk premium is defined by

$$u(\mathcal{E}_v[y] - R) = \mathcal{E}_v[u[y]] \tag{11}$$

(Kreps 1990, Varian et al. 1992). The risk premium is that amount of money that leaves the farmer equally well-off regarding their utility for both situations: Playing the risky lottery or receiving the expected income for sure minus the risk premium. Now we can insert the utility function (Equation 5) into the definition of the risk premium:

$$\frac{(\int_0^\infty p \cdot s f_v(s) ds - R_v)^{1-\rho} - 1}{1-\rho} = \int \frac{(p \cdot s)^{1-\rho} - 1}{1-\rho} f_v(s) ds. \tag{12}$$

Thus, we resolve the risk premium R:

$$R_v = \int_0^\infty p \cdot s f_v(s) ds - \left(\int_0^\infty ((p \cdot s)^{1-\rho} - 1) f_v(s) ds + 1\right)^{\frac{1}{1-\rho}}. \tag{13}$$

In cases where $s = 0$, we replaced the zero by a one as the function is not defined for $s = 0$. This does not change the result to a great extent because the income distributions have such a broad range. Additionally, we can determine the certainty equivalent (CE), it is the difference between the expected income and the risk premium. It is this amount of money the farmer is indifferent between receiving that amount of money or playing the risky lottery:

$$CE_v = \mathcal{E}_v[y] - R_v. \tag{14}$$

We can now determine the expected income and the risk premium for each combination of the pollinator groups and for each management scenario.

The insurance value is the change of the risk premium due to changes in the level of biodiversity (v). Thus, a species group, i has an insurance value:

$$V_i = R_0 - R_{0+i}. \tag{15}$$

The insurance value is then given by the differences of the risk premium for the honey bee and the other species group and the wild bee species group for each management scenario. The economic insurance value for the wild bee species is given by:

$$V_w = R_{ho} - R_{how}. \tag{16}$$

While the insurance value for the other species group is defined as:

$$V_o = R_h - R_{ho}. \tag{17}$$

And for all wild pollinators, the insurance value is defined as:

$$V_{ow} = R_h - R_{how}. \tag{18}$$

That is, if V_v is positive, wild pollinator groups are expected to stabilize the income distribution and therefore reduce the risk of the lottery. Thus, the risk premium is expected to decrease with a higher level of v.

2.3 Data

Each data set was provided by Klein et al. (2012). The main data set includes observations of species-specific flower visits in almond orchards in California. That is, it includes the frequencies of flower visits by the different pollinator species. Further, one data set includes the fruit set, which is the number of fruits that developed successfully from the flowers on one tree. For determining the income of the ecosystem manager we also used data about almond weights, market price and the extent of the risk-aversion.

2.3.1 Flower visitors, observation frequencies and number of flowers

Klein et al.'s (2012) observations of flower visits were conducted from 25 February to 18 March 2008, at times when temperatures were above $13^{\underline{o}}$ C (Delaplane et al. 2000), with sunny to lightly overcast skies, and the wind speed was $<2.5\,\mathrm{m\ s}^{-1}$. In each of the 23 orchards, flower visitors were observed on three separate days. For each orchard, five trees at the edge of the orchard (near the natural habitat or adjacent strip, when present) and five trees in the orchard interior at 50-60 m (five small orchards) or 100-110 m (18 large orchards) from the edge were observed. All observed trees were in full bloom. At each tree, eight groups of flowers were each observed for 20 s: two each in the inner top, inner bottom, outer top and outer bottom quadrants of the trees.

Klein et al. (2012) selected flowers for observation so that the observer could see the interior of each flower. Thus, the number of flowers observed per time period was determined by practical feasibility. Observation time per orchard was 26.7 min per orchard and day, and 80 min per orchard in total over 3 days. For one orchard there was an observation time of 26.2 min and for another orchard observation time was 29 min per day. For each 20 s observation period, the number of flower visits by *Apis mellifera*, non-Apis wild bees, hover flies (family Syrphidae) and other visitors were counted. The original data set included a separate row for each flower visitor observation or each time period of 20 s and per quadrant of the tree. We assembled all species which were observed in each of the different quadrants, that is, we assembled all observations on one tree. We describe the number of flower visits per time period as observation frequency and use histograms to depict the results. Thus, we have observation frequencies on the x-axis and call the y-axis abundance which is here the number of cases Klein et al. (2012) counted the observation frequencies.

As explained above, honey bee grouping only included the European honey bee, while wild bee species included each wild bee species that belonged to the Apoidea superfamily: here, Klein et al. (2012) observed *Andrena* spp., *Anthophoridae* spp., *Bombus* spp., *Xylocopa* sp., *Dialictus* sp., *Eucera*, *Evylaeus* spp., *Halictidae*, *Hapropoda*, *Lasioglossum*, *Osmia* sp. and *Panurginus* sp.. Other species classified species such as hoverflies (Syrphidae), *Bombyliidae* and all other pollinators that do not belong to the Apoidea superfamily nor to the Apis-bees.

Klein et al. (2012) counted the visitation frequencies by each visitor for each observation period of 20 s. Thus, for each orchard there were observations of 240 times 20 s. We combined the data sets of each site belonging to the same scenario to gain a distribution of the pollination services for each scenario. Further, we divided these data sets according to the flower visits of the different groups and generated separate distributions only for the honey bee group, for the combined honey bee and others species group (*ho*) and for the combines group of all pollinator groups (*how*) for each scenario. Thus, we had three different pollination distributions per scenario.

Klein et al. (2012) documented the flowers observed per time period and the estimated number of flowers on each tree. Thus, we could create a relative measure for each observation period between the observed flowers and the number of flowers at that tree. We could then determine the mean relative measure for each scenario for scaling up the observations for an entire almond tree.

2.3.2 Fruit set

Klein et al. (2012) counted the number of post-anthesis (i.e. after the period the flower was fully open and functional) flowers along a 1 m length of a tagged branch on five trees at each orchard edge in late March 2008. In July they counted the number of developed fruits on the same branches to calculate fruit set. They excluded extremely small and deformed fruits from their analysis as fruits that do not contain edible or marketable nuts (Klein et al. 2012). They could then calculate the fruit set for each site. This data allowed us then to determine the mean value of the fruit set for each management scenario. We used these mean values to obtain the farmer's expected income from the mean number of flowers per tree in each scenario.

2.3.3 Almond weight

Klein et al. (2015) investigated almonds harvested under four different treatments: a) normal water and nutrients b) reduced water/normal nutrients c) no nutrients/normal water d) reduced water and no nutrients. To each of these nutrient treatments, three different pollination treatments were applied: a) supplemental hand-pollination to maximise cross-pollination b) open-pollination with flowers exposed to bees freely foraging in the field and c) pollinator exclusion. The data set included 1,547 samples of weighted almonds for all treatment combinations.

We analysed these data about almond treatments and weights to determine the average weight of one almond. This is crucial for quantifying the income per tree for an orchard farmer because the almond price is stated as price per pound. We determined the mean value for the weight over all treatment combinations to provide a robust average almond weight.

2.3.4 Almond market price

The almond market price was \$ 1.45 per pound in the year 2008 (United States Department of Agriculure, National Agricultural Statistics Service 2013), the year, in which the data about flower visitation frequencies were collected.

2.4 The farmer's risk-aversion

Here, we use $\rho = 1.5$ because most people are known to be risk-averse and are described by a risk-aversion with ρ between 0.88 and 1.69 (Olbrich et al. 2011, Harrison et al. 2007).

2.5 Data upscaling

We scaled up the data to one almond tree for one entire almond season because we wished to determine our values of interest per tree and for one almond season.

2.5.1 Upscaling in time

Almond flowering typically takes place between the end of February and mid-May, where one individual tree is flowering for two weeks (Soodan et al. 1989). Here, we consider an almond tree flowering in the first two weeks of March. During this time there are on average 3.5 days of rain and 9 hours of sunshine per day (*Der internationale Klimaindex* 2015). Additionally, flowers open only between 10:00 a.m. and 12:00 p.m. (Soodan et al. 1989). Further, honey bees forage only when wind speed is $< 2.5\ \mathrm{m\,s^{-1}}$ and temperatures are above 12-13 $^{\text{o}}$C. (Vicens et al. 2000, Kevan et al. 1983). That is, in the morning and the late afternoon, temperature is too low for honey bees to forage. Moreover, in March there are some windy days (Brittain et al. 2013) so that in total one flower is open for approximately 6 hours in 4 days during that time in which honey bees will forage.

The data about the observation frequencies of pollinators in almond orchards represent the flower visits in 20 s time periods and 240 times per orchard (in two orchards 236 and 341 respectively). For each management scenario there are 960-1,200 observations of 20 s time periods, where 4,320 x 20 s represent an entire almond season on a per flower basis. Given the distribution of flower visits by each pollinating group, we scaled up the observation frequencies of each case by using the appropriate factor to gain a pollination distribution of 4,320 $\cdot$ 20 s time periods.

2.5.2 Upscaling in space

We scaled up the given pollination distribution for one almond season to an entire almond tree. Therefore, we aggregated the observations for each of the same trees, that is 8 observations per tree. Then, we used a relative measure of the estimated number of flowers per tree and the number of flowers that were observed during each time period. Further, we averaged this relative measure over each site belonging to the same management scenario. For each scenario we multiplied the number of flower visits by the averaged relative measure, so we obtained a pollination distribution that showed the expected flower visits by the pollinator groups for one tree. Thus, overall we had the pollination distribution for one entire almond tree and for an entire almond season.

2.5.3 Converting the pollination distribution into an income distribution

We converted the given pollination distribution for an entire almond season and an entire almond tree into the distribution of the farmer's income per tree and season. That is, we calculated the number of expected almonds with the fruit set and with the estimated number of flowers per tree for each scenario. We also converted the expected number of almonds into the farmer's income by using the data about the almond weight and almond market price.

Further, we used the observation frequencies to calculate a factor for each pollinator group and scenario that gives the contribution of one flower visit to the income. Thus, we converted the pollination distribution into an income distribution.

3 Results

Here, we present the results of data analysis, the statistical numbers of the income distributions and the economic values of the different pollinator groups namely risk premium, certainty equivalent and insurance value.

3.1 Results of the data analysis

In this section, we present the results of the data analysis, which include the results of each empirical data set and the results of the upscaled data to one almond tree and one almond season.

3.1.1 Flower visitors and observation frequencies

In the five different management scenarios, different compositions of flower visitors were observed. In scenario (a), organic orchards with a low percentage of surrounding natural habitat, Klein et al. (2012) observed 417 visits by honey bees, and 466 visits by the combined honey bee and other species group (*ho*). In scenario (b), organic orchards with a high percentage of surrounding natural habitat, Klein et al. (2012) observed 177 visits by honey bees, 391 visits by the combined group (*ho*) and 577 visits by all pollinators (*how*). In scenario (c), conventional orchards with low percentage of surrounding natural habitat, they observed 596 visits by the honey bee and 607 visits by all pollinators (*how*). In scenario (d), conventional orchards with a high percentage of surrounding natural habitat, Klein et al. (2012) observed 500 visits by the honey bee group, 747 visits by the combined honey bee and other species group (*ho*) and 931 visits by all pollinator groups together (*how*). In scenario (e), conventional orchards with a low percentage of surrounding natural habitat but with an adjacent strip of semi-natural vegetation along one orchard side, they observed 721 visits by the honey bee group, 838 visits by the combined honey bee and other species group and 851 visits by all pollinators (*how*). In scenario (a) and scenario (c), both of which with a low percentage of surrounding natural habitat, no visits by species of the wild bee species group were observed. Thus, there is no combination of the honey bee group, the other species group and the wild bee species group (*how*).

Furthermore, we combined the distribution of flower visits of each site belonging to the same management scenario to obtain one distribution of flower visits per scenario. As mentioned in above, we separated these distributions according to the three pollinator group combinations to gain information about the contribution of the pollinator groups to the total flower visits and thus, to the pollination services. The flower visitation frequencies have the smallest ranges from zero to 19 (scenarios (a) and (c)), and the widest ranges from zero to 29 (scenario (e)). Over all, an increase in pollinator species diversity increases also flower visitation frequencies. That is, the wild pollinator species (the other species group and the wild bee species group) contribute to larger abundances concerning flower visitation frequencies.

3.1.2 Fruit set

Klein et al. (2012) calculated the fruit set for each site. We used this to determine the mean value of each site's contribution to a given management scenario to have one value for each management scenario for further calculations (Table 1).

Table 1: Fruit set in the different management scenarios.

management scenario	fruit set [%]
(a)	32.43
(b)	66.00
(c)	31.18
(d)	46.98
(e)	37.59

3.1.3 Almond weight

Almond weight over all treatments was on average 1100.5 mg.

3.1.4 Data upscaling

Upscaling in time Klein et al. (2012) collected data about the visitation frequencies on each site on three separate days. From these observations we obtained the distribution of flower visitors in 20 s time periods and from that we obtained the probability distribution of flower visits in a 20 s time period. Thus, we scaled up this data from each scenario to one almond season, which is on average 24 hours on a per flower basis. That is, we multiplied the flower visitation frequencies (x-axis) by a factor of 4320 to gain a probability distribution for an entire almond season (subsection 2.5). For the distribution of the flower visits, the upscaling in time only changes the frequencies of observations. Thus, the shape of the probability distribution does not change.

Upscaling in space The results of the upscaling in space are the probability distributions of the flower visits on one almond tree and for one almond season. For this, we used the relative measure of the flowers on one tree and multiplied the observed flower visits during one season by that relative measure. Thus, the values of the x-axis of the probability distribution change, whereas the probability on the y-axis does not. That is, we obtained a probability distribution for the flower visits by the different combinations of the pollinator groups for each scenario.

Converting the pollination distribution into an income distribution We converted the probability distribution for the flower visits for one entire almond tree and for one almond season into a probability distribution for income by determining the contribution of one single visit by each pollinator species to the total income. The income ranges (the x-axis) differ strongly between the different scenarios: In scenario (a) the income range is shortest from zero to \$ 28.48, whereas in scenario (b) the income range is largest ranging from zero to \$ 188.53. Income distributions are shown in Figure (1).

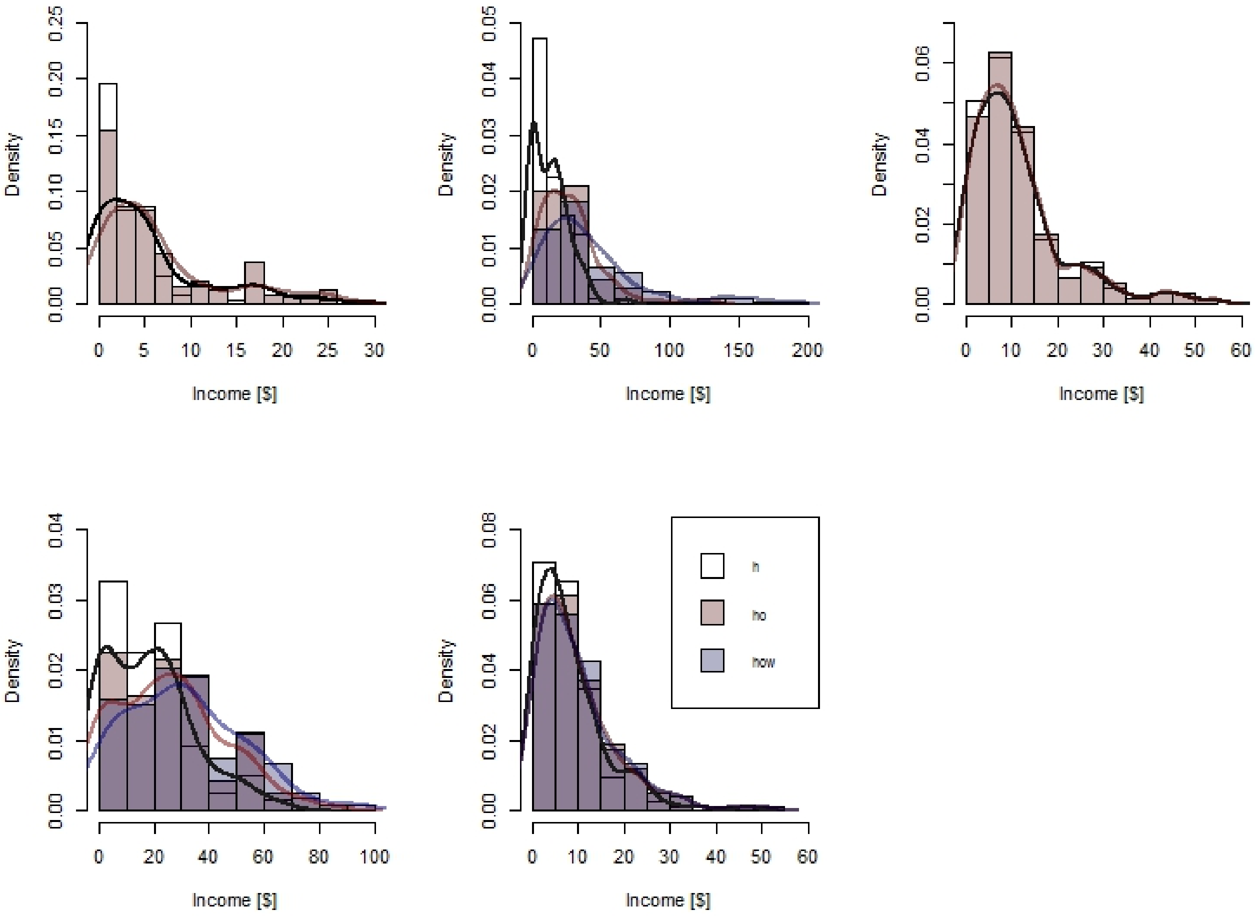

Figure 1: Histograms of income distributions for scenarios (a), (b), (c), (d) and (e) (from left to right). The histograms for the income due to flower visits of different pollinator compositions are superimposed. Lines show the shape of each histogram.

3.2 Statistical Numbers

Here, we present the statistical numbers characterizing the different income distributions due to the pollination services by the different pollinator groups (Table 2). In each scenario the expected income increases with higher pollinator diversity. However, the standard deviation increases in four scenarios and decreases in one scenario due to higher levels of pollinator diversity. Further, the coefficient of variation decreases in each scenario with an increase in pollinator diversity. Each income distribution was right-skewed and remained right-skewed also by increasing the pollinator diversity. Nevertheless, an increase in pollinator diversity had different effects on the skewness of the distributions. In scenario (a) and (e) an increase in pollinator diversity decrease the skewness of the distribution, that is, the distribution is shifted towards a more symmetrical distribution. In scenario (c) pollinator diversity does not change the skewness of the distribution. In scenario (b) wild pollinating species even increase the skewness, that is, the distribution is even more right-skewed with high pollinator diversity. Further, in scenario (d) wild bee species group decreases the skewness of the distribution but the additional other species group lead again to an increase in skewness. Here, we cannot see a consistent pattern of the influence of pollinator diversity on the skewness of income distribution.

Table 2: Results of mean, standard deviation, coefficient of variation and skewness of income distribution due to different pollinator species diversity

management scenario	**(a)**			**(b)**			**(c)**			**(d)**			**(e)**		
	h	**ho**	**how**	**h**	**ho**	**how**	**h**	**ho**	**how**	**h**	**ho**	**how**	**h**	**ho**	**how**
$\mathcal{E}_v[y]$ [\$]	5.67	6.69		13.30	27.98	42.23	11.27	11.48		17.93	25.82	29.81	8.31	9.69	9.84
$SD_v[y]$ [\$]	6.29	6.72		13.33	22.99	38.12	10.30	10.26		15.41	18.61	20.46	7.79	8.75	8.84
$CV_v[y]$	1.11	1.00		1.00	0.81	0.90	0.91	0.89		0.86	0.72	0.69	0.94	0.90	0.90
$g_v[y]$	1.47	1.36		1.09	1.72	1.77	1.66	1.66		0.74	0.51	0.53	1.7	1.66	1.59

3.3 Risk premium and insurance value of wild pollinators in the different management scenarios

Here, we present the results of the ecological-economic model that we applied to our data. Our values of interests are depicted in Table 3 for each management scenario. In four management scenarios the risk premium increases with an increase in pollinator diversity. However, in scenario (c) the risk premium decreases slightly with increasing pollinator diversity. Further, the certainty equivalent (CE) increases in each scenario with higher levels of pollinator diversity. The insurance value for wild pollinating species is negative in four management scenarios and it decreases with higher levels of pollinating species. However, in scenario (c) there is a positive insurance value (0.09) for wild pollinating species. That is, we find different trends of the economic values of pollinator diversity.

Table 3: Values for the risk premium, certainty equivalent and insurance value for the pollinator groups

management scenario	**(a)**			**(b)**			**(c)**			**(d)**			**(e)**		
	h	**ho**	**how**	**h**	**ho**	**how**	**h**	**ho**	**how**	**h**	**ho**	**how**	**h**	**ho**	**how**
Risk premium [$]	2.80	3.19		9.44	15.79	24.07	5.52	5.43		17.42	25.23	29.45	7.61	8.95	9.08
CE [$]	2.87	3.50		3.86	12.29	18.16	5.75	6.05		0.51	0.59	0.37	0.71	0.74	0.76
Insurance value V [$]		−0.39			−6.26	−8.37		0.09			−7.81	−4.22		−1.34	−0.13
Insurance value V [$]						−14.63						−12.03			−1.5

The table shows the values for the risk premium, the certainty equivalent and the insurance value. The values for the insurance value V in each column refers to the change from the previous column to that column. That is, the values in the column "ho" refer to the change from having only the honey bee to having the honey bee and also the other species group. There are two rows for V. The values in the first row of each pair and the column "how" refer to the change from having the honey bee and other species (*ho*) to having the honey bee, the other species group and the wild bee group (*how*). Thus, the values depicted represent the values for having the wild bee group additionally. The values in the second row of each pair and the column "how" refer to the change from having only the honey bee (*h*) to having all pollinators (*how*). That is, the values for all wild pollinators (*ow*).

4 Discussion

Results of data analysis were only used for applying the ecological-economic model, thus, we focus on the results of the statistical numbers and our economic values of interest. As the diversity of pollinator composition increases, the expected income (mean) also increases. Further, the contribution of each pollinator group differs in each scenario. In scenario (c), conventional orchards with a low percentage of surrounding natural habitat, the expected income increases only by \$ 0.21 when the other species group was included; wild bee species did not occur in that scenario. However, in scenario (b), organic orchards with a high percentage of surrounding natural habitat, wild pollinators (ow) contribute most to the farmer's expected income. The other species group increases the expected income by \$ 14.68 and including also wild bee species, the expected income increases additionally by \$ 14.25 (i.e. a total of \$ 28.93). In the scenarios which had a high percentage of surrounding natural habitat the expected income increases by a range of \$ 11.88 to \$ 28.93 due to the pollination services of diverse pollinators. That is, wild pollinators can contribute immensely to the farmer's income because of their pollination services if there is a high percentage of surrounding natural or semi-natural habitat. Our results indicate that higher levels of biodiversity increase ecosystem service productivity. In each scenario, the expected income for farmers increases with an increase in the level of biodiversity. This confirms the hypothesis that a high level of biodiversity can augment ecosystem service productivity (Baumgärtner 2007), a result which was also reported for natural systems, inter alia, by Blaauw et al. (2014).

The standard deviation of the income distribution increases in four scenarios with more diverse pollinator compositions. Here, wild pollinator species lead to a higher expected income and simultaneously extend the income distribution ranges because they contribute to larger visitation frequencies. However, in scenario (c), conventional orchards with low percentage of surrounding natural habitat, the standard deviation decreases slightly with higher pollinator diversity. That is, the wild pollinating species do not extent the income distribution range but increase the probability for income in the given range by the honey bee group. Thus, we see both effects: An increase in pollinator diversity can lead to a higher variance of income, but it can also stabilize the income distribution.

The coefficient of variation ranges from 0.69 (scenario (d), having the pollinator group composition *how*) to 1.11 (scenario (a), having only honey bees) and decreases in four scenarios with a more diverse pollinator composition. More diverse pollinator compositions extend the variance of the income distributions but their contributions to a larger expected income are so large that the relative variations decrease. In scenario (b) the coefficient of variation first decreases but increases again after having the additional wild bee species group. That is, the other species group increase the variance but their contribution to the expected income is so large that the relative variance decreases. However, additional wild bee species increase the variance again but their contribution to higher expected income is low, so the relative variance increases again. Thus, in most cases the coefficient of variation decreases indicating that higher levels of pollinator diversity decrease the relative variance. For the relative variance, higher levels of pollinator diversity seem to have a stabilizing effect on the pollination services and thus, on the income. Similar findings have already been reported for wild bee species in highbush blueberry: wild bee richness was a good predictor for pollination services and the different pollinator species stabilized pollination services by responding differently to changing weather conditions (Rogers et al. 2014).

The skewness of the distribution change with additional wild pollinating species. We find different effects of the level of pollinator diversity on the skewness: Skewness can increase (scenario (b)), decrease (scenario (a), (c) and (d)) and do not change at all (scenario (c)) due to visits of different pollinator compositions. Nevertheless, each distribution is right-skewed and does not change to a symmetrical or left-skewed distribution. Thus, each income distribution has a high upside-risk.

In four scenarios, the risk premiums increase with more diverse pollinator compositions and in scenario (c) the risk premium slightly decreases with more diverse pollinator compositions. Furthermore, the certainty equivalents (CE) range from \$ 0.37 (scenario (d), *how*) to \$ 18.16 (scenario (b), (*how*)). That is, the farmer is indifferent between having the amount of the CE for sure and playing the risky lottery with the expected income. In scenario (a), (b), (d) and (e) the risk premiums increase with more diverse pollinator composition and also the CEs increase but are at a low level. Only in scenario (d) the change in pollinator composition from *ho* to *how* leads to a decrease in the CE (from $ 0.59 to $ 0.37). Overall, that is, the income lottery in these scenarios is very risky, which is also indicated by the high standard deviations in these scenarios, thus, the farmer will be equally well-off between having the relatively low CE for sure and playing the risky lottery with a relatively high expected income. However, in scenario (c) the risk premium decreases slightly with more diverse pollinator composition. The CE still increases with more diverse pollinator composition but is at a low level compared to the expected income, which shows that the lottery is still very risky.

The economic insurance values range from $ -14.63 (scenario (b), (*how*)) to $ 0.09 (scenario (c), *ho*), whereas only in scenario (c) there is a positive insurance value. In each other scenarios insurance values are negative. That is, wild pollinating species can increase not only the expected income but also the riskiness of the lottery, so that for risk-averse farmers wild pollinators do not need to have an insurance value. However, in one scenario, wild pollinators stabilize the income distribution (the standard deviation decreases) and therefore have a positive insurance value. However, the coefficient of variation (variance related to the mean) decreases in most scenarios. This can also be interpreted as a risk-reducing effect. However, the utility function used here only takes into account that the standard deviation increases and neglects to take into the account the coefficient of variation. That is, whether there is in economic insurance value of pollinator diversity is dependent on the farmers' risk preferences.

5 Conclusion

All in all, we find that wild pollinators increase expected farm income and can have different effects on the income distributions. On the one hand, wild pollinating species increase the standard deviation in most cases, but on the other hand, taking the coefficient of variation into account, wild pollinating species can also have a stabilizing effect on income distributions. We see these effects also in the economic values: risk premiums increased in most cases because the utility function takes into account the standard deviation (and not the coefficient of variation) which leads to negative insurance values in most cases. When the standard deviation decreases due to more diverse pollinator composition (scenario (c)), the risk premium decreases and we find a positive insurance value. That is, whether pollinator diversity have an insurance effect strongly depends on the exact type of risk preferences of the farmer.

References

[1] M. H. Allsopp, W. J. De Lange, and R. Veldtman. “Valuing insect pollination services with cost of replacement”. In: *PLoS One* 3.9 (2008).

[2] K. J. Arrow. *Aspects of the theory of risk-bearing.* Yrjö Jahnssonin Säätiö, 1965.

[3] S. Baumgärtner. “The insurance value of biodiversity in the provision of ecosystem services”. In: *Natural Resource Modeling* 20.1 (2007), pp. 87–127.

[4] S. Baumgärtner and S. Strunz. “The economic insurance value of ecosystem resilience”. In: *Ecological Economics* 101 (2014), pp. 21–32.

[5] B. R. Blaauw and R. Isaacs. “Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop”. In: *Journal of Applied Ecology* 51.4 (2014), pp. 890–898.

[6] M. M. Bos, D. Veddeler, A. K. Bogdanski, A.-M. Klein, T. Tscharntke, I. Steffan-Dewenter, and J. M. Tylianakis. “Caveats to quantifying ecosystem services: Fruit abortion blurs benefits from crop pollination”. In: *Ecological Applications* 17.6 (2007), pp. 1841–1849.

[7] C. Brittain, C. Kremen, and A.-M. Klein. “Biodiversity buffers pollination from changes in environmental conditions”. In: *Global change biology* 19.2 (2013), pp. 540–547.

[8] M. Burgett, R. R. Rucker, and W. N. Thurman. “Economics and honey bee pollination markets”. In: *American bee journal* 144.4 (2004), pp. 269–271.

[9] S. A. Corbet, M. Fussell, R. Ake, A. Fraser, C. Gunson, A. Savage, and K. Smith. “Temperature and the pollinating activity of social bees”. In: *Ecological Entomology* 18.1 (1993), pp. 17–30.

[10] T. Crocker and J. Shogren. *Frontiers of Environmental Economics.* Ed. by H. Folmer, H. Gabel, S. Gerking, and A. Rose. 2001. Chap. Ecosystems as lotteries, pp. 250–271.

[11] K. S. Delaplane, D. R. Mayer, and D. F. Mayer. *Crop pollination by bees.* Cabi, 2000.

[12] *Der internationale Klimaindex.* 2015. URL: `http://www.eklima.de/?d=klimadaten&s=Sacramento,%20California&o=&i=1439&z=USA#USA` (visited on 03/04/2015).

[13] J. Free. "The flower constancy of honeybees". In: *The Journal of Animal Ecology* (1963), pp. 119–131.

[14] N. Gallai, J.-M. Salles, J. Settele, and B. E. Vaissière. "Economic valuation of the vulnerability of world agriculture confronted with pollinator decline". In: *Ecological Economics* 68.3 (2009), pp. 810–821.

[15] L. A. Garibaldi, I. Steffan-Dewenter, R. Winfree, M. A. Aizen, R. Bommarco, S. A. Cunningham, C. Kremen, L. G. Carvalheiro, L. D. Harder, O. Afik, et al. "Wild pollinators enhance fruit set of crops regardless of honey bee abundance". In: *Science* 339.6127 (2013), pp. 1608–1611.

[16] G. W. Harrison, J. A. List, and C. Towe. "Naturally occurring preferences and exogenous laboratory experiments: A case study of risk aversion". In: *Econometrica* 75.2 (2007), pp. 433–458.

[17] S. Hill, D. Stephenson, and B. Taylor. "Almond pollination studies: pollen production and viability, flower emergence and cross-pollination tests". In: *Animal Production Science* 25.3 (1985), pp. 697–704.

[18] C. A. Holt and S. K. Laury. "Risk aversion and incentive effects". In: *American economic review* 92.5 (2002), pp. 1644–1655.

[19] J. Jackson and G. Clarke. "Gene flow in an almond orchard". In: *Theoretical and Applied Genetics* 82.2 (1991), pp. 169–173.

[20] P. Kevan and H. Baker. "Insects as flower visitors and pollinators". In: *Annual review of entomology* 28.1 (1983), pp. 407–453.

[21] A.-M. Klein, C. Brittain, S. D. Hendrix, R. Thorp, N. Williams, and C. Kremen. "Wild pollination services to California almond rely on semi-natural habitat". In: *Journal of Applied Ecology* 49.3 (2012), pp. 723–732.

[22] A.-M. Klein, S. Hendrix, Y. Clough, A. Scofield, and C. Kremen. “Interacting effects of pollination, water and nutrients on fruit tree performance”. In: *Plant Biology* 17.1 (2015), pp. 201–208.

[23] C. Kremen, N. M. Williams, and R. W. Thorp. “Crop pollination from native bees at risk from agricultural intensification”. In: *Proceedings of the National Academy of Sciences* 99.26 (2002), pp. 16812–16816.

[24] D. M. Kreps. *A course in microeconomic theory.* Harvester Wheatsheaf New York, 1990.

[25] J. E. Losey and M. Vaughan. “The economic value of ecological services provided by insects”. In: *Bioscience* 56.4 (2006), pp. 311–323.

[26] R. A. Morse and N. W. Calderone. “The value of honey bees as pollinators of US crops in 2000”. In: *Bee culture* 128.3 (2000), pp. 1–15.

[27] R. Olbrich, M. F. Quaas, A. Haensler, and S. Baumgärtner. *Risk preferences under heterogeneous environmental risk.* 208. University of Lüneburg Working Paper Series in Economics, 2011.

[28] L. Pejchar and H. A. Mooney. “Invasive species, ecosystem services and human well-being”. In: *Trends in Ecology & Evolution* 24.9 (2009), pp. 497–504.

[29] J. W. Pratt. “Risk aversion in the small and in the large”. In: *Econometrica: Journal of the Econometric Society* (1964), pp. 122–136.

[30] S. R. Rogers, D. R. Tarpy, and H. J. Burrack. “Bee Species Diversity Enhances Productivity and Stability in a Perennial Crop”. In: *PloS one* 9.5 (2014).

[31] A. Soodan, A. Koul, and B. Wafai. “Floral biology of almond (Prunus amygdalus L. Batsch) under cultivation in Kashmir valley”. In: *Proceedings: Plant Sciences* 99.3 (1989), pp. 297–300.

[32] United States Department of Agriculure, National Agricultural Statistics Service. 2013.

[33] H. R. Varian and W. Norton. *Microeconomic analysis.* Vol. 2. Norton New York, 1992.

[34] N. Vicens and J. Bosch. “Weather-dependent pollinator activity in an apple orchard, with special reference to Osmia cornuta and Apis mellifera (Hymenoptera: Megachilidae and Apidae)”. In: *Environmental Entomology* 29.3 (2000), pp. 413–420.

[35] R. Winfree, N. M. Williams, J. Dushoff, and C. Kremen. “Native bees provide insurance against ongoing honey bee losses”. In: *Ecology Letters* 10.11 (2007), pp. 1105–1113.