Measuring the economic value of pollination services: principles, evidence and

knowledge gaps.

Nick Hanley[1] , *

Tom D. Breeze [2]

Ciaran Ellis [3]

David Goulson [4]

1. Department of Geography and Sustainable Development, University of St Andrews, Fife,
   Scotland, UK. Email ndh3@st-andrews.ac.uk
2. Centre for Agri-Environment Research, University of Reading, Reading, UK. Email
   t.d.breeze@reading.ac.uk
3. School of Natural Sciences, University of Stirling, Stirling, UK. Email c.r.ellis@stir.ac.uk
4. School of Life Sciences, University of Sussex, Brighton, Sussex, UK. Email
   D.Goulson@sussex.ac.uk

Revised version, July 18th 2014.

---

* Corresponding author.

Measuring the economic value of pollination services: principles, evidence and knowledge gaps.

Abstract

An increasing degree of attention is being given to the ecosystem services which insect pollinators supply, and the economic value of these services. Recent research suggests that a range of factors are contributing to a global decline in pollination services, which are often used as a "headline" ecosystem service in terms of communicating the concept of ecosystem services, and how it ties peoples' well-being to the condition of ecosystems and the biodiversity found therein. This paper explains how valuation of pollinators can aid policy design and ecosystem accounting, offers a conceptual framework for measuring the economic value of changes in insect pollinator populations, and then reviews what evidence exists on the empirical magnitude of these values (both market and non-market). This allows us to highlight where the largest gaps in knowledge are, where the greatest conceptual and empirical challenges remain, and where research is most needed.

1. Pollination: a headline ecosystem service?

Animal pollination, usually via insects, birds or bats, influences the reproductive success of ~87% of flowering plants world-wide (Ollerton et al. 2011). In temperate regions, most animal pollination is provided by honeybees (*Apis mellifera*), bumblebees (*Bombus* spp.), solitary bees, wasps and hoverflies, while in the tropics, butterflies, moths, birds and bats become important (Klein et al, 2007). Some crops, such as oilseed rape, are effectively pollinated by a broad range of insects, while others are specialized for pollination by particular insects; for example cocoa (*Theobroma cacao*) is primarily pollinated by midges (Klein et al, 2007). A number of bee species are actively managed, most notably the honeybee. Globally, evidence is emerging that wild bees and other insects are more important to crop pollination than managed bees (Garibaldi et al, 2013, 2011). Managed bumblebees are most commonly used in enclosed production systems (glasshouses and tunnels), but the other managed species are predominantly used for field and orchard crops.

Since pollination is an ecosystem service which humans depend on through its link to world food production, it has become an often-cited example of how ecosystems services are economically valuable. Worldwide, ~1,500 crops require insect pollination (Klein et al, 2007), and ~3-8% of global crop production (in tonnage) depends on insect pollination (Aizen et al, 2009). Recent estimates suggest that crop pollination by insects underpins £430 million of crop production in the UK (Smith et al, 2011), and $361 billion worldwide (Lautenbach et al. 2012). However, there is considerable doubt over the precision, reliability, usefulness and interpretation of such figures.

The ecosystem service values derived from pollinators depend to a large extent on the condition and extent of the stock of pollinators, which is part of an area's natural capital. The value of pollinators as a natural capital asset depends on the stream of economic benefits which such populations provide over time. However, in many areas, the ability of this natural capital asset to

supply us with benefits has been diminished due to pollinator population declines. Vanbergen et al (2013) list the main pressures on the supply of pollination services as:

1. Landscape change in agricultural landscapes: wild pollinators such as certain bumblebees may be disadvantaged from the loss of food sources due to decline in the area of wild flower meadows (Osgathorpe et al, 2011). More specialised pollinators tend to be more sensitive to the types of land use change inherent in land use intensification (Winfree et al, 2009). The increasing use of monocultures has been demonstrated to benefit wild pollinator abundances (e.g. Holzschuh et al, 2013) but can cause adverse community shifts (e.g. a reduction in long tongue bumblebees; Diekotter et al, 2010) and may draw pollinators away from wild plants (Holzschuh et al, 2013). Increased synthetic fertiliser use and increased livestock stocking density can also cause significant long-term shifts in floral communities, reducing available forage resources for pollinating insects (Isbell et al, 2013; Hudewenz et al, 2012). On the other hand, farmer enrolment in agri-environment schemes which provide bee-friendly habitat will reduce the negative effects of agricultural landscape change (Scheper et al, 2013).

2. Growing use of certain pesticides: there is evidence that insecticides such as neonicotinoids have significant non-lethal effects on both wild and managed bees, leading to reductions in foraging performance, decreased navigational abilities, reduced fecundity, and increased susceptibility to disease (e.g. Whitehorn et al, 2012; Di Prisco et al. 2013; Goulson, 2013). There is also growing evidence that contact with herbicides (Cousin et al, 2013), fungicides (Pettis et al, 2013) and even certain miticides (Berry et al, 2012) can have negative effects upon honeybee colony survival.

3. The introduction of alien species: Invasive plants can have detrimental effects on native pollinators by displacing native flowers (e.g. Sugiura et al. 2013), although in some instances invasive plants species may benefit native pollinators; an example is the spread of Himalayan Balsam in Europe (Bartomeus et al. 2010). Invasive, non-native bees can displace

native species either through direct competition or via spread of non-native diseases (Goulson 2003; Arbetmann et al. 2013).

4. Pathogens and parasites. Pollinators suffer from a range of parasites, notably mites such as *Varroa destructor* which widely affects honeybees across the world (Vanbergen et al, 2013) and a range of bacterial, viral, protozoan and fungal diseases. The large scale anthropogenic movement of managed bees (primarily honeybee colonies and commercial bumblebee nests) has been linked with increased disease loads in the surrounding landscape (Meeus et al, 2011) and the spread of non-native parasites and pathogens against which they have little resistance (Graystock et al. 2013). The best known example is *Varroa destructor*, which was accidentally introduced to Europe and the Americas from Asia.

5. Climate change: climate change has been linked with changes in species range (Franzen and Ockinger, 2012) and growing mis-matches between insect emergence and floral bloom (Kudo and Ida, 2013). Which bees pollinate which crops in specific regions may also change. Honey bees are less vulnerable due to their managed status and the broad range of climates they can occupy, although their activity, and therefore service delivery may alter (Rader et al, 2013). Climate change may also facilitate the growing of new insect pollinated crops in some regions e.g. the expansion of fruits northwards, but is also likely to result in the abandonment of some crops.

These pressures, many of which are the result of economic activities, ultimately result in economic losses to the flow of ecosystem services from the stock of pollinators. The economic value flows from pollinators are both market and non-market, as explained in detail in section 3. Market-valued benefits from pollinators consist of the contribution they make to the growing of a range of agricultural and horticultural crops (Gallai et al, 2009). Non-market benefits come from the utility which people derive from seeing pollinators or simply knowing they are being conserved and the indirect values derived from the aesthetic and cultural value of the wild flowers and garden plants which require pollination to sustain them. At any point in time, the present value of the future

stream of market- and non-market valued benefits from pollinators defines the value of this natural asset within a landscape.

In this paper, we provide an overview of why the economic valuation of pollination services in particular is useful to policy-makers and other stakeholders. This is followed by a brief review of the methods presently utilised to measure the economic values of insect pollinators for different end uses, highlighting the shortcomings of these methods in relation to their potential end uses. We then review the empirical literature and the proposed frameworks to highlight the main gaps in the evidence base.

2. Why measure the economic value of pollination services?

The economic valuation of pollination, as with any ecosystem service, has a number of potential context-specific uses. First, economic valuation of ecosystem services is a means of illustrating the value (benefits) of conserving pollination services (Costanza et al, 2014), and highlights the risks of these services diminishing to policy makers and other stakeholders that may not have previously considered or understood their benefits (Abson and Termenson, 2010).

Secondly, once quantified economically, the market and non-market values of pollination can be included as part of cost-benefit analysis to inform policy or business decisions and land planning (Hanley and Barbier, 2009). For instance, a decision on whether to maintain the current EU ban on neonicotinoid pesticides would be better informed if the economic benefits of restricting the use of such pesticides, in terms of foregone pollination services, could be compared with the economic costs of such a policy, such as declines in agricultural yields (Goulson, 2013). Similarly, the economic benefits of enhanced wild pollinator populations arising from agri-environmental measures could be compared with the costs of such schemes, in order to prioritise and rationalise public expenditures to enhance the production of public goods (Breeze et al, 2014).

Finally, valuation allows for the construction of extended or environmentally-adjusted national accounts which show the value of changes in a country's natural capital, and to track changes in the value of ecosystem assets which make up the natural capital stock (Barbier, 2011). Internationally agreement is slowly emerging on the importance of registering the economic value of ecosystem service flows in national economic and environmental reporting and accounting (ONS, 2012; UNEP, 2012; UN, 2013). An environmentally-adjusted value for Net Domestic Product (a measure of national income) would ideally incorporate both market and non-market benefits which are supplied by pollinators in any year, and also include a depreciation/net investment term to capture year-on-year changes in the capital value of the asset – its ability to provide direct and indirect benefits over time. However, the value of benefits to crop producers in year t from pollinators would not be added to the adjusted Net Domestic Product in year t since that value would already be included in the value of agricultural production (Nordhaus, 2006).

3. Conceptual frameworks for measuring the economic benefits from pollinators.

In this section, the ways in which stocks of pollinator populations generate economic values is explained for (i) market-valued outputs (ii) non-market values. This leads to an explanation of how such values can be quantified for applied use. From an economic valuation viewpoint, economic value is often thought of in terms of marginal values; that is, as a pollinator population rises or falls by one "unit" (e.g. by one additional colony in a landscape), what are the change in benefits people potentially receive from pollinators?

3.1 Market values

Pollinators provide economic value to crop production through increasing the quantity and quality of crops produced, resulting in greater economic output which is in turn influenced by

market prices for the crop. The extent of these benefits will vary between crops (Klein et al, 2007) and varieties (e.g. Hudewenz et al, In Press) depending on the degree of floral self-compatibility. As such, pollination services (*PS*) act as an input into total crop production in a similar manner to conventional inputs such as plant protection products. This can be captured as part of a crop output production function, a form of economic model which relates the physical yield of a given crop, x1, to variations in the supply of pollination services *PS*:

$$Q(x1) = f(Y, PS, \varepsilon) \tag{1}$$

where Q(x1) is the economic output per hectare per year, Y is a vector of inputs (e.g. labour hours, pesticides etc.) and ε represents stochastic factors such as rainfall and temperature. There will be a separate production function for each crop (x1, x2, x3..) relevant to a farmer's choices of what to grow. PS effectively represents the probability that any given flower will be sufficiently pollinated (*v*) above a threshold number of grains required to produce marketable fruit of a specified quality. As such, the lower the chance of a flower being sufficiently pollinated, the higher the marginal value of additional pollination services. As farmers will also have the option of switching between crops, these values are also heavily influenced by the costs in substituting between crops, particularly if switching to non-insect pollinated crops. This is likely to be very low in arable crops but much higher in orchard and small fruit crops where substitutes are themselves pollinator dependant (Klein et al, 2007).

However, the supply of pollination services is different from other agricultural inputs because of its direct link to plant reproduction. As such in some crops, pollination is essential to producing any positive level of output and thus other inputs in the "no pollination" scenario can generate zero output for some crops. In other crops, pollination only slightly enhances yield (Klein et al 2007). Pollination services could therefore be distinguished from other inputs by using a scaling function *Z,* the value of which lies between zero and one, which is then applied to *potential* output which depends on use of other inputs such as fertiliser and labour:

$$Q(x1) = \{(f'\,(Y)) * Z(\,PS)\}, \varepsilon \qquad\qquad\qquad (2)$$

Through this direct production, pollination also influences consumer welfare: by maintaining supplies of a crop relative to demand pollination acts to keep prices to consumer low, thus increasing consumers' surplus (Gallai et al, 2009; Lautenbach et al, 2012).

Unlike many other inputs, pollination services are often provided for little or no cost to the producer; particularly wild pollination services which are often produced from habitats that are left to develop on land with poor access and productivity, minimising opportunity costs to the producers. Mass flowering crops can themselves sustain crop pollinators through the temporary abundance of floral resources, effectively creating a positive feedback loop (e.g. Holzschuh et al, 2012). As such pollinators provide a service for a low cost that would otherwise have to be paid by the producer if they wished to optimise yield (Allsopp et al, 2008; Partap and Ya, 2012), reducing their marginal production costs per unit and as such increasing producer welfare (Kasina et al, 2009).

3.2 non-market values

Beyond crop production, insect pollinators provide a number of non-market benefits. From an economic value viewpoint, this happens in at least two ways. First, individuals derive pleasure from seeing pollinators and knowing they exist. This is known as non-use, passive use or existence value. Such values are direct benefits to individuals from the presence, diversity and abundance of pollinators and as such changes to the presence, abundance and/or diversity will change utility. The monetary value of such changes in utility is given by an individual's willingness to pay (WTP) for an improvement in pollinator populations, or WTP to avoid a loss of pollinators. For an individual *a,* we could write therefore that their utility *U* depends on:

$$U_a = f\,(S1, S2, S3, Y, N, E) \qquad\qquad\qquad (3)$$

where Y is income, capturing ability to pay, E is other environmental attributes and N is all other goods and services in the individual's choice set. The marginal, direct non-market value of a change in population S1 is given by wtp^* in (4), where $S1^0$ is some initial population of pollinator species S1 and $S1^1$ is a higher population level (here we assume that the populations of other pollinators S2 and S3 are un-changing):

$$U_a (S1^0, S2, S3, Y, N, E) = U_a (S1^1, S2, S3, Y\text{-}wtp^*, N, E) \qquad (4)$$

The marginal utility and thus marginal WTP for pollinator diversity or abundance will likely be lower, the higher the level of species diversity or abundance in an area.

Second, individuals may care about the consequences of pollinators' actions. For example, this could be through the effects of wild pollinators on the diversity and abundance of wild flowers and trees. Several studies have noted that respondents derive greater aesthetic utility from increasingly floristically diverse landscapes (Lindeman-Matthies et al, 2010), indirectly benefitting from the actions of pollinators. Wild pollinators are also important for the production of fruit and seeds for wild birds through their action on wild and garden plants (Jacobs et al, 2009), thus indirectly contributing to the utility from bird-watching. If we assume that the variable *E* in equation (3) captures the importance of wild flowers and trees and of gardens and allotments to people, then the indirect, non-market economic value of pollinators is given by the effects of changes in pollinator populations on E. Ideally, we would want to empirically measure the partial derivative of *E* with respect to S multiplied by the partial derivative of *U* with respect to *E*.

4. Empirical evidence on the application of pollination service valuation.

4.1 Market values

The majority of studies into the economic value of pollination services have been purely illustrative and used to raise awareness of the impact of pollination services on regional or national agriculture (e.g.: Jai-dong and Chen, 2011; Calderone et al, 2012). Almost all of these studies have focused on producer benefits of crop production. Early studies equate the benefits of insect pollination with the total value of crops produced (Matheson and Schrader, 1987; Costanza et al, 1997), or else use rents paid to bee-keepers for pollination services (Burgett et al, 2004) as the value of pollination services. However, neither of these methods are ideal, as most crops are able to produce some yield in the absence of insect pollination (Klein et al, 2007) and as many countries lack a well-defined market for honeybee pollination services (Carreck et al, 1997). Furthermore, even in countries where hive rental is widespread, honeybees often provide only a minority of pollination services (Garibaldi et al, 2013) and hiring them for pollination may be uncommon for many crops (e.g. Oilseed Rape; Carreck et al, 1997).

Most studies have focused on estimating the value of pollination as an input into crop production using a simplified production function known as a dependence ratio (DR) which measures the proportion of crop output lost without pollination services. This DR approach was taken in the UKNEA (Smith et al, 2011) to measure the economic value of pollination for all UK crops in 2007 and has been similarly applied in numerous countries (Table 1). DR values are typically based on field research into the impacts of pollination services on yield or reviews of this work (e.g. Klein et al, 2007) and can capture the variation in benefits from insect pollination of different crops. As such the marginal benefits of pollination will rise in proportion to DR. The DR approach has served to illustrate the benefits of pollination by highlighting regions where total production is especially vulnerable to pollinator declines, and thereby to highlight areas where spending on pollinator conservation would be most beneficial (e.g. Lautenbach et al, 2012). Cook et al (2007) also use this method to compare the benefits of pollinator conservation to the costs of preventing *V. destructor* impacts in Australia.

Although easily applied and updated using regional or national production statistics, DR

values are susceptible to a number of biases based on the studies they are drawn from. Firstly, studies may not use standardised methods, leading to bias arising from methodological differences. Second, the studies used may not account for all economically significant aspects of output that are influenced by pollination, such as crop quality or producer costs (Garratt et al, 2014). Third, applying a single DR value to a crop may misrepresent varietal differences in pollination service benefits (e.g. Hudewenz et al, In Press), which is particularly important where varietal turn-over is high. Finally, DR methods innately assume that pollination services are already at a maximum, which may not be the case (e.g. Garratt et al, 2014) and only estimate a 100% loss of pollination service rather than marginal losses.

Some studies have attempted to rectify these faults by assessing the per hectare benefits from comprehensive field studies that account for the effect of market quality benefits, cultivar variations (Garratt et al, 2014) and storage life (Klatt et al, 2014) as well as the effect on varying producer profits. Like DR studies, however, these yield analysis (YA) studies remain largely illustrative, as they lack mostly lack the information to link marginal changes in pollination services to crop output (but see Ricketts and Lonsdorf, 2013). However, if supported with sufficient data relating pollination services to local landscapes, it is possible for these small scale studies to develop estimates of the potential natural capital value of pollination services from particular surrounding habitats. This application has been undertaken by Ricketts and Lonsdorf (2013) for coffee production in Costa Rica, a study which highlights the effects on the marginal value of forest patches with increasing distance. There are however a range of issues in extrapolating upward from any small scale study, most notably as the representativeness of the site or landscape (Eigenbrod et al, 2010) and the marginal variation in demand for pollination services.

Other studies have expanded the DR model to illustrate the impacts of changes in pollination services on consumer welfare, using econometric techniques to calculate losses in consumer surplus (CS); an economic measure of the disparity between the price paid for a good and the price that the public are willing to pay. Although more comprehensive than DR studies, accurate estimates of the

relations between crop prices, production and consumer welfare require extensive data and partial equilibrium econometric analysis (e.g. Southwick and Southwick, 1992), which would ideally include an analysis of trade effects for traded crops, which most current CS studies have not incorporated (Kevan and Phillips, 2001). As CS estimates are extensions of DR analyses they also suffer from the same flaws of DR analyses.

An alternative to these basic production function approaches is to examine costs avoided by the presence of pollinators by estimating the costs of replacing them (e.g. Allsopp et al, 2008). Unlike DR studies these replacement costs (RC) methods are less susceptible to geographic or cultivar variations and do not require assumptions to be made regarding current service levels. Again, these studies remain almost exclusively illustrative due to their inability to highlight the effects of marginal changes in both insect or artificial pollination services and the impacts on crop prices that would result from the adoption of such methods. It is unlikely that this method would be applicable for all crops, as artificial pollination methods have proven ineffective on a number of crops (e.g. Kempler et al, 2002), and, more importantly, are unlikely to accurately estimate the full value of a these ecosystem services, due to issues of substitutability, joint products and the need for the least-cost alternative to be considered when such avoided costs are calculated (Hanley and Barbier, 2009).

More recently, Winfree et al (2011) combined DR, CS and RC methods into a single assessment of the value of pollination for watermelon production in Pennsylvania based upon a detailed YA study. This combination of methods produced a more comprehensive examination of pollination service benefits to the crop, both within and beyond the state of Pennsylvania. However, much of the data collected remains very case specific and is of limited use in broader cost:benefit analysis.

 4.2 Non-market values

Whilst many studies in the literature have applied stated preference methods to estimate the value non-market benefits of biodiversity, at present only one study has undertaken stated preference estimates of either direct or indirect non-market pollinator benefits,(Mwebaze et al, 2010). This resulted in an estimate for the existence value of protecting honeybees in the UK of £1.77bn/year. However, this study is based on a small and non-random sample of the public, whilst the question used to elicit willingness to pay means that this figure confuses the market- and non-market values of pollinators. Moreover, since the survey did not contain any statement regarding the consequentiality of responses, there was no incentive for participants to reveal their true values.

5. Expanding the evidence base.

Although economic valuation of pollination services has a number of potential end uses, our review has highlighted that presently most studies are mainly illustrative of the economic benefits of pollinators. Although illustrative research has uses in raising awareness, policy engagement on pollination services has become particularly strong in many countries with major policy initiatives such as the UK's National Pollinator Strategy (DEFRA, 2014). In the following section we present an expanded framework for market valuation and propose methodologies for non-market valuation of pollination service benefits that can facilitate the production of evidence which is more useful to the kinds of objectives outlined in section 2.

5.1. Expanding methods – Market Valuation

Most existing valuations of pollination services are not applicable to cost-benefit analyses concerning particular policies because they do not measure the impacts of marginal changes in pollinator populations on consumer and producer well-being. At a primary, bio-economic modelling level, it will be of critical importance to expand the production function models described previously

in order to assess the full breadth of impacts arising from pressures/mitigations of concern for cost-benefit analysis and the transferability between sites required in natural capital asset valuation.

As pollination services are provided by communities of mobile organisms they are largely stochastic and depend on a range of factors within the community. Foremost, the supply of pollination services *PS* is influenced by both the relative pollination efficiency of different insect species (honeybees, bumblebees, hoverflies etc.), S, and the overall diversity of taxa within the landscape. The efficiency of individual pollinator species is in turn a product of their effectiveness as pollinators (*E*), usually in terms of pollen grains deposited/visit (e.g. Winfree et al, 2011), their visitation rate/period (*T*) (e.g. Woodcock et al, 2013). This in turn will be affected by the probability of a species making a visit (R) and their overall abundance (*A*) within the landscape. The pollination services provided by an individual species *i* for a given crop X1 can therefore be expressed as:

$$PS_i(X1) = h\,(E, T(R, A)) \hspace{4cm} (5)$$

This framework allows for direct modelling of the economic impacts of drivers that affect pollinator efficiency, particularly in systems that rely heavily upon a single pollinator such as glasshouse crops.

In most systems however, pollination services are provided by a range of species. These species may each provide services independently, resulting in additive benefits. However in several systems, pollinators act as compliments, with the activities of one species or group of species enhancing the service efficiency of others (e.g. Brittan et al, 2013a; Greenleaf and Kremen, 2006). Similarly, species may act as substitutes for one another, maintaining service levels under pressures such as the population declines and adverse climate conditions (e.g. Brittan et al, 2013b; Winfree and Kremen, 2009). The rate of substitutability between pollinators (ie the change in PS if population S1 falls by 5%, whilst population S2 rises by 5%) , particularly between managed and wild species,

also informs the insurance value of pollinators in maintaining the flow of pollination services in the event of a major disease outbreak (Baumgartner, 2007).

$$PS (x1) = g (S1, S2, S3....) \hspace{4cm} (6)$$

Information on such community level production functions for pollination services would allow for an assessment of the costs and benefits of certain policies that are likely to affect multiple pollinators; for instance if a new agrochemical causes a 10% decline in S1 but leaves S2 and S3 unaffected. As the abundance of any species within the community changes, the function (6) should allow the estimation of the effects on output. The overall community composition in a landscape will be influenced by a number of local factors, including the intensity of pressures (e.g. agrochemicals) local foraging resources and the strength of a source population (Scheper et al, 2013; Kleijn et al, 2011). These can be modelled as part of (6) based on existing projective models such as the inVEST model (Lonsdorf et al, 2009) and linked back to service value by way of (5) above.

Finally, production function models can be further expanded by incorporating measures of farmer costs in order to examine the effects of different cropping patters within the landscape and interventions on overall profits. In this case, the prices of all outputs (crops) the farmer could grow, along with the costs and marginal physical products of each input, would be relevant to determining the maximum profit he can make, and determining the combination of crops and management regime which result in this maximum. The effects of changes in the supply of pollination services on farm-level profits could thus be estimated. Existing modelling approaches could be used to describe such an optimisation system, incorporating ecological links between farm management and ecosystem service supply, as described for example in Armsworth et al (2012) or Hanley et al (2012), in order to link the PS values estimated by the production function models such as (5) and (6) to land use planning and predictive modelling of changes in farmer behaviour.

5.2. Expanding methods - Non-Market valuation

To date the non-market benefits of pollination services have only been vaguely explored (Mwbaze et al, 2010). As such these benefits remain a major uncaptured knowledge gap despite the availability of methodologies to do so. Economists have developed a range of methods for empirically estimating such non-market values (Hanley and Barbier, 2009). For both direct and indirect non-market values of insect pollinators, it seems likely that only stated preference approaches would be a feasible method. Stated preferences work by asking a sample of individuals to either state whether they would be willing to pay a particular sum of money for an increase in an environmental good, or their willingness to accept compensation for a decline in this good (contingent valuation); or by asking people to make choices between different "bundles" of environmental attributes and a price (choice experiments). These responses are obtained in the context of a carefully-constructed hypothetical market for the good in question. Features of such markets which have been shown to be important are (i) that respondents feel that their responses are consequential (Vossler et al., 2012); (ii) that a non-voluntary payment mechanism be used (iii) that the environmental change in question be clearly described, and that any uncertainty over this environmental change is also well-described and (iv) that the hypothetical market is realistic and does not encourage ethical rejection (Riera et al, 2012) .

For direct benefits, where people care about the populations of pollinators, either contingent valuation or choice experiments could be used to estimate willingness to pay for a change in such populations (e.g. a 10% increase in bumblebee abundance over a 5 year period in England). Choice experiments would enable the researcher to measure the impacts of different attributes of such a policy change on people's preferences – such as whether they prefer an increase in species diversity rather than abundance, and whether they prefer policy to be targeted at endangered or common species. Either method could be used to show how the non-market direct benefits of pollinators vary across the country and across income groups, or between rural and

urban households, and both have been used to estimate the utility benefit of changes in biodiversity across a wide range of settings (Atkinson et al., 2014; Jobstvogt et al, 2014). The main challenges of applying SP methods to estimating direct utility values of pollinator populations would be to meet the good design requirements noted as (i) – (iv) above. Moreover, individuals may feel that they lack sufficient knowledge about the ecological importance of pollinators to be able to state their preferences in terms of Willingness to Pay for prospective changes in pollinator populations (Christie et al, 2006), although methods are available which can reduce this lack-of-knowledge barrier to valuing changes in biodiversity (e.g. LaRiviere et al, 2014; Colombo et al, 2013).

For indirect benefits, choice experiments and contingent valuation could be used to value marginal changes in the environmental goods which pollinators help to produce, such as wild flower meadows. However, it would be difficult to design a study in such a way that one could isolate the contribution of (wild) pollinators to the production of the environmental good which people are valuing (e.g. a 25% rise in the number of wild flower meadows in Devon).

6. Knowledge gaps

Whilst there is a clear conceptual basis for measuring the economic value of insect pollinators to the detail required for application by policy, and whilst there are a range of methods that exist for estimating these values, there remain deficiencies and omissions in the empirical literature on market values of pollination, and an almost total lack of empirical studies on non-market values. One significant barrier to wider and better use of production function approaches is the lack of generalizable, empirical functions (production functions) which relate pollinator efficiency, abundance and diversity to crop output outside of local case studies.

6.1. Market based valuation

To date, studies on the efficiency of individual pollinators have focused on comparisons between different managed species (e.g. Thompson and Goodall, 2001) although some more recent studies have begun to more formally address the efficiency of wild species groups (Winfree et al, 2011). However, even these studies have not provided enough information to generalise species service efficiency beyond their particular case study areas, focusing instead on observations of individual species or generalised groups. A traits based approach, in which morphological (e.g. size or tongue length) and behavioural traits (e.g. activity period) are linked to individual species efficiency (Ne'eman et al, 2010) would allow for a greater degree of value transfer on a per crop basis and could theoretically be linked with crop flower traits (e.g. flower size, pollen production) to better generalise these relationships and identify those wild and managed pollinators which are likely to be of particularly high economic value.

Pollinator abundance is important in determining both individual species efficiency within the landscape (eq. 5) and their contribution to overall service delivery (eq. 6) which is in turn affected by the abundance of other species within the landscape. Several recent studies have linked the abundance and diversity of pollinators to their service delivery (Hoehn et al, 2008; Rader et al, 2009), however the effects of substitution and interaction between species have also only been explored in a few specific case studies (e.g. Greenleaf and Kremen, 2006; Rader et al, 2013). As with species efficiency, a traits based approach linking diversity to services would be ideal for facilitating a more accurate and transferrable assessment of pollination service values without having to know all species identity.

Another research gap relates to threshold effects. Threshold effects in the supply of pollination services due to a decline in the condition of the pollinator asset would result in large changes in the marginal economic value of pollinators. These thresholds are likely to occur at lower levels for crops or wild plants that are more reliant on specific pollinators such as field beans (Free, 1993). Areas reliant on honeybees are also vulnerable to collapse, as diseases can spread quickly

between colonies, and can spill over into wild bumblebees (Furst et al. 2014). The integrity of the pollinator asset could decline in a non-linear way if there is a positive feedback between wild flower diversity loss and pollinator diversity. There are also issues of reversibility; once a population has suffered significant losses it may be difficult or impossible to recover without intervention (Ellis et al, 2013). Understanding population thresholds and reversibility, using existing ecological models of population dynamics, is therefore a key factor when examining the long term costs and benefits of actions that are likely to increase pressures on pollinators.

Although ecological research has linked the abundance and diversity of pollinators to landscape features such as agrochemical use and semi-natural habitat (Scheper et al, 2013 and references therein) these links have yet to be widely generalised. As such, attempts to map the availability of pollination services still rely heavily on expert appraisal (e.g. Lonsdorf et al, 2009; Schulp et al, 2013), leaving it difficult to determine the potential or actual service delivery of pollinators at a landscape level. This knowledge gap, an essential barrier to accurate integration of wild pollinators into natural capital accounts, could be most accurately filled by the development of systematic monitoring schemes, methodologies for which are already well established (LeBuhn et al, 2013). Unfortunately, while a number of schemes monitor the diversity of species within landscape, no systematic monitoring scheme has yet widespread trends in pollinator abundance, although the UK government has acknowledged the need for such a scheme (DEFRA, 2014). This in turn allows for a more detailed assessment of the costs and benefits of different pressures and mitigation actions on pollinator populations by comparing the status and trends of populations in landscapes with different management.

Beyond the ecological aspects of estimating market benefits, our review highlights a limited number of studies examining market benefits to stakeholders beyond producers. While models exist to assess the impacts on consumer surplus (e.g. Lautenbach et al, 2012), limited information at how national crop prices react to yield changes, particularly when the crop is widely traded

internationally (Kevan and Phillips, 2001), prevents these models being more widely used (but see Winfree et al, 2011). As such, time series econometric analyses of these relationships would have substantial value in assessing the wider benefits of changes in pollination services and assessing the marginal costs of changing to non-insect pollinated crops. Furthermore, many of the studies examining consumer effects have only explored the value based on prices paid to farmers, which will often represent what supermarkets and other distributors will pay, pointing to a need to examine the broader supply chain.

Perhaps most fundamentally, pollination production functions are complex ecological-economic models and such, a multi-stage, data intensive modelling approach as proposed here is likely to require extensive research to implement. The species links between abundance at an individual and community in particular represents a major challenge for modelling.

6.2. Non-Market Valuation

Although non-market valuation methods are well established for ecosystem services in general they have yet to be applied to any wider degree regarding pollination services, in itself a significant knowledge gap when considering the total economic benefits of pollination. Part of the complexity in assessing these values is the inherent difficulty of separating the value of pollination from that of pollinators. Limited public knowledge of the linkages between pollinators and pollination services is also likely to complicate the use of stated preference approaches (Christie et al, 2006). A major knowledge gap in assessing these non-market values is therefore the extent of public knowledge and information about pollination services, and how this relates to public willingness to pay for programmes designed to increase pollinator populations.

More significantly however there remains the challenge to identify links between marginal shifts in pollinator populations and the values attributed to the non-market benefits arising from

them. When attributing value to the aesthetic values of floral diversity, large plant-pollinator networks can be involved, adding additional complexity to assessments of the marginal changes in pollinator communities (Burkle et al, 2012). As such, it becomes difficult to generalise key pollinators in landscapes and therefore identify the impacts of marginal changes caused by pressures or mitigations. This is likely to be true of other indirect, non-market benefits from pollination services.

7. Conclusions

This paper has reviewed the conceptual basis and rationale for evaluating the economic benefits of pollination services. Of the principal uses of valuation, existing work has focused almost exclusively on illustrative studies, with few studies generating values which can be used in cost-benefit analyses or natural capital accounting. To this end we have presented a more detailed framework for valuing marginal impacts of shifts in pollinator communities on the market and non-market values associated with pollination services. The knowledge gaps identified highlight the significant ecological complexity of developing such models, with extensive field ecology required to build the comprehensive production function models to answer these questions.

These knowledge gaps in turn highlight the principal difficulties in developing valuation in a form that is suitable for cost-benefit analysis and/or natural capital – the increasing complexity required to make assessments of benefits transferrable and comprehensive. While a number of localised studies have developed methods suitable for assessing costs and benefits (Winfree et al, 2011; Cook et al, 2007) and contributions to natural capital (Ricketts and Lonsdorf, 2013), these are highly case-specific. Extrapolating from these studies therefore runs the risk of presenting erroneous values or over-generalising fringe situations (Eigenbrod et al, 2010). However, it is these broad, region and national scale analyses that are of particular interest to stakeholders and policy (Vanbergen et al, 2012; UNEP, 2012). As such, if research is to achieve the demands for truly

functional valuation it will be imperative for policy makers and other stakeholders to increase support for pollination services research. However, based upon the conceptual framework for valuation set out in this paper, we recommend the following priority areas for research: 1) the Identification of key pollinator traits in a range of representative crops, 2) assessment of the behavioural and morphological traits that facilitate substitution and synergy (complementarity) within pollinator communities, 3) evaluation of the links between habitat variables and the populations of pollinators, ideally using a systematic monitoring scheme, 4) econometric analyses of the links between insect pollinators, production and consumer prices for these crops and 5) an assessment of the non-market benefits of pollination services utilising stated preference techniques to reveal the wider values of pollination as a headline ecosystem service.

References

Abson D. and Termansen M. (2010) Valuing Ecosystem Services in Terms of Ecological Risks and Returns. *Conservation Biology* **25**, (2), 250-258.

Aizen M.A. Garibaldi L.M., Cunningham S.A. and Klein A.M. (2009) How much does agriculture depend on pollinators? Lessons from long-term trends in crop production; *Annals of Botany 103*, (9), 1579-1588

Allsopp, M.H., W.J. de Lange, and R. Veldtman (2008), Valuing Insect Pollination Services with Cost of Replacement. *PLoS ONE* **3**,(9)

Arbetman, M.P. Meeus, I., Morales, C.L., Aizen, M.A. & Smagghe, G. (2013) Alien parasite hitchhikes to Patagonia on invasive bumblebee. Biological Invasions 15: 489-494.

Armsworth P, Acs S, Dallimer M, Gaston K, Hanley N and Wilson P (2012) "The costs of simplification in conservation programmes" *Ecology Letters,* Volume 15, Issue 5, Pages: 406–414.

Atkinson G., Bateman I.J. and Mourato S. (2014) "Valuing ecosystem services and biodiversity" in Helm D. and Hepburn C. (eds) *Nature in the Balance.* Oxford: Oxford University Press, pages 101-134.

Barbier, E.B. (2011) *Capitalizing on Nature.* Cambridge: Cambridge University Press.

Bartomeus, I., Vila, M. and Steffan-Dewenter, I. (2010) Combined effects of *Impatiens glandulifera* invasion and landscape structure on native plant pollination. *Journal of Ecology* **98**: 440-450.

Baumgartner, S., (2007) The insurance value of biodiversity in the provision of ecosystem services. *Natural Resource Modelling,* 2007. **20**: p. 87-127.

Berry J.A., Hood W.M., Pietravalle S. and Delaplane K. (2012) Field-Level Sublethal Effects of Approved Bee Hive Chemicals on Honey Bees (Apis mellifera L); *PLoS One 8*, (10), e76536

Brading P., El-Gabbas A., Zalat S. and Gilbert F. (2009) Biodiversity Economics: The Value of Pollination Services to Egypt; *Egyptian Journal of Biology 11*, 45-51

Brittan C., Williams N., Kremen C. and Klein A.M. (2013) Synergistic effects of non-Apis bees and honey bees for pollination services; *Proceedings of the Royal Society B – Biological Sciences 280* 20122767

Breeze T.D., Bailey A.P., Balcombe K.G. & Potts S.G. (2014) Costing Conservation: An Expert Appraisal of the Pollinator Habitat Benefits of England's Entry Level Stewardship; *Biodiversity and Conservation 23*, (5), 1193-1214

Burkle L.A., Marlin J.C. and Knight T.M. Plant-Pollinator Interactions over 120 Years: Loss of Species, Co-Occurrence, and Function; *Science 339*, 1611-1615

Burgett M., Rucker R.R. and Thruman W.N. (2004) Economics and Honey Bee Pollination Markets; *American Bee Journal 144*, (4), 269-276

Calderone, N.W., (2012) Insect pollinated crops, insect pollinators and US agriculture: trend analysis of aggregate data for the period 1992-2009. *PLoS One*. **7** (5): e37235

Calzoni G.L. and Speranza A. (1998) Insect controlled pollination in Japanese plum (*Prunus salicina* Lindl.); *Scientia Horticulturae **72***, 227-237

Canadian Honey Council (2001) Pollination Value; *Hivelights **14***, (4), 15-21
http://www.honeycouncil.ca/index.php/pollination_value

Carreck N.L., Williams I. H. and Little D.J. (1997) The Movement of honey bee colonies for crop pollination and honey production by beekeepers in Great Britain; *Bee World 78*, (2), 67-77

Carreck N. and Williams I. (1998) The Economic Value of Bees in the UK; *Bee World **79**,* (3), 115-123

Christie M., Hanley N., Warren J., Murphy K., Wright R. and Hyde T. (2006) Valuing the Diversity of Biodiversity *Ecological Economics 58*, 304-317

Colombo S., Christie M. and Hanley N (2013) "What are the consequences of ignoring attributes in choice experiments? Implications for ecosystem service values". *Ecological Economics*, 96, Pages 25-35.

Cook D.C., Thomas M.B., Cunningham S.A., Anderson D.L. and de Barro P.J. (2007) Predicting the Economic Impact of an Invasive Species on an Ecosystem Service; *Ecological Applications 17*, (6), 1832-1840

Cousin M., Silva-Zacarin E., Kretzschmar A., El Maataoui M., Brune J.L. and Belzunces L.P. (2013) Size Changes in Honey Bee Larvae Oenocytes Induced by Exposure to Paraquat at Very Low Concentrations; *PLoS One **8*** (5): e65693

Costanza R., d'Arge R., deGroot R., Farber S., Grasso M., Hannon B., Limburg K., Naeem S., O'Neill R.V., Paruelo J., Raskin R.G., Sutton P. and vandenBelt M. (1997) The Value of the World's Ecosystem Services and Natural Capital; *Nature 387* (6630) 253-260

Costanza R., de Groot R., Sutton P., van der Ploeg S., Anderson S.J., Kubiszewski I., Farber S. and Turner K. (2014) Changes in the Glaobal Value of Ecosystem Services; *Global Environmental Change 26*, 152-158

DEFRA (2014) A consultation on the National Pollinator Strategy: for bees and other pollinators in England; https://consult.defra.gov.uk/plant-and-bee-health-policy/a-consultation-on-the-national-pollinator-strategy/supporting_documents/140305%20National%20Pollinator%20Strategy_final.pdf

Delaplane K. S. and Mayer D. E. (2000) *Crop Pollination by Bees,* CABI Publishing; Wallingford

Di Prisco, G., Cavaliere, V., Annoscia, D., Varricchio, P., Caprio, E., Nazzi, F., Gargiulo, G. and Pennacchio, F. (2013) Neonicotinoid clothianidin adversely affects insect immunity and promotes replication of a viral pathogen in honey bees; *Proceedings of the National Academy of Science of the United States **110***, (46): 18466-18471.

Diekötter T., Kadoya T., Peter F., Wolters V. and Jauker F. (2010) Oilseed Rape Crops Distort Plant-Pollinator Interactions; *Journal of Applied Ecology 47*, (1), 209-214.

Eigenbrod F., Armsworth P., Anderson B.J., Heinemeyer A., Gillings S., Roy D.B., Thomas C.D., Gaston K.J. (2010) Error propagation associated with benefits transfer-based mapping of ecosystem services; *Biological Conservation 143*, 2487-2493

Ellis C., Goulson, D., Breeze, T. and Hanley N. (2013) "Pollination Services" in *A Natural Capital Asset Check.* London: Eftec.

Franzen M. and Ockinger E. (2012) Climate-driven changes in pollinator assemblages during the last 60 years in an Arctic mountain region in Northern Scandinavia; *Journal of Insect Conservation 16*, 227-238

Free J. (1993) *Crop Pollination by Insects* (2nd Edition); Academic Press, London

Furst, M.A., McMahon, D.P., Osborne, J.L., Paxton, R.J., Brown, M.J.F (2014) Disease associations between honeybees and bumblebees as a threat to wild pollinators. *Nature 506,* 364-366.

Gallai, N., et al., (2009) Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics,* **68** (3): p. 810-821

Garibaldi L.A et al. (2011) Stability of pollination services decreases with isolation from natural areas despite honey bee visits; *Ecology Letters* **14**, 1062-1072

Garibaldi L.A. et al (2013) Wild pollinators enhance fruit set of crops regardless of honey-bee abundance; *Science* **339**, 1608-1611

Garratt M.P., Breeze T.D., Jenner N., Polce C., Biesmeijer J.C and Potts S.G. (2014) Avoiding a bad apple: insect pollination enhances fruit quality and economic value; *Agriculture Ecosystems and Environment* **184**, 34-40

Gill R.A. (1991) The Value of Honeybee Pollination to Society; *Apiacta 4* http://www.apimondiafoundation.org/foundation/files/1991/R.A.%20GILL.pdf

Goulson, D. (2003). Effects of introduced bees on native ecosystems. Annual Review of Ecology and Systematics 34: 1-26

Goulson, D., (2013) An overview of the environmental risks posed by neonicotinoid insecticides. *Journal of Applied Ecology*, 2013. **50** (4): p. 977-987.

Goulson, D., et al., (2002) Colony growth of the bumblebee, Bombus terrestris, in improved and conventional agricultural and suburban habitats. *Oecologia*, **130** (2): p. 267-273

Goulson D., Lepais O., O'Connor S., Osborne J.L., Sanderson R.A., Cussans J., Goffe L. and Darvill B. (2010) Effects of land use at a landscape scale on bumblebee nest density and survival. *Journal of Applied Ecology* **46**: 1207-1215

Graystock P., Yates, K., Darvill, B., Goulson, D. & Hughes, W.O.H. (2013) Emerging Dangers: Deadly Effects of an Emergent Parasite in a New Pollinator Host. *Journal of Invertebrate Pathology* **114**, 114-119.

Greenleaf S. and Kremen C. (2006) Wild Bees Enhance Honey bees Pollination of Hybrid Sunflower; *Proceedings of the National Academy of Sciences of The United States Of America* **103**, (37) 13890-13895

Guerra-Sanz (2008) Crop Pollination in Glasshouses in James R.R. and Pitts-Singer T.L. eds. *Bee Pollination in Agricultural Ecosystems*, Oxford University Press, Oxford

Hanley N. and Barbier E.B. (2009) *Pricing Nature: Cost-Benefit Analysis and Environmental Policy.* Cheltenham: Edward Elgar.

Hanley N, Acs S., Dallimer M, Graves A, Morris J, Gaston K and Armsworth P. (2012) "Farm-scale ecological and economic impacts of agricultural change in the uplands." *Land Use Policy*, 29 (3), 587-597

Hoehn, P. et al (2008) "Functional group diversity of bee pollinators increases crop yields" *Proceedings of the Royal Society B,* 275, 2283-2291.

Holzschuh A., Dormann C. F., Tscharntke T. and Steffan-Dewenter I. (2011) Expansion of mass-flowering crops leads to transient pollinator dilution and reduced wild plant pollination; *Proceedings of the Royal Society of London - B. Biological Science* **278**, 3444-3451.

Holzschuh A., Dormann C.F., Tscharntke T. and Steffan-Dewenter I. (2013) Mass-flowering crops enhance wild bee abundance; Oecologia 172, (2), 477-484

Hudewenz A., Klein A-M, Scherber C., Stanke L., Tscharntke T., Vogel A., Weigelt A., Weisser W.W. and Ebeling A. (2012) Herbivore and pollinator responses to grassland management intensity along experimental changes in plant species richness

Hudewenz A., Pufal G., Bogeholz A-L. and Klein A-M. (In Press) Cross-pollination benefits differ among oilseed rape varieties; *Journal of Agricultural Science* http://dx.doi.org/10.1017/S0021859613000440

Isbell F., Tillman D., Polasky S., Binder S. and Hawthorne P. (2013) Low biodiversity state persists two decades after cessation of nutrient enrichment; *Ecology Letters* **16**, 454-460

Jacobs J.H., Clark S.J., Denholm I., Goulson D., Stoate C. and Osborne J.L. (2009) Pollination Biology of Fruit Bearing Hedgerow Plants and the Role of Flower Visiting Insects in Fruit Set; *Annals of Botany* **104**, 1397-1404

Jai-Dong A.N. and Chen W.F (2011) Economic Value of Insect Pollination for Fruits and Vegetables in China; *Acta Entomologica Sinica* **54**, (4), 443-450

Jobstvogt N., Hanley N., Hynes S., Kenter J. and Witte U. (2014) "Twenty thousand sterling under the sea: estimating the economic value of protecting deep sea biodiversity" *Ecological Economics*, Volume 97, 10-19.

Kasina J.M., Mburu J., Kraemer M. and Holm-Mueller K. (2009) Economic Benefit of Crop Pollination by Bees: A Case of Kakamega Small-Holder Farming in Western Kenya; *Journal of Economic Entomology* **102**, (2), 467-473

Kevan P.G. and Phillips T.P. (2001) The Economic Impacts of Pollinator Declines: An Approach to Assessing the Consequences; *Ecology and Society 5*, (1), 8 http://www.ecologyandsociety.org/vol5/iss1/art8/main.html

Kempler C., Harding B and Ehert D. (2002) Out-of-season raspberry production in British Columbia, Canada; *Acta Horticulturae 585*, 629-632

Klatt B.K., Holzchuch A., Westphal C., Clough Y., Smit Y., Pawelzik E. and Tscharntke T. (2014) Bee pollination improves crop quality, shelf life and commercial value; *Proceedings of the Royal Society B – Biological Sciences 281*, 20132440. http://dx.doi.org/10.1098/rspb.2013.2440

Klein, A.M. et al (2007) Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B-Biological Sciences, 274* (1608): p. 303-313.

Kleijn D., Rundlof M., Scheper J., Smith H. and Tscharntke T. (2011) Does conservation on farmland contribute to halting the biodiversity decline?; *Trends in Ecology and Evolution 26*, 474-481

Kudo G. and Ida T.Y. (2013) Early onset of spring increases the phenological mismatch between plants and pollinators; *Ecology 94*, 2311-2320

LaRiviere J., Czajkowski M., Hanley N., Aanesen M., Falk-Petersen J., and Tinch D. (2014) "The Value of Familiarity: Effects of Knowledge and Objective Signals on Willingness to Pay for a Public Good" *Journal of Environmental Economics and Management*, forthcoming.

Lautenbach S., Sepplett R., Leibscher J. and Dormann C. (2012) Spatial and Temporal Trends of Global Pollination Benefit; *PLoS One 7,* (4): e35954

LeBuhn G. et al (2013) Detecting Insect Pollinator Declines on Regional and Global Scales; *Conservation Biology 27*, 1-13

Lindemann-Matthies P., Junge X. and Matthies D. (2010) The influence of plant diversity on people's perception and aesthetic appreciation of grassland vegetation; *Biological Conservation 143* 195-202

Lonsdorf E., Kremen C., Ricketts T., Winfree R., Williams S. and Greenleaf S. (2009) Modelling pollination services across agricultural landscapes; *Annals of Botany 103*, 1589-1900

Losey J.E. and Vaughn M. (2006) The Economic Value of Ecological Services Provided By Insects; *Bioscience 56*, (4), 311-323

Matheson A. and Schrader M. (1987) The value of bees to New Zealand's primary production. Nelson (New Zealand): Ministry of Agriculture and Fisheries. 5p.p.

Mayer D.F. and Lunden J.D. (1991) Honey bee foraging on dandelion and apple in apple orchards; *Journal of the Entomological Society of British Columbia 88*; 15-17

Meeus I., Brown M. J. F., de Graaf D. C. and Smagghe G. (2011) Effects of Invasive Parasites on Bumble Bee Declines; Conserv. Biol. 25, 662–671.

Morse R.A. and Calderone N.W. (2000) The value of honey bees as pollinators of U.S. crops in 2000; *Bee Culture 128*: 1-15 http://www.beeculture.com/content/PollinationReprint07.pdf

Mwebaze P., Marris G.C., Budge G.E., Brown M., Potts S.G., Breeze T.D. & MacLeod A. (2010) Quantifying the Value of Ecosystem Services: A Case Study of Honeybee Pollination in the UK; *Contributed Paper for the 12th Annual BIOECON Conference*

Ne'eman G., Juergens A., Newstrom-Lloyd L., Potts S.G. and Dafni A (2010) A Framework for Comparing Pollinator Performance: Effectiveness and Efficiency; *Biological reviews 85*, (3), 435-451

Nordhaus W. (2006) "Principles for national accounting for nonmarket assets" in Jorgensen et al (eds.) *A New Architecture for the US National Accounts.* Chicago: University of Chicago Press.

Ollerton, J., Winfree, R., Tarrant, S., (2011) How many flowering plants are pollinated by animals? *Oikos **120**,* (3), 321–326

Olschewski R., Tscharntke T., Benitez P.C., Schwarze S. and Klein A-M. (2006) Economic Evaluation of Pollination Services Comparing Coffee Landscapes in Ecuador and Indonesia; *Ecology and Society **11***, (1), 7; http://www.ecologyandsociety.org/vol11/iss1/art7/

ONS (2012), Accounting for the Value of Nature in the UK: a roadmap for the development of natural capital accounts within the UK Environmental Accounts. Office of National Statistics, UK.

Osgathorpe L, Park K., Goulson D., Acs S and Hanley N (2011) "Trade-offs between agriculture and biodiversity in marginal areas" *Ecological Economics*, 70 1162–1169

Partap U. and Ya T. (2012) The Human Pollinators of Fruit Crops in Maoxian County, Sichuan, China; *Mountain Research and Development 32*, 176-186

Pearce D.W. and Atkinson G. (1993) Capital theory and the measurement of sustainable development: an indicator of weak sustainability. *Ecological Economics* 8: p. 103-108.

Pettis J.S., vanEngelsdorp D., Johnson J. and Dively G. (2012) Pesticide exposure in honey bees results in increased levels of the gut pathogen Nosema; *Naturwissenschaften **99***, 153–158

Pimtel D., Wilson C., McCullen C., Huang R., Dwen P., Flack J., Tran Q., Saltman T. and Cliff B. (1997) Economic and Environmental benefits of Biodiversity; *Bioscience **47***, (11), 747-757

Rader R., Reilly J., Bartomeus I. and Winfree R. (2013) Native bees buffer the negative impact of climate warming on honey bee pollination of watermelon crops; *Global Change Biology 19*, 3103-3110

Rader R, Howlett B.G, Cunningham S.A, Westcott D.A, Newstrom-Lloyd L.E, Walker M.K, Teulon D.A.J. and Edwards W. (2009) Alternative Pollinator Taxa are Equally Efficient but not as Effective as the Honeybee in a Mass Flowering Crop; *Journal of Applied Ecology 46*, (5), 1080-1087

Ricketts T., Daily G.C., Ehrlich P.R. and Michener C.D. (2004) Economic value of tropical forest to coffee production; *Proceedings of The National Academy of Sciences of The United States Of America 101,* (34), 12579-12582

Ricketts T. and Lonsdorf E. (2013) Mapping the margin: comparing marginal values of tropical forest remnants for pollination services; *Ecological Applications 23,* 1113–1123

Riera P. et al (2014) "Non-market valuation of forest goods and services: good practice guidelines" *Journal of Forest Economics,* 18 (4), 259-270.

Robinson W.S., Nowogrodzki R., Morse R.A. (1989) The value of honey bees as pollinators of the United States crops; *American Bee Journal 7*, 477-487.

Scheper J. Holzschuh A., Kuussaarri M., Potts S.G., Rundolf M., Smith H. G. and Kleijn D. (2013) Environmental factors driving the effectiveness of European agri-environmental measures in mitigating pollinator loss – a meta-analysis; *Ecology Letters **16***, 912-920

Schulp C.J.E., Lautenbach S. and Verburg P.H. (2014) Quantifying and mapping ecosystem services: Demand and supply of pollination in the European Union; *Ecological Indicators **36***, 131-141

Shipp L.H., Whitfield G.H. and Papadopoulos A.P. (1994) Effectiveness of the Bumblebee, *Bombus impatiens* Cr. (Hymenoptera: Apidae), as a Pollinator of Greenhouse Sweet Pepper; *Scientia Horticulturae **57***, 29-39

Southwick E.E. and Southwick L. (1992) Estimating the Economic Value of Honey Bees (Hymenoptera: Apidae) and Agricultural Pollinators in the United States; *Journal of Economic Entomology **85**,* (3), 622-633

Smith P. et al (2011) UK National Ecosystem Assessment Technical Report – Chapter 14: Regulating Services, UNEP-WCMC; Cambridge

Stanley D.A., Gunning D. and Stout J.C. (2013) Pollinators and Pollination of Oilseed Rape Crops (*Brassica napus* L.) in Ireland: Ecological and Economic Incentives for Pollinator Conservation; *Journal of Insect Conservation **17***, (6), 1181-1189

Sugiura, S., Tsuru, T. and Yamaura, Y. (2013). Effects of an invasive alien tree on the diversity and temporal dynamics of an insect assemblage on an oceanic island. *Biological Invasions **15***, 157-169.

Thompson J.D. and Goodall K. (2001) Pollen Removal and Deposition by Honeybee and Bumblebee visitors to Apple and Almond Flowers; *Journal of Applied Ecology 38*, 1032-1044

United Nations Environment Programme (2012), *The Inclusive Wealth Report 2012.* Cambridge University Press.

United Nations (2013) *System of Environmental-Economic Accounting 2012 – Experimental Ecosystem Accounting.* United Nations Statistical Office.

Vanbergen A. et al (2013) Threats to an ecosystem service: pressures on pollinators; *Frontiers in Ecology and Evolution **11***: 251–259

Vanbergen A.J. et al (2012) *Insect pollinators: linking research and policy. Workshop report, U.K. Science and Innovation Network.* https://wiki.ceh.ac.uk/download/attachments/162464248/Final+Report+of+International+Pollinator+Workshop+2012.pdf?version=1&modificationDate=1355138969000

Vossler, Christian A., Maurice Doyon, and Daniel Rondeau (2012) "Truth in Consequences: Theory and Field Evidence on Discrete Choice Experiments." *American Economic Journal: Microeconomics*, 4 (4), 145-171.

Whitehorn, P.R., et al., (2012) Neonicotinoid pesticide reduces bumble bee colony growth and queen production. *Science,* **336**: p. 351-352

Willmer, P.G., Bataw, A.A.M. and Hughes, J.P., (1994). The Superiority of Bumblebee to Honeybees as Pollinators - Insect Visits to Raspberry Flowers. *Ecological Entomology,* **19,** (3), 271-284

Winfree R. and Kremen C. (2009) Are ecosystem services stabilized by differences among species? A test using crop pollination; *Proceedings of the Royal Society B – Biological Sciences* **276**, 229-237

Winfree R., Aguilar R., Vazquez D.P., LeBuhn G. and Aizen M. (2009) A meta-analysis of bees' responses to anthropogenic disturbance; *Ecology 90*, (8), 2068-2076

Winfree, R., B.J. Gross, and C. Kremen, (2011) Valuing pollination services to agriculture. *Ecological Economics,* **71**: p. 80-88

Woodcock B.A., Edwards M., Readhead J., Meek W.R., Nuttall P., Falk S., Nowakowski M. and Pywell R.F. (2013) *Agriculture, Ecosystems and Environment 171*, 1-8

Zych M. and Jakubiec A. (2006) How Much is a Bee Worth? Economic Aspects of Pollination of Selected Crops in Poland; *Acta Agrobotanica 59*, (1), 298-299

Table 1. Studies assessing the economic value of pollination services

Study	Region	Value (2010 GBP)	Method
Matheson and Schrader (1987)	New Zealand	£1.83bn	Crop Value
Costanza et al (1997)	Global	£118.4/ha	Crop value
Calderone (2012)	USA	£10.6bn	DR
Jai-Dong and Chen (2011)	China (horticulture)	£29.3bn	DR
Kasina et al (2009)	Kenya (small holdings)	£25-£1,910/ha	DR
Losey and Vaughn (2006)	USA	£2.30bn	DR
Morse and Calderone (2000)	USA	£12.1bn	DR
Zych and Jakubiec (2006)	Poland	£520.2M	DR
Carreck and Williams (1998)	UK	£322.1M	DR
Canadian Honey Council (2001)	Canada	£406.2M	DR
Gill et al (1991)	Australia	£0.5-£0.9bn	DR
Pimtel et al (1997)	Global	£165.7bn	DR
Guerra-Sanz (2008)	Spain (glasshouse)	£470M	DR
Brading et al (2009)	Egypt	£1.3bn	DR
Robinson et al (1989)	USA	£12.4bn	DR
Garratt et al (2014)	UK (Apples)	£36.7M	YA
Klatt et al (2014)	EU (Strawberries)	£750.7M	YA
Stanley et al (2013)	Ireland (Oilseed Rape)	£3.32M	YA
Greenleaf and Kremen (2006)	USA (sunflower)	£16.6M	YA
Olschewski et al (2006)	Indonesia & Ecuador (coffee)	£30-£31/ha	YA
Ricketts et al (2004)	Costa Rica (coffee)	Up to £97/ha	YA
Shipp et al (1994)	Canada (glasshouse peppers)	Up to £41,6450/ha	YA
Gallai et al (2009)	Global	£121.8bn	DR, CS
Southwick & Southwick (1992)	USA	£2.5-£8.3bn	DR, CS
Allsopp et al (2008)	South Africa	£17.9-£78.6m	RC
Calzoni and Speranza (1998)	Italy (plums)	£274/Ha	RC
Winfree et al (2011)	NJ, USA (watermelons)	£0.13-£2.3M	RC, YA, CS

Legend: DR = Dependence Ratio; CS = Consumer Surplus, RC = Replacement Costs, YA = Yield Analysis