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Estimating consequences of losing pollination services: an evaluation of the pollinator dependency of plants

by

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Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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ESTIMATING CONSEQUENCES OF LOSING POLLINATION SERVICES: AN EVALUATION OF THE POLLINATOR DEPENDENCY OF PLANTS

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Exponential population growth and the increased demand of land for food production present the challenge to secure enough food for everyone whilst preserving natural landscapes and biodiversity. The targets of biodiversity conservation and food production have been historically perceived as conflicting, yet the productivity of many crops is maximised by pollinator abundance and diversity. The Ecosystem Service approach addressed this dichotomy by putting emphasis on the benefits that humans obtain from conserving biodiversity. An example is ensuring a diverse food supply by maintaining diverse pollinator communities. Pollinators are intimately connected to our welfare, securing a variety of food and maintaining ecosystem function and health. Consequently, the ongoing global decline of wild pollinators prompted a growing body of research on the extent to which reproductive success of plants is enhanced by flower-visiting animals and how land-use change affects wild pollinators. The overarching aim of this thesis is to understand how losing pollination services can affect human well-being. The objectives of my research are: (1) to elucidate pollinator contribution to wild and crop plants; (2) to develop practical methods for pollination services site-scale assessment; and (3) to pilot the novel tools developed in this thesis in a nature reserve within an agricultural matrix.

Little is known about the potential consequences of losing vertebrate pollinators on plants. I used a systematic review protocol to give an overview of the importance of vertebrate pollinators for the reproductive success of the plants they pollinate. Based on a meta-analysis of 126 experiments on animal-pollinated plants, I found that an exclusion of vertebrates from plants visited by both insects and vertebrate pollinators may reduce fruit and seed production by 63%. Model selection based on Akaike's Information Criterion (AIC) further revealed that tropical plants are more reliant on vertebrate pollination than

their temperate counterparts, and bat-pollinated plants are more dependent on vertebrate pollination than those pollinated by other vertebrates. These findings highlight the potential importance of vertebrate pollinators for the long-term maintenance of both natural and agricultural tropical systems**.** This study also demonstrated the need for effective conservation action for threatened flower-visiting vertebrate species. More research is needed on the pollination system of plants and their vertebrate pollinators at a community level.

Information on the production dependence of plants on their vertebrate pollinators is scant. Here, I created a dataset of the degrees of production dependence of wild and crop plants on vertebrate pollination based on field exclusion experiments. The database includes information on 126 sites for 29 countries and 90 plants species and information on site details, plants and flower visitors. The production dependence in this dataset can be used for economic valuations of pollination services provided by vertebrates to increase understanding of their importance for food production and the maintenance of natural ecosystems, particularly in the tropics, and to better guide conservation actions.

Currently available tools for pollination service assessment operate at a global or regional scale or rely on high technical expertise. I used expert elicitation techniques to develop a practical tool for the site-scale assessment of pollination services**.** Three sets of methods were developed to suit different levels of technical expertise and resource availability: desk-based (Red standard method), observational (Amber standard method) and experimental (Green standard method). The novel tool was applied to estimate the value of pollination services provided by a small protected area in Hampshire, UK. The annual net economic value of pollination service in the current state was greater than the alternative state by between £111 and £151 ha^{-1} $year^{-1}$.

This thesis adds novel insight into the potential effects of the decline of pollinator taxa in different regions by assessing variations in the reproductive success of wild and crop plants at a global and local scale; thus increasing the much-needed knowledge of the dependence of flowering plants on flower-visiting animals, both invertebrates and vertebrates. The methods developed in this thesis can be useful to a broad range of users including scientists, governments, land managers and conservation practitioners. The accessibility of this tool provides rapid and practical means to generate robust data to inform decision-making in various regions, ecosystems and socio-cultural contexts.

To my late parents,

"The busy bee has no time for sorrow"
(William Blake)

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DECLARATION OF AUTHORSHIP

I, ...[please print name]

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

[title of thesis] ....

....

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
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Abbreviations

AIC	Akaike's Information Criterion
AIC_c	Akaike's Information Criterion corrected for small sample bias
ARIES	Artificial Intelligence for Ecosystem Services
CICES	Common International Classification of Ecosystem Services
DR	Dependence Ratio, Dependency Ratio
EIA	Environmental Impact Assessment
ES	Ecosystem Services
FWAG South East	Farming and Wildlife Advisory Group
GWCT	Game and Wildlife Conservation Trust
HIWWT	Hampshire and Isle of Wight Wildlife Trust
IESA	Integrated Ecosystem Services Assessment
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPI	International Pollination initiative
lnR	Log Response Ratio
MEA	Millennium Ecosystem Assessment
NE	Natural England
NPS	National Pollination Strategy
NTFP	Non Timber Forest Products
OSR	Oilseed rape
PA	Protected Area
PA-BAT	Protected Areas Benefits Assessment Tool

PS	Pollination Services
TEEB	The Economics of Ecosystems and Biodiversity
TESSA	Tool for Ecosystem Services Site-Based Assessment
SAC	Special Area of Conservation
SINC	Site of Importance for Nature Conservation
SLP	Selborne Landscape Partnership
SNH	Semi-natural Habitat
SSSI	Site of Special Scientific Interest
UAA	Utilised Agricultural Area
UNEP-WCMC	UN Environment World Conservation Monitoring Centre
UNESCO	The United Nations Educational, Scientific and Cultural Organization
WTP	Willingness To Pay
YA	Yield Analysis

Chapter 1 General introduction to pollination services and thesis overview

Anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist. (Kenneth Boulding)

The awareness that humans benefit from nature, both directly and indirectly, has been entrenched in our society for millennia. In modern days, this idea has been captured in the concept of "Ecosystem Services"(Costanza *et al.* 1997). One of the first classification methods to describe ecosystem services was the Millennium Ecosystem Assessment (MEA), which defined them as "the functions and products of ecosystems that benefit humans, or yield welfare to society" (MEA 2005). According to the MEA, ecosystem services can be classified into the following four categories: supporting, provisioning, regulating and cultural services. The Economics of Ecosystems and Biodiversity study (TEEB) introduced the new "Habitat or Supporting Services" and comprises the categories "Habitat for species" and "Maintenance of genetic diversity" (TEEB 2010). More recently, the Common International Classification of Ecosystem Services (CICES) moved away from the category of "supporting" ecosystem services and describes them as ecological functions, "the underpinning structures and processes that ultimately give rise to ecosystem services" (Haines-Young and Potschin 2013). The services supported by functions such as soil formation, water regulation and pollination, can, in turn, provide goods essential to humans such as food and drinking water. Nevertheless, our impact on the natural environments is unprecedented (Goudie 2018), and thus there is a need to recognise the consequences of our actions on these crucial ecosystem processes and on the services they underpin.

This chapter will set the scene for the PhD by introducing the concept of pollination services and describing the wide range of pollinators and their ongoing decline. I will then describe the potential implications of pollinator decline for human well-being concerning agricultural production, provision of essential micronutrients, supporting of biodiversity and socio-cultural benefits. This chapter then summarises the current knowledge and methodologies related to measuring and valuing pollination services and considers existing questions on pollinator dependency of plants at global and site-scale. Finally, the overall aims and research objectives of this thesis are outlined.

1.1 Pollination Services

Pollination, which is classified as a regulating service, is the process whereby plant pollen is transferred from the male to the female reproductive organs to allow fertilization (Potts *et al.* 2016). In flowering plants, pollen is transferred from the anthers (male part) to the stigma (female part) either by wind (anemophily) or by animals (zoophily). The latter is estimated to contribute to the reproduction of 87.5% of modern angiosperms (Ollerton *et al.* 2011) and 75% of the world's major food crops (Klein *et al*. 2007). This interaction affects humans' survival by contributing to the maintenance of terrestrial ecosystems and, more directly, by benefitting to various degrees the production of many crops (Klein *et al.* 2007).

The vast majority of animal pollination is carried out by insects (entomophily)(Figure 1-1). Bees are the predominant pollinator group for most plants in the majority of ecosystems (Ollerton 2017), with around 20,000 described species globally (Ascher and Pickering 2014). Of these, 50 species are managed, and 12 species are used for crop pollination, including *Apis mellifera* (western honeybee), and *Apis cerana* (eastern honeybee) as well as members of the *Bombus* sp. (bumblebees), stingless and solitary bees (Potts *et al.* 2016). Flies (order Diptera) are arguably the most common flower visitors after bees (Larson *et al.* 2001) and are dominant in higher-latitude biomes such as the tundra (Rader *et al.* 2016; Ollerton 2017). More than 70 families of Diptera are known to contain flower visitors of about 555 plant species (Larson *et al.* 2001). According to Orford *et al.* (2015), these comprise more than 100 crops including oilseed rape (Jauker and Wolters 2008; Jauker *et al.* 2012), mango (Dag 2009) and onion (Sajjad 2008). The Lepidoptera group contains around 140,000 flower-visiting species (Ollerton 2017). Of these, the majority of pollinating butterflies are found in the Papilionoideae family, while the Noctuidae (owlet moths) and Sphingidae (hawkmoths) contain most of the flower-visiting moths (Winfree *et al.* 2011a). Hawkmoths are indeed the most important pollinators amongst moths (Wardhaugh 2015) and have been found to be important pollinators of cultivated papaya (Martins and Johnson 2009).

Other invertebrate taxa such as Hymenoptera, Vespidae, Scoliidae, and Pompilidae contain flower-visiting species (Winfree *et al.* 2011a). Notable examples of wasp pollination are the figs (*Ficus*) pollinated by the fig wasps (Agaonida) (Weiblen 2002), and species of sexually deceptive orchids (Shiestl *et al.* 2003). Twenty species of wild plants are known to be visited by ants (Hymenoptera, formicidae)(Rico-Gray and Oliveira 2007), and it has been suggested that some plant taxa may depend on thrips (Thysanoptera) for pollination (Mound 2005; Klein 2007). In a literature review of 34 plant families containing beetle-pollinated species, Bernhardt (2000) found that approximately 17 families of Coleoptera visit flowering plants.

Over 920 species of birds are known to pollinate plants (Whelan *et al.* 2008) including Nectarinidae (sunbirds), Trochilidae (hummingbirds), Meliphagidae (honeyeaters) and Loridae (lories). Birds pollinate about 5.4% of the 960 cultivated plants species for which pollinators are known (Nabhan S. 1997 pers. comm.) and typically pollinate 5% of a region's flora and 10% of an island flora (Anderson 2003; Kato and Kawakita 2004; Bernardello *et al.* 2006). Amongst mammals, bats are the major pollinators, with flower-visiting bats mostly found in two families: Pteropodidae (fruit bats), occurring mainly in Asia and Australia, and Phyllostomidae (leaf-nosed bats), found throughout the Neotropics (Fleming and Muchhala 2008). Approximately 528 plant species in 67 families and 28 orders worldwide are pollinated by bats (Kunz *et al.* 2011). Non-flying mammals such as primates, rodents, and marsupials also are known to visit at least 85 species of plants worldwide (Carthew and Goldingay 1997). Flower visitation is reported for 37 species of lizard, mainly island-dwelling species (Olesen and Valido 2003). Despite the importance of vertebrate pollination, particularly in tropical ecosystems, and their essential role in the reproduction of economically valuable crop species (e.g. *Hylocereus undatus* (dragon fruit), Ortiz-Hernández and Carrillo-Salazar 2012) and *Durio* spp. (durian), Bumrungsri *et al.* 2009), information on their contribution to plant reproductive success remain sparse. See the Introduction section to Chapter 2 for more details on this issue.

Figure 1-1 Example taxa representing major groups of invertebrate pollinators. From top left to bottom right: Common carder bee (*Bombum pascuorum*)(Photo: FR), Hummingbird Clearwing (*Hemaris thysbe*)(Photo: Larry Master www.masterimages.org), German wasp (*Vespula germanica*)(Photo: Emma Joslin), Hoverfly (*Eupeodes spp.)*(Photo: FR).

1.2 Pollinator decline

Over the past few decades, a substantial decline in managed, feral and wild bees has occurred throughout North America and Europe (Potts *et al.* 2010b; Van Engelsdorp and Meixner 2010). Although population changes in wild pollinators are not comprehensively documented, studies have shown the steady decline of some groups throughout Europe such as bumblebees in the UK and Belgium (Goulson *et al*. 2008) and wild bees and hoverflies species richness in Holland and the UK (Biesmeijer *et al.* 2006; Keil *et al.* 2011). The Northern hemisphere has seen reductions in abundance, extinctions and reduced ranges of bumblebees (Cameron *et al.* 2011; Bommarco *et al.* 2012a) and butterflies (Warren *et al.* 2001), including moths (Fox 2013). In the tropics, recognized threats such as deforestation and agricultural intensification are likely to put pressure on pollinator populations, although evidence for pollination decline in these regions is still scant (Freitas *et al*. 2009).

1.2.1 Drivers of pollinator decline

There are several potential factors adversely affecting pollinator diversity and abundance: land-use change, alien species, increased use of pesticides, the spread of pests and pathogens and climate change have been described as the major drivers (Potts *et al.* 2010a, 2016; Vanbergen *et al.* 2013). Mammalian and avian pollinators are also experiencing population declines that are mainly driven by agricultural expansion, the spread of invasive alien species, hunting and fire (Regan *et al.* 2015).

Habitat loss and degradation are widely believed to be the most significant drivers of pollinator decline (Vanbergen *et al.* 2014). The total land modified by man, especially for agricultural use, accounts for more than 40% of the entire ice-free land surface (Ellis *et al.* 2010). In such highly modified environments, nesting and foraging resources are not sufficient for pollinators to thrive (Kennedy *et al.* 2013). Overall, research indicates that pollinator diversity and abundance is reduced by habitat loss (Winfree *et al.* 2009). Pollinator visitation rates, species richness and mean levels of crop fruit set also decline with increased isolation from semi-natural habitats (Ricketts *et al.* 2008; Garibaldi *et al.* 2011, 2013). Furthermore, evidence suggest that the increased use of pesticides and insecticides have important effects on both managed and wild bees, causing a number of non-lethal effects affecting foraging performance, fecundity, navigation ability and susceptibility to diseases (Di Prisco *et al.* 2013; Goulson 2013; Rundlöf *et al.* 2015; Woodcock *et al.* 2017).

Introduced non-native pollinators, whether for agricultural purposes or accidental, can displace native pollinator through direct competition or by spreading pests and diseases (Goulson 2003; Le Conte *et al.* 2010; Arbetman *et al.* 2013). Non-native plants can also disrupt native plant-pollinator interactions and displace pollinators from native plants by providing abundant nectar resources (Pysek *et al.* 2011; Sugiura *et al.* 2013). Pollinators are also subject to a range of pathogens and pests, which are the predominant reason for honeybee decline in the Americas and Europe (Vanbergen *et al.* 2013). The *Varroa destructor* mite, which was accidentally introduced from Asia, represents the most well-known example of the effect of the spread of non-native parasites to which managed bees have little resistance (Graystock *et al.* 2013). Several other pests and pathogens disperse amongst managed and wild bees (Cameron *et al.* 2011; Core *et al.* 2012) with potentially serious consequences for pollination networks and ecosystems (Kaiser-Bunbury *et al.* 2010b). Finally, climate change has been associated with shifts in the distribution of pollinator species (Warren *et al.* 2001, 2018; Kerr *et al.* 2015) and has been shown to disrupt the synchrony between floral blooms and pollinator emergence (Kudo and Ida 2013).

Climate change may also cause the abandonment of some crops in certain areas, and the expansion northwards of some insect-pollinated crops such as fruits (Hanley *et al.* 2015).

The worldwide concerns over the decline in abundance and diversity of both managed and wild pollinators encouraged the establishment of a number of initiatives by the Convention of Biological Diversity (e.g. the International Pollination Initiative FAO 2018). Several national and regional schemes such as the National Pollination Strategy (Defra 2014) and the UK Pollinator monitoring Scheme (Carvell 2017) were also initiated to address pollinator declines.

1.3 Importance of pollinators to human well-being

Pollinators are intricately related to human well-being for their influence in securing quantity and diversity of food, maintaining wild plant populations and supporting cultural and aesthetic values (Potts *et al.* 2016). Consequently, the ongoing decline of pollinators is likely to have a significant adverse impact on these numerous benefits.

1.3.1 Agricultural production and economic benefits from cash crop

Pollinators enhance human quality of life and well-being primarily for their contribution to agricultural production and food security. Animal pollination directly contributes to the yield of approximately 75% of the global leading crops such as fruits vegetables and seeds (Klein *et al.* 2007). Bees belonging to the genus *Apis* and more specifically *Apis mellifera* (honeybee) are believed to be the predominant contributor to crop pollination (Klein *et al.* 2007). However, recent research has highlighted the important contribution of wild bees and the diversity of their community assemblages to crop production (Breeze *et al.* 2011; Garibaldi *et al.* 2013; Rader *et al.* 2016). Examples are watermelon (Kremen *et al.* 2002, 2004), raspberries and blackberries (Cane 2005), and cherries (Bosch *et al.* 2006). More recent studies show an increased marginal production of sweet cherry (Holzschuh *et al.* 2012), high-bush blueberries (Isaacs and Kirk 2010), squash (Hoehn *et al.* 2008) and pumpkins (Artz *et al.* 2011) attributable to wild bee pollination. Furthermore, wild pollinators have been linked to an increase in quality and shelf life of some agricultural products such as oilseed rape (Bommarco *et al.* 2012b), apples (Garratt *et al.* 2014a) and strawberries (Klatt *et al.* 2014).

Approximately 1.4 billion people are employed in agriculture, particularly in poorer developing countries where 70% of communities rely on agriculture for employment (Altieri 2002). In these regions, more than 2 billion people rely on subsistence agriculture and yet pollinator research has widely neglected such nations (Steward *et al.* 2014). Several highly valuable cash crops such as coffee and cocoa are dependent on animal pollination and are a source of employment for millions of people (Klein *et al.* 2007). For example, cocoa provides the main source of income for smallholder farmers in developing countries in Latin America, West Africa, and Indonesia, which produce approximately 70% of the total global production (Franzen and Borgerhoff Mulder 2007). The reduction in cocoa production, in the absence of pollinators, is estimated to be over 90 per cent (Klein *et al.* 2007). Coffee is another important animal-pollinated cash crop, with over seventy countries currently producing coffee and a total export value of US $24 billion in 2012 (FAO 2015). Diversity and abundance of pollinators enhance both highland and lowland coffee yield by up to 40%(Klein *et al.* 2003a, b; Priess *et al.* 2007). In the developed world, almond is a top agricultural export with 80% of the world's almonds being exported by California alone (USDA (National Agricultural Statistics Service) 2016). The U.S. produced $5.3 billion of almond crop in 2015 (USDA (National Agricultural Statistics Service) 2016). Most varieties of almond tree are self-incompatible, and pollen transfer relies on pollinator activity (Koh *et al.* 2017) which greatly increases production (Klein *et al.* 2007).

Due to their link to food production, pollination services directly affect global crop markets, contributing to the annual global crop output by approximately US $235-577 billion (Lautenbach *et al.* 2012) and £430 million in the UK alone (Smith *et al.* 2011). A loss of pollination services could reduce global crop production by an estimated 5- 8% (Aizen *et al.* 2009), corresponding to €153 billion (£134 billion) annually (Gallai *et al.* 2009). This includes highly valuable commodities such as oilseed rape, coffee, many seeds, fruits and nuts (Lautenbach *et al.* 2012; Garibaldi *et al.* 2014). Yet, this estimate is conservative as it does not include the production of forage crops (e.g. alfalfa, soybean, and clover) for the production of meat and dairy nor the contribution to crop seed production (Klein *et al.* 2018). Over the last few decades, pollinator-dependent crops have been expanding at a faster rate than non-dependent crops, resulting in a growing demand for pollination services (Aizen *et al.* 2009). Particularly in the developing world, land devoted to pollinator-dependent crops has risen more rapidly than in developed countries (Aizen *et al.* 2008). These regions are consequently 50% more pollinator-dependent, and hence more vulnerable to pollinators shortages (Aizen *et al.* 2008). For instance, West Africa produces 56% of global stimulant crops, with a vulnerability of 90% to pollinators decline (Gallai *et al.* 2009).

Pollinators are also vital for the provision of agricultural products beyond food such as biofuels, construction materials (e.g. *Eucalyptus spp.*) and fibre (e.g. cotton)(Potts *et al.*

2016). The biofuel crop oilseed rape (*Brassica napus*) has an estimated pollinator dependency up to 30% depending on the varieties (Stanley *et al.* 2013; Garratt *et al.* 2014b) while the yield and quality of Jatropha oil (*Jatropha curcas*) is enhanced by exposure to bee pollination (Romero and Quezada-Euán 2013; Negussie *et al.* 2015). Furthermore, Carvalheiro *et al.* (2010, 2011) show an improved quality and quantity in sunflower crop in the presence of pollinators. Eucalyptus trees, which are an important timber source, depend on animal pollination for seed production (Pavan *et al.* 2014) and cotton farm production, especially organic production, benefits from the maintenance of pollinator communities (Pires *et al.* 2014). Insect pollination can also enhance the value of culturally important non-food crops such as holly and mistletoe (Ollerton *et al.* 2016).

Although a growing body of pollination research has focused on the benefits provided to crop yield by animal pollination (Garibaldi *et al.* 2011b, 2013), information on the contribution of pollinators to the yield of many crops is still lacking. The currently best available source of crop dependency on animal pollination is the Klein *et al*. review (2007), which uses a categorical approach and does not take into account dependence variations between varieties and regions (Bartomeus *et al.* 2014).

1.3.2 Provision of essential micronutrients and health benefits

Wind-pollinated crops represent the primary source of energy in the human diet (FAO 2004), and up to 60% of global food crops originate from plants that are not dependent on animal pollination, both in developed and developing countries (Aizen *et al.* 2009). Half of the agricultural production value is accounted for by nine crops worldwide (Aizen *et al.* 2009; Gallai *et al.* 2009). This explains the relatively small contribution of animal-mediated crops to the global agricultural production aimed at human consumption (Aizen *et al.* 2009). However, the nutritional contribution of animal-pollinated crops is more valuable to a balanced human diet than suggested by the total mass of food produced (Steffan-Dewenter *et al.* 2005). Pollinator-dependent crops are the primary source of important micronutrients such as vitamin A, C, and E as well as calcium, fluoride and folic acid (Eilers *et al.* 2011; Smith *et al.* 2015).

Currently, more than one in seven people is affected by some form of malnutrition worldwide, in particular micronutrient malnutrition is globally prevalent in both industrialized and developing countries (FAO 2009). The predominant types of malnutrition are vitamin A and Iron deficiency (Allen *et al.* 2006). Vitamin A is the most pollinator-dependent micronutrient as major sources of vitamin A are pumpkin, melon, and mango (Chaplin-Kramer *et al.* 2014). Although dependence varies regionally; for example, peach is the predominant source of vitamin A in Mexico and tropical fruits in India and Thailand (Chaplin-Kramer *et al.* 2014).

Anaemia, caused by Iron deficiency, is believed to affect 40% of the global population and it is the most widespread nutritional disorder in both industrialized and developing countries (Allen *et al.* 2006). We derive 29% of iron supply from pollinator-dependent crops such as legumes and nuts (Eilers *et al.* 2011). Folate is another crucial micronutrient, the deficiency of which is a predominant cause of neural tube defects such as anencephaly and spina bifida (Bjorklund and Gordon 2006). Eilers *et al.* (2011) show that animal-pollinated crop plants provide 55% of the available folate through dark green leafy vegetables and beans, and that animal pollination directly increases these plants' yield by 7.3%. Furthermore, areas of global malnutrition have been shown to overlap with areas of high pollinator dependency on nutrients (Chaplin-Kramer *et al.* 2014). For example, areas with the highest dependency on pollinators for vitamin A and iron are three times more likely to experience micronutrient deficiencies (Chaplin-Kramer *et al.* 2014). Therefore, even though a decrease in pollinators would not affect the production of staple crops, it could have severe repercussions on access to micronutrients and public health (Potts *et al.* 2016). In an extreme scenario, this could cause additional potential deaths of 1.4 million per year (Smith *et al.* 2015).

1.3.3 Supporting biodiversity and other ecosystem services

Animal pollination is a vital regulating service in nature as it is the predominant mechanism for sexual reproduction in flowering plants, hence crucial for their propagation and evolution (IPBES 2016). Approximately 308,000 species (87.5%) of the world's flowering plants depend to various degrees on animal-mediated pollination, ranging from 78 per cent in temperate communities to 94 per cent in tropical zone communities (Ollerton *et al.* 2011). Particularly, insect pollinators play multiple key roles in the stability of several terrestrial food webs, as they are crucial components of most terrestrial ecosystems (Scudder 2017) and plant communities (Ballantyne *et al.* 2017). Honeybees and many species of beetles are also keystone species of many natural communities (Traveset *et al.* 2017), thus maintaining the integrity of those ecological structures. Pollinator decline and the consequent decrease in the production of seeds, fruits, nuts, roots, and leaves could potentially cause a trophic cascade affecting many species of frugivores, insects birds and mammals (National Research Council 2007). Pollinators can also be part of a trophic cascade, for example, adult dragonflies in Florida predate on pollinators, and their larvae are in turn a source of food for fish (Knight *et al.* 2005). Plants near fish-free ponds are more pollen limited than those near ponds with dragonfly-eating fish, showing the importance of pollinators in food webs (Knight *et al.* 2005).

Plants form the base of many food webs, and the loss of their pollinators could affect the terrestrial ecosystems they underpin (Vanbergen *et al.* 2014, Ollerton *et al.* 2011). For example, fig trees are considered keystone species in many tropical communities, as they are essential for a large number of frugivores (Kalko *et al.* 1996; Korine *et al.* 2000). The loss of their pollinating wasps (Agaonidae, Chalcidoidea) (Galil and Eisikowitch 1968; Cook and Rasplus 2003) could potentially have a cascading effect on a whole ecosystem. The network of plant-pollination interactions are relatively robust to species loss due to ecological characteristics such as species redundancy (Memmott and Waser 2002; Bartomeus *et al.* 2013). Hence the loss of a small number of pollinator species may have limited ecological consequences (National Research Council 2007). However, higher species diversity can maintain functional redundancy and thus ecosystem resiliency (Laliberté *et al.* 2010). Losing pollinator species could reduce such resiliency, potentially exacerbating the effect of further pollinator losses (National Research Council 2007). Simulation models show potential sudden crashes in plant diversity if pollinator extinction continues and eliminates species that are stronger interactors (Kaiser-Bunbury *et al.* 2010a).

Moreover, Klein *et al.* (2018) highlight that by securing the reproduction, diversity, and abundance of wild plants, pollinators support other ecosystem services that benefit humans in agricultural, urban, and unmanaged ecosystems. In agricultural systems, wild plants are important elements of the semi-natural habitats, providing habitat for pollinators and natural enemies (Holland *et al.* 2015; Sutter *et al.* 2017). In urban ecosystems, wild plants may support human well-being by regulating temperatures, through air filtration and carbon sequestration (Weber *et al.* 2014; Säumel *et al.* 2016). In unmanaged ecosystems, biotic pollination benefits wild plants that are used for non-timber forest products (NTFPs, e.g. fruits, seeds, nuts, bark, flowers, resin, and roots). For example, Rehel *et al.* (2009) show that 40 per cent of NTFPs in India benefit from animal pollination. Biotic pollination can also sustain livelihood through the selling of wild-plant based products (Cummings and Read 2016) and through honey-hunting and beekeeping, which has been reported in over 50 countries (Crane 1999).

Estimating the economic and ecological consequences of pollinator loss to wild plants communities is challenging partly due to the great number of species concerned (Ollerton *et al.* 2011). The impact of pollinators and their decline on wild plant reproductive success is documented at a species level (e.g. Davidar *et al.* 2015; Theobald *et al.* 2016). However, the vast majority of research available investigating the contribution of pollinators to plants reproduction focuses on insect pollinators visiting crop flowers (Garibaldi *et al.* 2014; Kleijn *et al.* 2015; Rader *et al.* 2016). The only global review of the degree of dependence of plant reproduction on pollination focuses exclusively on crop plants (Klein *et al.* 2007) while information on the global contribution of pollinators to wild plants remains unquantified.

1.3.4 Socio-cultural benefits

Pollinators and the products derived from their activities provide a variety of socio-cultural benefits to humans. Many pollinator larvae are consumed as food worldwide (Jongema 2015) and regarded as potentially important for food security (Van Huis 2013; Rumpold and Schluter 2013). Additionally, many medicinal products are derived from honey, including those which are anti-fungal, anti-bacterial, anti-viral (Kumar and Bhowmik 2010; Jull *et al.* 2015) and anti-diabetic (Amudha and Gurtu 2013; Begum *et al.* 2015).

Many cultural activities such as art, religion, music, traditions, and education found inspiration in pollinators (Potts *et al.* 2016). Bees, in particular, have inspired many religious traditions, for example, passages dedicated to bees are found in the Qur'an (Adam 2012), and images of bees are found in Christian iconography (Hogue 2009). Bees and honey have also appeared in literature and poetry from ancient Egyptians to Shakespeare and in both classical and pop music (Hogue 2009). Hummingbirds, butterflies and other pollinators feature as symbols of many nations, such as the hummingbird *Trichcilius polymus* in Jamaica (Bigley and Permenter 2009) and the butterfly *Troides darsius* in Sri Lanka (Howse 2010). Many practices that rely on pollinator-dependent plants such as Kimjang (making and sharing kimchi in the Republic of Korea, UNESCO 2013) are recognized as important by the *Convention for the Safeguarding of the Intangible Cultural Heritage 2003.* Furthermore, the *Convention Concerning the Protection of the World Cultural and Natural Heritage 1972* features several sites that need pollination to preserve their value. For example, the *Agave Landscape and Ancient Industrial Facilities of Tequila in Mexico* are recognized for the biocultural diversity (UNESCO 2006).

Lastly, pollinators hold intrinsic values attached to their existence (Mwebaze *et al.* 2010) and have indirect aesthetic values derived from attractive insect-pollinated wildflowers, roses and orchids, which are important elements of gardens and landscapes (Schmitt and Rákosy 2007; Wratten *et al.* 2012). The promotion of several recreational activities such as beekeeping (Gupta and Stangaciu 2014) and enjoyment of aesthetic wildflowers (Breeze *et al.* 2015) relies on pollinators.

1.4 Measuring and valuing pollination services

The interest in measuring and valuing ecosystem services has substantially increased in the past few decades as a result of the improved awareness and understanding of the importance of the natural environment to human well-being (Neugarten *et al.* 2018). Particularly, pollination is one of the most widely studied ecosystem services worldwide, primarily because of the link to food production (Klein *et al.* 2007; Ricketts *et al.* 2008; Potts *et al.* 2010a; Breeze *et al.* 2011; Hanley *et al.* 2015).

1.4.1 Why measuring pollination services?

The information originating from measuring pollination services can be useful for a wide range of stakeholders, decision-makers and non-government organizations to highlight their importance for both humans and biodiversity (see Section 1.3). Measuring and valuing pollination services can help to optimise the allocation of conservation efforts to areas that are more relevant for biodiversity and pollination services delivery (Neugarten *et al.* 2018). Furthermore, quantifying benefits provided by the natural ecosystem can improve governments understanding of what their contribution is at the national level, and ensure that the value of ecosystems is considered in policy-making (Defra 2007).

1.4.2 Measuring and valuing pollination services at a site-scale

The provision of ecosystem services varies widely across different scales as they depend on ecological and social interactions (Peh *et al.* 2013). Therefore, whilst measuring ecosystem services at a broad scale shows how they change spatially across landscapes (Naidoo *et al.* 2008), it is not as informative as at a finer spatial scale. The majority of land management decisions relate to marginal changes to a resource or a landscape, such as conversion of natural habitat to agriculture (Ricketts and Lonsdorf 2013). Therefore, it is fundamental to estimate pollination services at a site-scale to increase understanding of the biophysical and socio-economic conditions required for their provision and to inform appropriate management.

Sites of importance for nature conservation such as protected areas are valuable to humans not only for their biodiversity but also for the suite of ecosystem services that they provide, including pollination services. Neugarten *et al.* (2018) compiled a detailed list of reasons for measuring ecosystem services at a site-scale (Table 1-1). These encompass, amongst others, the importance of measuring ES to support policies, site management, planning, the private sectors as well as the well-being of people. Several of these reasons are relevant to pollination services and are highlighted in Table 1-1. For example, information on pollination services specific to individual sites can support the implementation of management strategies and help site managers build a stronger case for site conservation.

Table 1-1 List of reasons for measuring ecosystem services at a site-scale, extracted from Neugarten *et al.* (2018). The sections in grey are relevant reasons to measure the pollination services of sites.

Reasons for measuring the ES values of sites	**Main audience**
Public/policy support	
Provide additional evidence and justification for the importance of conserving a particular site	Government agencies, policy and decision makers, local stakeholders, businesses, donors
Foster local awareness of the ES provided by a particular site	Local communities, Indigenous and traditional people, local decision makers
Build support for the conservation of multiple sites through increased understanding of their wide range of benefits	Government agencies and ministries, civil society Government, international community
Link ES contributed by all sites in a country to international or national sustainability goals and national policies (e.g. SDGs)	Government agencies, policy and decision makers, local stakeholders, businesses, donors
Site management	
Establish the baseline of ES provided by a site, to enable monitoring of changes and support management planning	Site managers and others responsible for monitoring sites
Reveal synergies and possible trade-offs between ES and/or ES and conservation objectives to identify management options for the site	Site managers, local stakeholders
Develop, implement and update management strategies for the site, building on the understanding of ES (e.g. integration of ES into site's management plan or developing a business plan for the site)	Site managers, local communities, Indigenous and traditional people, conservation organizations, businesses
Human well-being	
Ensure a good understanding of the ES values that are important to resident, local and more distant stakeholders	Managers, communities, companies using ecosystem services, municipalities
Assess compensation options to resident and local stakeholders for ES forgone as a result of biodiversity conservation, to contribute to discussions about Free Prior and Informed Consent, conflict resolution, etc.	Land and water managers, communities living in or near the site
Planning	
Support spatial conservation planning and investment by identifying areas of particular importance for ES	Government agencies, conservation organizations, donors
Assess potential consequences of different sectoral (e.g. agriculture, hydropower, infrastructure) decisions and policies on ES delivered by sites (scenario comparison)	Government agencies and ministries, businesses, land-owners, resource rights holders, local communities, multilateral financial institutions
Assess potential consequences of climate change scenarios on ES provided by a site	Government agencies and ministries, conservation organizations, land-owners, Indigenous and traditional people, businesses, communities living at or near a site, managers
Integrate ES delivered by sites into land-/water-/resource-use planning at regional, national or sub-national scales (e.g. Strategic Environmental Assessment), understand implications for management of surrounding areas to improve flows from or resilience of site ES	Government agencies and ministries, conservation organizations
Private sector engagement	
Help businesses manage risks and meet their social and environmental responsibility targets, by identifying possible impacts on ES and beneficiaries (e.g.	Businesses, consultants or conservation organizations working with businesses,

Environmental Impact Assessments, corporate sustainability assessments)	government agencies, eco-certification assessors
Provide businesses incentives to engage in the conservation of sites, by demonstrating the dependence of the businesses on ES provided by sites (e.g. public-private funding schemes, in- kind support, branding)	Businesses, site managers, local communities, Indigenous and traditional people, consultants or conservation organizations working with businesses, government agencies, eco- certification assessors
Funding and investment	
Attract government and donor investment from other sectors concerned with conservation of ES (e.g. water management, public health, national security) and/or donors interested in sustainable development	Government ministries, development agencies and organizations
Support the development of new sustainable finance mechanisms for conservation of the sites, such as Payments for Ecosystem Services (PES) or carbon financing such as Reduced Emissions from Deforestation and Forest Degradation (REDD+)	Businesses, public and private investors, government agencies, conservation organizations, local communities
Knowledge generation	
Inform research on ES provided by sites locally, nationally, regionally or globally	Academics, students, conservation organisations, research organisations
Inform research on the synergies and trade-offs between conserving biodiversity and ES, between different ES, and between different stakeholders	Academics, students, conservation organisations, research organisations

As suggested in Neugarten *et al*. (2018), pollination services, as other ecosystem services, have the potential to be integrated into wider ecosystem service assessments and used in resource-use planning (e.g. Strategic Environmental Assessment) at both the regional and national scale. Currently, however, there are no examples of Environmental Impact Assessments (EIA) explicitly taking pollination into account (IPBES 2016); in a recent review of the application of EIA to the fruit sectors there is no mention of pollination (Cerutti *et al.* 2011).

Information from pollination services assessments could be used by private businesses to determine the potential impact of their activities on pollination services and identify potential risks and opportunities, for example through the Corporate Ecosystem Services Review (Hanson *et al*. 2012). In addition, measuring the value of pollination services could encourage farmers to play a part in site conservation by highlighting the enhanced productivity of animal-pollinated crops in the proximity of natural areas. Bateman *et al*. (2013) suggest that modifying CAP (Common Agricultural Policy) into a form of PES (Payment for Ecosystem Services), whereby farmers are funded according to the delivery of ecosystem services, could be an effective mechanism to ensure beneficial land-use changes. Measuring pollination services at a site-scale can generate information to support such mechanisms.

Measuring pollination services at a site-scale can also enable the assessment of opportunity costs, for example when land that could be converted to agriculture use or developed is managed for biodiversity conservation. At a small local scale, measuring pollination services could help farmers distribute their crops strategically around protected areas to maximise production (Sharp *et al*. 2014).

1.4.3 Methodologies and tools for pollination services assessment

The increasing need to inform and facilitate environmental management and policy decision-making has raised demand for assessment tools to measure ecosystem services (Neugarten *et al.* 2018). Currently available methodologies for pollination assessment principally aim at measuring the effect of pollination on crop production. Large scale assessments mostly use measures of pollinator abundance or diversity as a proxy for the pollination service (Winfree *et al.* 2011b). At the individual study level, the marginal contribution of pollinators to crop yield is measured using exclusion experiments (e.g. Bumrungrsi *et al.* 2009, Garratt *et al.* 2014a,b), whereby pollinators are experimentally prevented from accessing plants by bagging or caging. The difference in yield between excluded and control plants represents the increased production directly attributable to animal pollination. Alternatively, differential pollinator abundance, species richness and visitation rate are used to assess the values of pollination to crops as visitation rate of pollinators to flowers is a strong predictor of pollination services (Vázquez *et al.* 2005; Winfree *et al.* 2015).

Before this doctoral thesis, there were four tools for ecosystem services assessment at different spatial scales that include pollination services. These are: the Artificial Intelligence for Ecosystem Services (ARIES; Villa *et al.* 2014), the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST, Sharp *et al.* 2018), the Protected Areas Benefits Assessment Tool (PA-BAT, Dudley and Stolton 2008) and Co$ting Nature (Mulligan 2015). Here, I provide a brief summary of the above ES assessment tools and their application to pollination services assessment. A detailed overview and comparison of these tools, including an analysis of their strengths, limitations and applications, can be found in Neugarten *et al.* (2018) recently published book "Tools for measuring, modelling, and valuing ecosystem services provided by Key Biodiversity Areas, natural World Heritage sites, and protected areas".

1.4.3.1 ARIES

Artificial Intelligence for Ecosystem Services (ARIES) is a software technology for ecosystem services assessment, which has been developed since 2007 (Villa *et al.* 2014). The ARIES models aim at assessing and valuing ecosystem services through the use a collaborative software (k.LAB), whereby artificial intelligence is used to pair spatial data with ecosystem services models. This produces spatially explicit, quantitative outputs of the flows of ES for a certain area. ARIES is free access and can be used at local, regional, and national scale. Although ARIES could be used to model any ecosystem service, to date models have been developed for some provisioning, regulating, and cultural ecosystem services, including pollination.

The ARIES model has been implemented for a number of ecosystem services in different regions (e.g. La Notte *et al.* 2015; Balbi *et al.* 2016). The ARIES pollination model was developed following the ESTIMAP approach (Ecosystem Services Mapping at European Level, Zulian *et al.* 2013), which is derived from InVEST (section 1.4.3.2) and adapted to continental-scale mapping. This model was recently developed and tested at a fine scale in Sicily, Italy, where Martinez-Lopez *et al.* (unpublished 2017) assign values of nesting suitability and floral availability to different land cover categories using CORINE 2012. A potential pollinator abundance is then calculated by multiplying these two factors. The resulting output is a map providing pollination supply and net pollination service in the influence area of cropland, set at 1 km around each crop area as the maximum foraging distance of pollinators (Martinez-Lopez *et al.* 2017 unpublished).

1.4.3.2 InVEST

The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST), developed by the Natural Capital Project (http://www.naturalcapialproject.org), offers a software package for quantifying, mapping, and valuing ecosystem services (Sharp *et al.* 2018). The main aim is to assess how land use and climate changes affect the spatial provision of flows of ecosystem services to people (Sharp *et al.* 2018). It currently includes 18 software models of ecosystem services, including a crop pollination model. The latter maps relative pollinator abundance, using information on flower resources and nesting sites, and the resulting potential pollination services across the landscape (Sharp *et al.* 2018).

The InVEST pollination model uses the "Lonsdorf model" which assesses wild bees' foraging and nesting potential of different land uses or cover types using expert judgement (Lonsdorf *et al.* 2009). The required data to run this model are a land cover map and a table of pollinator species relevant to the study area (Sharp *et al.* 2018). The model then maps each land cover type and derives a wild bee abundance index (the Lonsdorf Index) for each pixel. This is based on the foraging range of local bee species and the nesting and foraging potential of the neighbouring cells. The value of the pollination supplied from each pixel to agriculture corresponds to the economic impact of pollinators on crops that grow in pixels that are within the relevant foraging ranges of each pixel (Sharp *et al.* 2018).

InVEST has been applied in some case studies in various regions. Koh *et al.* (2016) use the crop pollination model to map the status and trend of wild bees across the United States and assess potential impacts on pollination services. This study shows that predictions of lowest bee abundance lie in areas of intense agriculture. Furthermore, InVEST has been recently applied at a finer scale in Nova Scotia (Canada) where Cunningham *et al.* (2018) use two sets of data - one based on published literature and another derived from field observations - to inform all the component of the model, in order to explore the differences in the model output. This highlights the need to have a practical method for collecting real data on the ground.

1.4.3.3 PA-BAT

The Protected area Benefits Tool (PA-BAT) is a rapid tool for identifying the suite of ecosystem services provided by a protected area. To implement this tool, a questionnaire is used in a participatory workshop with relevant stakeholders to assess the benefits provided by a protected area (Dudley and Stolton 2008). PA-BAT can be used in any region, site, and biome and it currently includes 24 benefits.

Before this doctoral research, PA-BAT was the only tool available for the rapid assessment of pollination service benefits to key stakeholders. The process to apply this tool is easy, quick and inexpensive and directly involves local people who are often an important source of information on services and benefits. This tool was entirely developed for assessment at a site-scale and it was broadly used on a number of protected areas, including National Parks in South-East Europe (e.g. Štefan *et al.* 2016; Sekulić *et al.* 2017). However, although pollination services were sometimes acknowledged in these case studies, they were not as widely recognised as other services. PA-BAT has the potential to be applied on non-protected sites, although it may be challenging to identify relevant stakeholders of such areas (Neugarten *et al.* 2018).

1.4.3.4 Co$ting Nature

Co$sting nature is a web-based tool to analyse ecosystem services provided by the natural world and support policy. It identifies the beneficiaries of these ecosystem services and assesses the effect of management interventions and land use changes on their provision (Mulligan 2015). It includes ecosystem services for water provision and quality, carbon, hazard mitigation and nature-based tourism and focuses on costing nature by understanding the resource rather than focusing on the value (i.e. willingness to pay for the service)(Mulligan 2015). Co$ting Nature calculates a baseline of the current provision of ecosystem services and enables the user to test different policy interventions or scenarios of change to assess their effect on the delivery of ecosystem services (Mulligan 2015). Examples of its application are available (http://www.policysupport.org/costingnature/example-applications); however, even though version 3 includes a pollination model, to date no example focussed on the assessment of pollination services.

1.4.4 Need for a practical tool

Currently available tools such as ARIES and InVEST, mostly rely on high technical knowledge and data input demand. ARIES is a complex platform, requiring either a high level of expertise or training in order to be used. InVEST requires less technical expertise compared to ARIES, although it is not a rapid or simple tool to implement as specialised knowledge of GIS is required (Neugarten *et al.* 2018). Therefore, access to these tools may be limited to academics, users with high levels of technical expertise and are incompatible with rapid assessments. At the site level, InVEST can provide useful information on the potential pollination services currently provided by a site and offers scenario comparisons on how the delivery of the service can change under different management options. However, it does not provide information on the actual pollination services provided by a site. Furthermore, these tools are spatially explicit, producing maps as the main output, which due to the rough resolution of data, may not always reflect the reality on the ground (Eigenbrod *et al.* 2010). Finally, both tools include consultations with relevant stakeholders as an optional step, and can be run without any input from stakeholders.

PA-BAT is the only tool currently available that is rapid, site-specific and involves local stakeholders and beneficiaries (Neugarten *et al.* 2018). However, it is an entirely qualitative assessment based on local stakeholders' opinion as opposed to quantitative data, hence its results may not be generalisable. Co$sting nature is the most rapid and easy to use available tool for pollination services assessment. However, because it gathers data from global datasets, it may not be as accurate when applied at a site-scale, especially for very small sites (Neugarten *et al.* 2018). Recognised limitations from the developer are that is not a fully parameterised, physically-based model and does not allow mapping of individual ecosystem services nor analysis of trade-offs and valuations.

Consequently, there is a clear need to develop more rapid, accessible and quantitative methods for the assessment of pollination services. Such tools should focus at the site-scale, which reflects local conditions and it is more relevant for decision making. A small-scale approach is ideal for pollination services as their provision relies on the distribution of floral resources at a resolution that is too fine to be captured by typical remotely sensed imagery (Cunningham *et al.* 2018). An effective and rapid pollination assessment method needs to be accessible to land managers and local policy-makers whilst still providing quantitative robust estimations of the service values. Affordability and practicality are equally important features of the method in terms of time, equipment and resources required (Peh *et al.* 2013a). The Toolkit for Ecosystem Services Site-based Assessment (TESSA) provides a suitable framework for this aim due to a number of unique characteristics, which distinguish it from other tools (See Table 1-2 for a detailed comparison between assessment methods).

1.4.4.1 TESSA

This toolkit was developed by a consortium with input from seven organisations and many ecosystem services experts. It provides guidance on sets of low-cost methods to evaluate the benefits that people gain from nature at particular sites. Version 1.0 of TESSA (Peh *et al*. 2013b) includes methods for the assessment of five classes of ecosystem services: global climate-regulating services, water-related services, harvested wild goods, cultivated goods and nature-based recreation. TESSA provides an interactive PDF that includes guidance on how to recognise which ecosystem services are provided by a site, the data required to measure these ecosystem services, and what methods can be used to gather the data. Once the PDF is downloaded, it does not require an internet connection or a specialised software to run.

Unlike other tools, TESSA focuses on a site-scale in response to the need to bring ecosystem services assessments down to the site level and recommends the use of locally collected data which are more relevant to the site of interest (Peh *et al.* 2013a). TESSA consists of two successive steps: a preliminary scoping appraisal (implemented via a stakeholder participatory workshop), to generate qualitative information on the ES provided by a site and a full assessment. Methods for estimating each ecosystem service are provided within the toolkit.

The preliminary scoping appraisal, which involves stakeholders and beneficiaries, aims to gain an overview of the site, the services it provides and to identify a plausible alternative state. In the context of this toolkit, an alternative state is a description of how the site might plausibly change as a result of different management decisions (e.g. a patch of natural habitat converted to cropland). Simple ecosystem services assessments, done on a particular site are useful to understand the benefits of a service or a suite of services to people. However, comparative assessments may be more useful to decision makers as they identify the differences in ecosystem services provision resulting from land-use changes. This may increase decision makers' awareness of the impact of their decisions on biodiversity and ecosystem services and consider which land-use scenario delivers the greatest benefits (Peh *et al.* 2013b).

The methodologies provided by TESSA are accessible to non-experts and users with low technical expertise as they do not contain any complex modelling. The main skills required are basic scientific training, a basic understanding of socio-economic methods and good computer and numeracy skills. Accessibility is also achieved by providing an initial decision tree that guides the user through a series of questions to the methods that better suit their circumstances and resource availability. The methods are relatively rapid and inexpensive as they require basic equipment such as a computer, some basic field equipment and a team of staff or volunteers. This toolkit is accessible to a wide range of professional figures such as conservation practitioners, land-use planners, development organizations and businesses.

Table 1-2 Overview of existing tools for multi-ecosystem services assessment that include pollination services, extracted from Neugarten *et al.* (2018).

Criterion	ARIES	Co$ting nature	InVEST	PA-BAT	TESSA
Cost / availability	Free/open-source	Free (policy /analyst/scientist version) Paid license (advanced user/commercial versions), closed-source	Free/open-source	Free/open-source	Free/open source
Time requirements	Low for global models; High for new case studies	Low	Moderate to high	Low to moderate	Low to high
Data input demand	Low to high	Low	Moderate to high	Low	Moderate to high
Skill requirements	Low to high	Low	Moderate to High	Low	Low
Scale of analysis	Local to global	Local to global	Local to regional	Local	Local
Quantitative / qualitative	Quantitative or Qualitative	Quantitative (relative values)	Quantitative or Qualitative	Qualitative	Quantitative or Qualitative
Monetary / nonmonetary	Monetary or nonmonetary	Monetary or nonmonetary	Monetary or nonmonetary	Nonmonetary	Monetary or nonmonetary
Spatially explicit?	Yes	Yes	Yes	No	No
Technical requirements	Computer and internet access	Computer and internet access	GIS software	None	Field equipment (optional)
User support	Moderate	Moderate	High	Moderate	Moderate
Level of development & documentation	Case studies & global models developed and documented	Partially documented	Fully developed and documented	Fully developed and documented	Fully developed and documented
Interface	Specialized software (k.LAB/Eclipse) and web application	Web application	Desktop application; Python API (optional)	Survey form (.pdf). slides for workshop (.ppt), database for results	User manual (interactive .pdf)

Criterion	ARIES	Co$ting nature	InVEST	PA-BAT	TESSA
Generalizability (applicability in new contexts)	High for global models, low for local models	High	High, though limited by availability of underlying data	high	High
Approach to uncertainty	Uncertainty through Bayesian networks, machine learning, and Monte Carlo simulation	Uncertainty through sensitivity analysis	Uncertainty through varying inputs (automated)	None (paper form)	Guidance provided on level of confidence
Nonmonetary & cultural perspectives	Biophysical values, can be monetized	Outputs indexed, bundled ES values	Biophysical values, can be monetized	Describes monetary and nonmonetary values and economic potential	Biophysical values and non-monetary valuation of cultural services
Level of stakeholder engagement required	Low	Low	Low	Moderate	High
Absolute vs. Relative value	Either	Relative	Either	Relative	Absolute or relative
Scenario comparison	Yes	Yes	Yes	Yes	Yes
Single/multiple site	Single or multiple	Single or multiple	Single or multiple	Single	Single
Static/dynamic (time)	Static or dynamic	Static	Static	Static	Static
Range of time for full application in a new site (scoping, data collection, analysis, follow ups	Days to weeks for pre-existing models; months to a year for a new case study	Minutes to hours for application of the model with all provided data	1-3 months for smaller projects, less if data exists and scenarios identified up- front; 6 months to 2 years for larger projects with multiple ES, depending on level of stakeholder involvement	1 day workshop, days to weeks for preparation, subsequent analysis of workshop results, follow-up	20-60 person days for preparation, primary data collection (biophysical and socioeconomic), and analysis

1.5 Economic valuation of pollination services

Pollination is a major ecosystem service with high economic significance (Gallai *et al.* 2009). Economic measures can provide a rationale for adequate, more sustainable management strategies of pollinators and strengthen justifications for conserving pollination services (Costanza *et al.* 2014). Furthermore, economic valuations can be used to inform land planning decisions or policy as part of cost-benefit analyses (Hanley and Barbier 2009). For example, to provide the public with value for money, Breeze *et al.* (2014) compared the cost of implementing agri-environment schemes to the economic gain of enhancing wild pollinators.

1.5.1 Market values

The economic value of pollinators mainly derives from the increased quantity and quality of crops, which increases economic output (Hanley *et al.* 2015). Indeed, the magnitude of these increased economic benefits depends on the crop type and their degree of dependence on animal pollination (Klein *et al.* 2007). Hanley *et al.* (Hanley *et al.* 2015) state that, from an economic perspective, the value of pollination is expressed as marginal values, where the changes in pollinator "units" will reflect a change in benefits potentially delivered to people.

Early studies such as Costanza *et al*. (1997) used the total price of animal-pollinated crops to measure the value of the service. However, this approach produces overestimations as it attributes the entire market value of crop to pollination services (Breeze *et al.* 2016). More recently, this method was improved by using the Production Function approach also known as the Production Value approach (Winfree *et al.* 2011b). This approach uses pollination as an input into crop production where the value of pollination is the proportional magnitude of improvement in production attributable directly to animal pollination (Hanley *et al.* 2015). According to recent reviews (Hanley *et al*. 2015, Breeze *et al.* 2016), the majority of economic evaluation of pollination services have focused on the use of two simplified production functions: Dependence Ratio (DR) and Yield Analysis (YA). In the DR approach, the reduction in yield caused by pollinators decline is approximated using the dependency factor (Klein *et al.* 2007), a theoretical metric of the crop yield that would be lost in the absence of pollinators (Hanley *et al*. 2015). The extracted yield loss is multiplied by the market value of the crop (Morse and Calderone 2000; Losey and Vaughan 2006; Brading *et al.* 2009) using the following formula:

EVIP = D × Q × P

Where EVIP is the economic value of insect pollination, D is the proportion of crop yield directly attributable to pollinators, Q is the annual crop production, and P is the price of crops (Bauer and Sue Wing 2010). This approach is relatively simple and has been adopted by the UK National Ecosystem Assessment for the valuation of all UK crops in 2007 (Smith *et al.* 2011) and many other countries for different crop types (e.g. Zych and Jakubiec 2006; Kasina *et al.* 2009; Calderone 2012). However, according to Melathopoulos *et al.* (2015), it does not account for the effect of differences between cultivars (e.g. Hudewenz *et al.* 2014) nor the variations in environmental conditions, which can lead to considerable inaccuracies when applied at larger scales.

Similarly, yield analysis measures the market price of the marginal crop production attributable to pollination services (IPBES 2016). However, it estimates the benefits per hectare using primary fieldwork (pollinator exclusion experiments)(Breeze *et al.* 2016), which takes into account variations in crop varieties (e.g. Ricketts *et al.* 2004; Greenleaf and Kremen 2006; Stanley *et al.* 2013; Garratt *et al.* 2014a) crop quality and storage life (Klatt *et al.* 2014). Potential weaknesses of this approach are the lack of a standardised methodology (IPBES 2017) and the potential difficulties in generalising from small size studies to a broader scale (Eigenbrod *et al.* 2010; Hanley *et al.* 2015).

In their review, Breeze *et al.* (2016) highlight that the above methods do not illustrate the effect of pollinators on the consumer and producer economic welfare, although studies have addressed this by measuring the consumer surplus (e.g. Southwick and Southwick 1992; Gallai *et al.* 2009; Winfree *et al.* 2011b). This is calculated as "the impact that a rise in prices, following a change in the supply of pollinated crops, will have on consumer welfare" (Breeze *et al.* 2016). Bauer and Wing (2016) have recently expanded on this approach by using a general equilibrium model, which accounts for the ability of producers to compensate for losses of pollinators using other inputs (Breeze *et al.* 2016).

Another approach to estimating the economic value of pollination services is the replacement cost method (Allsopp *et al.* 2008). This is a cost-based method and estimates the value of the service as the cost of an alternative pollination technology such as mechanical pollination (i.e. hand pollination and pollen dusting) or beehive rental (Calzoni and Speranza 1998; Allsopp *et al.* 2008). The resulting estimated costs do not depend on yield benefits and avoid overestimation of the overall impact of pollination services (Allsopp *et al.* 2008). However, this approach does not represent actual behaviour or individual preferences as it ignores that farmers could decrease the losses in production, for instance by switching to another crop (Bauer and Sue Wing 2010). Also, it assumes an indefinite availability of honey bees (Winfree *et al.* 2011b) and overlooks the fact that techniques such as hand pollination are rarely applied as they are unfeasibly costly (Hanley *et al.* 2015).

1.5.2 Non-market values

Stated preference methods can be used to obtain the economic values of non-market benefits that we gain from pollination (Hanley *et al.* 2015). These can be either use-values such as the pleasure derived from seeing pollinators or existence-values, the enjoyment of the knowledge that they exist (Breeze *et al.* 2016). This method uses surveys to elicit respondents to state a preference for bundles of ecosystem goods or services within an hypothetical market and estimates the respondent's willingness to pay (WTP) to gain or maintain these services (Bateman *et al.* 2002, Breeze *et al*. 2015).

To date, stated preference methods have been used to estimate the intrinsic value of honey bees in the UK (Mwebaze *et al.* 2010), the willingness to pay to maintain the diversity of aesthetic wildflowers in UK (Breeze *et al.* 2015), the value of the migration of monarch butterflies (*Danaus plexippus*) in the US (Diffendorfer *et al.* 2014) and the value of conserving pollinators in Thailand (Narjes and Lippert 2016).

Research on economic valuation of pollination services has heavily focussed on market values of invertebrate pollinators, specifically bees. Some studies have estimated the economic value of ecosystem services provided by other groups of pollinators, e.g. seed dispersal provided by birds (Hougner *et al.* 2006), and pest control provided by bats (Cleveland *et al.* 2006; Betke *et al.* 2008; Federico *et al.* 2008). However, economic evaluations of pollination services provided by these groups have not been attempted so far, despite emerging research showing that vertebrate pollinators such as bats and flying foxes (Aziz *et al.* 2017) have a positive effect on the reproductive success of economically important plants (e.g. durian). Studies such as Aziz *et al.* (2017) contribute to determine the proportional increase in fruit production that is directly attributable to vertebrate pollinators and provide useful data for potential economic valuations.

1.6 Thesis Outline

The overarching aim of my thesis is to increase understanding of how losing pollination services can affect human well-being, with specific reference to the impact on both wild and crop plants' reproductive success. I pay particular interest to the estimation of pollinators' contribution to the reproduction of wild plant communities. I also evaluate current methods for pollination services assessment and develop a novel, more accessible approach, focusing mainly on single site-scale.

Chapter 2 quantifies the global importance of pollinators to wild plant reproductive success, focusing specifically on vertebrate pollinators. I use systematic review methodologies and meta-analysis to examine variations of this contribution across pollinator taxa, regions, climatic domains and taxonomic breadth of flower visitors. Systematic review methodology is widely used and recognized as a standard for the access, review, and appraisal of scientific data through the application of a rigorous protocol (Pullin and Stewart 2006). Meta-analysis provides a set of statistical tools for combining the results of different studies addressing the same research question (Koricheva *et al.* 2013). This method is based on expressing the results of each study on a standard scale, the "effect size", which represents the magnitude of an effect of interest (Koricheva *et al.* 2013). Meta-analysis reduces the subjectivity inherent in narrative syntheses and objectively quantifies the variation in results between studies; it also contributes to identifying gaps in research and highlight where more research is needed (Koricheva *et al.* 2013).

Chapter 3 addresses the knowledge gap on the production dependence of plants on their vertebrate pollinators. I collate a dataset based on the comprehensive literature review in Chapter 2, and create an easy-to-access spreadsheet containing degrees of production dependence of wild and crop plants on vertebrate pollination. To achieve this, I calculated the dependence ratios based on data originated from field exclusion experiments. Dependence ratio is defined as the proportional magnitude of improvement in production, which is attributable directly to animal pollination (in this case, vertebrate pollination). In this dataset, I categorized dependence ratios in scores following the classification system in Klein *et al.* (2007).

Chapter 4 addresses the need for a rapid and accessible tool for the site-scale quantification of pollination services, expressed as the contribution of animal pollination to the production of cultivated and harvested wild goods. This tool aims at providing sets of low-cost methods to value pollination services currently provided by a site compared with the provision of an alternative state of the site resulting from different land-use changes. This is achieved through the use of expert elicitation techniques namely an expert online forum and an expert workshop. Here, I also investigate the contribution of remnants of natural habitat to the delivery of pollination services in a predominantly agricultural landscape, using a Site of Special Scientific Interest in Hampshire in the UK as a first application of pollination tool. I also critically assess these new methods and discuss their feasibility, strengths, and limitations in comparison to alternative, landscape-scale approaches.

I conclude with a synthesis and summary of the overall findings and limitations of the study, the implications for policy, decision-making, and conservation, and directions for future research (Chapter 5).

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Chapter 2 : Global importance of vertebrate pollinators to plant reproductive success: A meta-analysis

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2.1 Abstract

Vertebrate pollinators are increasingly threatened worldwide, but little is known about the potential consequences of declining pollinator populations on plants and ecosystems. Here, we present the first global assessment of the importance of vertebrate pollinators in the reproductive success of selected flowering plants. Our meta-analysis of 126 experiments on animal-pollinated plants revealed that excluding vertebrate pollinators – but not insect pollinators – reduced fruit and/or seed production by 63% on average. We found bat-pollinated plants to be more dependent on their respective vertebrate pollinators than bird-pollinated plants (an average 83% reduction in fruit/seed production when bats were excluded, as compared to a 46% reduction when birds were excluded). Plant dependence on vertebrate pollinators for fruit/seed production was greater in the tropics than at higher latitudes. Given the potential for substantial negative impacts associated with the loss of vertebrate pollinators, there is a clear need for prompt, effective conservation action for threatened flower-visiting vertebrate species. Additional research on how such changes might affect wider ecosystems is also required.

2.2 Introduction

Animal pollination is necessary in the life cycle of many plant species. An estimated 87.5% of the world's flowering plant species are animal-pollinated (Ollerton *et al.* 2011), with 75% of the world's major crops species benefitting to some degree from animal pollination (Klein *et al.* 2007). Animal-pollinated plants are also used for medicines, forage and materials (Potts *et al.* 2010a, 2016; Ollerton *et al.* 2011) and play a crucial role in the long-term maintenance of biodiversity and natural ecosystems. While much scholarly and media attention has been focused on insect pollinators, the role of vertebrate pollinators is not as widely recognized. A global study revealed that, in recent decades, both mammal and bird pollinators are becoming increasingly threatened with extinction over time, with an average of 2.5 species per year moving one category closer to extinction on the IUCN Red List of Threatened Species (Regan *et al.* 2015). These declines in the populations of mammal and birds pollinators are thought to be driven by agricultural expansion, the spread of invasive alien species, hunting and fire (Regan *et al.* 2015).

Vertebrate pollinators are found in bird taxa, particularly hummingbirds, sunbirds and honeyeaters (Figure 2-1a). Amongst mammals, bats are the major pollinators, with flower-visiting bats mostly found in two families: Pteropodidae (fruit bats) and Phyllostomidae (leaf-nosed bats)(Fleming and Muchhala 2008)(Figure 2-1b). Non-flying mammals such as primates, rodents and marsupials are known to visit at least 85 species of plants worldwide (Carthew and Goldingay 1997)(Figure 2-1c). Flower visitation is reported in 37 species of lizard, mainly island-dwelling species (Olesen and Valido 2003)(Figure 2-1d)(See Chapter 1, section 1.1).

The declines in abundance and diversity of pollinators have raised concerns worldwide, prompting a growing body of research on the extent to which reproductive success of plants is enhanced by flower-visiting animals (Garibaldi *et al.* 2013; Kleijn *et al.* 2015; Rader *et al.* 2016). However, most of these studies focus on insect pollinators visiting crop flowers. The only global review of the degree of dependence of plant reproduction on pollination focused exclusively on crop plants (Klein *et al.* 2007), and it has been used extensively to value pollination services at national and international scales (Gallai *et al.* 2009; Lautenbach *et al.* 2012). Klein *et al*. (2007) reported that, throughout the world, crop pollinators are mainly bees. Nevertheless, vertebrates are essential for the reproduction of some economically important crop species such as *Hylocereus undatus* (dragon fruit) (Ortiz-Hernández and Carrillo-Salazar 2012), *Durio* spp.(Durian) and *Parkia* spp. (beans) amongst others (Bumrungsri *et al.* 2008, 2009).

Figure 2-1 Example taxa representing the four major vertebrate pollinator groups: (a) ruby-throated hummingbird (*Archilochus colubris*)(Photo: Larry Master), (b) lesser long-nosed bat (*Leptonycteris yerbabuenae*)(Photo: César Guzmán), (c) Namaqua rock mouse (*Micaelamys namaquensis*)(Photo: Petra Wester), and (d) bluetail day gecko (*Phelsuma cepediana*)(Photo: Dennis Hansen).

The best global-scale information available about the degree of dependence of wild plants on their pollinators (Ollerton *et al.* 2011) did not use empirical data on plant reproductive success but instead classified plants as either animal-dependent or not, in 42 surveyed plant communities, based on the judgement of ecologists or botanists. To our knowledge, there has never been a global meta-analysis of the extent of dependence of wild plants on any animal pollinators for fruit set, or seed set. Yet, this measure of dependence is crucial if we are to understand, perhaps even begin to value, pollinators for their role in wild plant pollination.

Global-scale meta-analyses have been conducted on the extent of pollen limitation (to what degree plant reproductive success can be enhanced by hand pollination) related to local and regional biodiversity patterns (Vamosi *et al.* 2006), and on the identity of important pollinators as they relate to pollination syndromes (Rosas-Guerrero *et al.* 2014). However, neither of these approaches help to evaluate the importance of current pollination to plant populations, communities and ecosystems.

We present the first global assessment of the overall importance of vertebrate pollinators for plant reproductive success (fruit and seed production for both crops and wild plants), using quantitative meta-analysis. We focus on vertebrate pollinators because, unlike invertebrates, the conservation status of most pollinating vertebrate species is well characterized at the global scale, and their distributions and diversity are mapped (Jenkins *et al.* 2013), making it possible to target and prioritize conservation actions globally. We pose two questions:

(1) What is the importance of vertebrate pollinators for plant reproductive success?

(2) How does this importance vary with vertebrate pollinator taxon, taxonomic breadth of flower visitors, geographical region, climatic domain, type of exclusion experiment and measure used for assessing reproductive success?

2.3 Materials and Methods

2.3.1 Systematic review

Using standard review protocols, we conducted a systematic literature search for studies that investigated the relationship between vertebrate flower visitors and plant sexual reproduction (Pullin and Stewart 2006). We defined a pollinator as a regular flower visitor that transfers pollen between plants, leading to successful pollination and ultimately the production of seeds (Carthew and Goldingay 1997). Pollinator performance can be assessed in two ways: pollination success (contribution to pollen deposited on female flower parts) and plant reproductive success (contribution to seed set)(Ne'eman *et al.* 2010). We included studies that quantitatively measured the latter, in terms of fruit and seed production. To retrieve these studies, we searched ISI Web of Knowledge, Scopus, CAB Abstract and Agricola databases (from 1900 to 2016 inclusive) and relevant grey literature sources (using Google, Google Scholar and Scielo) in both English and Spanish. Furthermore, we contacted authors to obtain their unpublished data, if necessary. We used a combination of search terms relating to potential vertebrate pollinators, measures of plant reproductive success, and pollination efficiency and effectiveness (Appendix A.1 for full search strings).

Our initial search yielded 4588 articles. After removing obviously spurious results, we screened the title and abstract of the remaining 467 articles for relevance, resulting in 389 appropriate studies. We had no access to 11 relevant articles, and read 378 articles in full to establish their suitability for the analysis (Figure 2-2). To determine whether the systematic review strategy was robust and unbiased, we quantitatively assessed the agreement between authors on study selection and exclusion. We calculated a Kappa statistic using a subset of the selected articles (50 publications per author, for two authors). We obtained a kappa value of 0.55, which corresponds to "fair agreement" and is within the acceptable range.

Publication bias, the tendency for studies reporting significant results to be overrepresented in the published literature (in this case studies where the exclusion of vertebrate pollinators had a significant effect on fruit and seed set), was minimised in the systematic review process by searching for grey literature and contacting authors active in the field. In addition, we estimated Rosenberg fail-safe number, which is the number of non-significant unpublished studies required to eliminate a significant overall effect size (Rosenberg 2005). Results are considered robust to publication bias when the fail-safe number is equal to or greater than $5n+10$, where n is the number of studies. We detected no evidence for publication bias, as the fail-safe number (101018) was much larger than the critical value ($640 < 101018$)(Appendix A.2).

2.3.2 Effect size estimations and meta-analysis

We included only studies that involved an experiment of manipulative exclusion wherein plant reproductive success in the presence and absence of vertebrate pollinators was observed; the exclusion of vertebrate pollinators was achieved by means of a physical barrier such as mesh bags or chicken wire. We categorised the plants that had been exposed to vertebrate pollinators through open/natural pollination as "control" (i.e. vertebrate pollinators present) and as "treatment" (i.e. vertebrate pollinators absent) those that undergone any manipulative exclusion of vertebrate pollinators, such as bagging or caging. These studies used either fruit production or seed production as a measure for plant reproductive success (response variables). We recorded the statistics – i.e. means, standard deviations (SD) and sample sizes – of fruit /seed production for both "control" and "treatment". When data was presented only in figures, we extracted the data using DataThief software (Tummers 2006). We contacted the lead authors of the studies that had incomplete data and abandoned these studies if we could not obtain the missing statistics. We could not tease apart the relative contributions from vertebrates and insects for studies using a very fine mesh; our analysis, therefore, excluded such studies unless we were certain that the insects were not important.

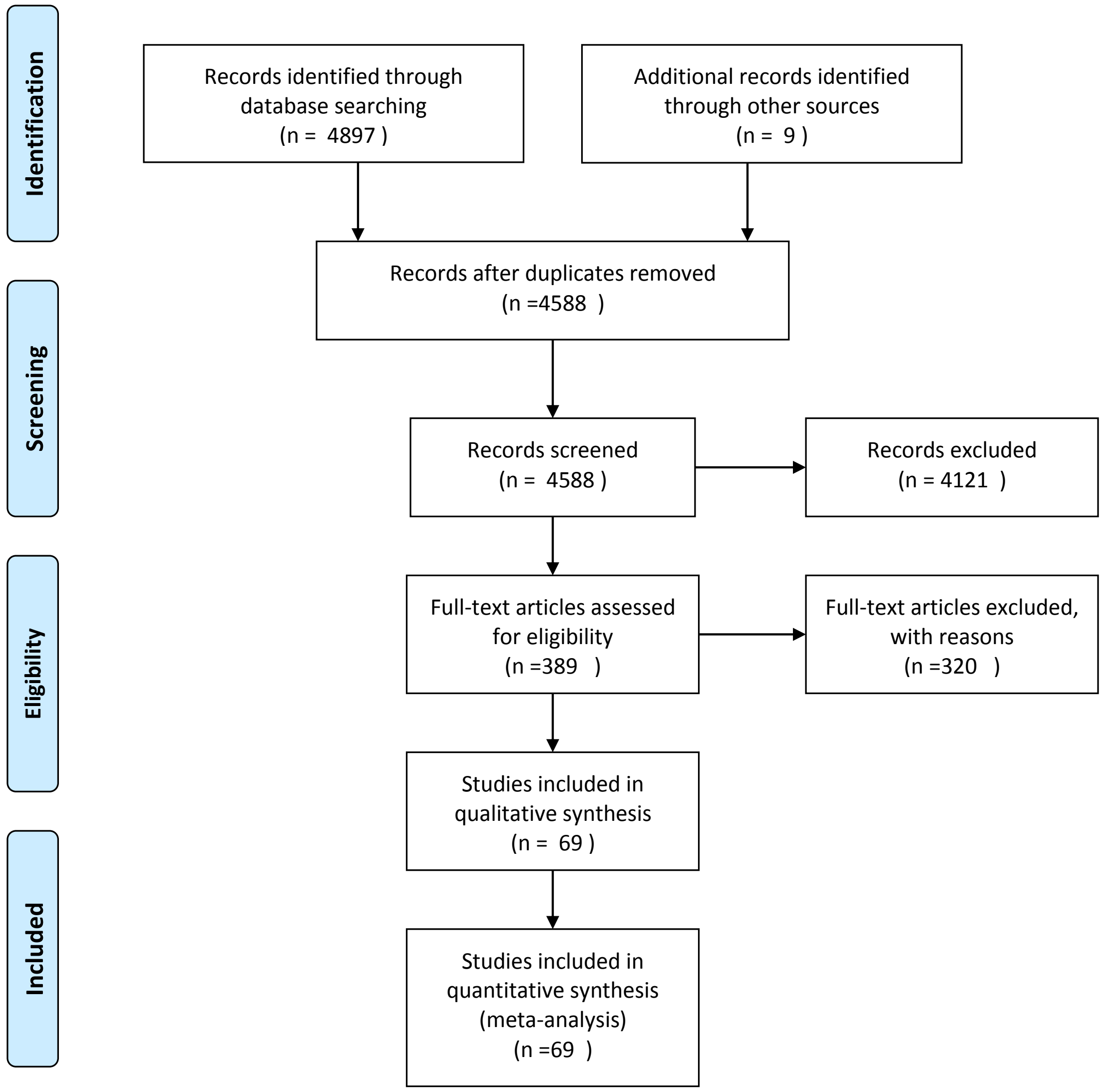

Figure 2-2 Preferred Reporting Items for Systematic Review and Meta-Analysis flowchart (PRISMA), summarising the sequence of information gathering and selection. Available at http://prisma-statement.org/PRISMAStatement/FlowDiagram.aspx.

We also excluded studies that were pseudoreplicated *sensu* Hurlbert's (1984), and only included studies that had replicated pollinator-excluded inflorescences spatially interspersed with replicated unmanipulated inflorescences. This is critical because studies that had low within-study variance arising as an artefact of the pseudo-replicated design, could have their importance inflated in a conventional meta-analytic model, which weights studies by the inverse of within-study variance (Halme *et al.* 2010). The incidence of pseudoreplicated studies nevertheless was low (n = 7). For studies that presented multiple years of data sampling at the same site, we used the most recent data to control for non-independence of temporal data (Gurevitch and Hedges 1993).

To investigate the importance of vertebrate pollinators for plant reproductive success, we compared the means of reproductive success (i.e. response variable: either fruit or seed production) under control (vertebrate pollinators present) and treatment (vertebrate pollinators absent) conditions. We used the natural log of response ratio (ln*R*) as the effect size, which expresses the proportional difference between the treatment and the control group (Hedges *et al.* 1999). The response ratio is calculated as: $\ln R = \ln(x_1) - \ln(x_2)$, where x_1 is the mean of reproductive success when vertebrate pollinators were absent (treatment) and x_2 is the mean of reproductive success when vertebrate pollinators were present (control). The use of natural logarithm linearizes the metric, treating changes in nominator and denominators equally and producing a normalised sampling distribution (Hedges *et al.* 1999).

A response ratio cannot be calculated if the means of reproductive success were equal to zero (n=16 in our dataset). We therefore conducted preliminary trials following Molloy *et al.* (2008), whereby a constant value (e.g. 1, 0.1, 0.001, 0.0001) was added to all estimates of reproductive success before calculating the response ratio. We concluded that adding 1 to all estimates had a negligible impact on the overall effect size. The meta-analysis was weighted by the inverse of the sample variance, which accounts for differences in sampling effort across studies.

To determine whether vertebrate pollinators significantly affected plants' sexual reproduction, we ran a random effects model in our meta-analysis using the metafor package in R (version 3.1.2.)(Viechtbauer 2010). Random effects models do not assume that any variation in the effect size is due to sampling error, and, instead, allow for a real random component of variation in effect size between studies. We calculated the confidence intervals using a bootstrap re-sampling procedure. An effect of vertebrate pollination was considered significant if the 95% biased-corrected bootstrap confidence intervals (CI) of the effect size did not overlap zero (Koricheva *et al.* 2013).

To explore whether shared evolutionary history between species affected the effect size, which can violate statistical assumptions of independence (Gurevitch *et al.* 2001), we performed a phylogenetic meta-analysis using phyloMeta 1.3 (Lajeunesse 2011). We constructed a phylogenetic tree for plant species in our dataset by binding species into a published phylogeny (Zanne *et al.* 2014) as polytomies at the genus level, using the R package pez (Pearse *et al.* 2015). The tree was then pruned to remove any species not in our dataset (Appendix A.3 for phylogeny). Two species (*Pilosocereus chrysacanthus* and *Ameroglossum pernambucense*), whose genera were not present in the phylogeny, were excluded from all analyses. Our main dataset included multiple effect sizes for a single plant species if, for example, it was pollinated by more than one pollinator group. PhyloMeta requires one effect size per species, so multiple effect sizes for a single plant species were pooled following Borenstein *et al.* (2009). The fit of the traditional and phylogenetic models were compared using Akaike Information Criterion (AIC) as in Wolowski (2014) and the former was favoured as it had better model fit. Therefore, we proceeded with the traditional meta-analysis.

2.3.3 Subgroup analysis

To investigate the variability of importance on plant reproductive success among the vertebrate pollinators, we classified studies according to the taxon of their vertebrate pollinators (bat, bird, and rodent). We did not include reptiles due to a small sample size (n = 2). To determine if the importance of vertebrate pollinators is dependent on the taxonomic breadth of the flower visitors, we classified the studies according to whether only vertebrates, or both vertebrates and insects, were observed visiting the flowers and making contact with the flowers' anthers and stigma (i.e. making legitimate pollination visits). We categorized it as low, pollinated by vertebrates only, and high, pollinated by both vertebrates and invertebrates. We classified studies into one of the five regions according to their study locations (North America, South-Central America, Asia, Africa, and Australasia) to determine if the importance of vertebrate pollinators differs among geographical regions. We classified studies into one of two climatic zones (tropical and extra-tropical) to determine if there is a difference among climate domains. We ranked each study in one of three categories according to the level of exclusion experiment (flower, inflorescence and whole plant) to check if there is a discrepancy among the different manipulations of the study plant. Lastly, we grouped studies according to their methods of assessing reproductive success (fruit production and seed production) to determine if these methods yield different results (Table 2-1).

Table 2-1 Explanatory variables included in the subgroup analysis and mixed model with subcategories for each variable.

Explanatory variables	Subcategories	Details
Pollinator taxon	Bats Birds Rodents Reptiles	
Taxonomic breadth of flower visitors	High: Vertebrates and invertebrates Low: Vertebrates	The categories show plants legitimately visited by both vertebrate and invertebrate taxa versus plants legitimately visited by only vertebrate taxa
Region	North America (NA) South-Central America (SCA) Africa Asia Australasia	These represent major biogeographic regions
Climatic domain	Tropical Extra-tropical	Categorized according to latitude reported in the study. Tropical < 23°27′, Extra-tropical > 23°27′
Experiment manipulation level	Flower Inflorescence Whole plant	Categories show the level of the manipulation: some flowers, or some inflorescences or the whole plants were mechanically excluded (bagged/caged)
Measure of reproductive success	Fruit production Seed production	Each category includes measures of reproductive success at fruit and seed level, respectively

2.3.4 Predicting reproductive success

To determine the parameters that predict reproductive success of plants, we compared linear regression mixed models for all possible parameter subsets in terms of parsimony and predictions on the basis of Akaike's Information Criterion (AIC) using the function 'dredge' within the package MuMIn (Barton 2011). All possible combinations of explanatory variables (pollinator taxon, climatic domain, taxonomic breadth of flower visitors, region and manipulation level) were considered but power was insufficient to allow for interaction effects. We used AIC_c - AIC corrected for small sample size - since $n/K < 40$, where n is the sample size and K the number of free parameters in the model. Effect size of reproductive success was the response variable in regressions and the parameters as fixed factors. To account for multiple comparisons and test robustness to methodological differences, each model included "Study", "Repeated control" nested in "Study" and "Measure of reproductive success" (fruit and seed production) as random factors. The difference in the AIC_c values between the top model and other models was calculated (Δ_i). Models were ranked in order of increasing Δ_i. Models with $\Delta_i < 6$ were considered the "best'' set of models, with models with $\Delta_i < 2$ being considered as good as the best model (Symonds and Moussalli 2011). Akaike parameter weights (sum of AIC weights) of each parameter found in these models were calculated following Newbold *et* *al.* (2013). We also evaluated the null model (Intercept only) which has no predictor variable and only a mean effect size is calculated.

2.4 Results

We retrieved 69 articles that satisfied the inclusion criteria (Appendix A.4 for the full list of included articles). Because some of these articles investigated multiple plant species, pollinator taxa, or locations, they provided 126 separate exclusion comparisons, hereafter referred to as 'studies'. The dataset included studies on 91 plant species (Appendix A.5), spanning 50 genera and 35 families: 84 studies investigated bird pollinators, 27 flying mammals, 13 non-flying mammals and 2 reptiles. Of 126 studies, 11 were from South and Central America, 37 from Africa, 36 from North America, 30 from Australasia and 12 from Asia (Figure 2.3).

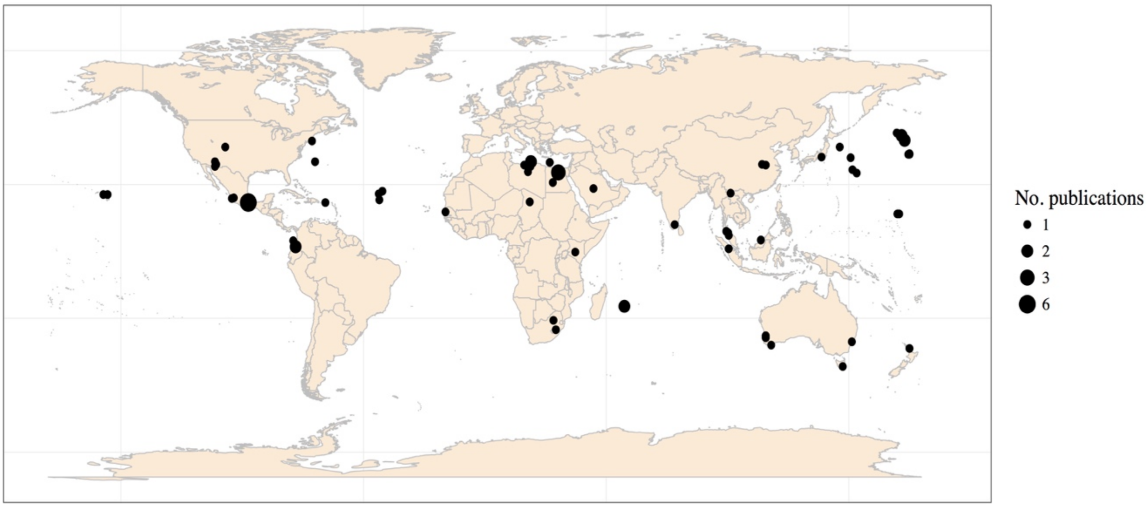

Figure 2-3 Location of studies featuring in our meta-analysis. Locations are based on geographical coordinates given in the publications or they were georeferenced using the provided description of the study area. Increasing circle sizes reflect the number of publications in a specific location.

The exclusion of vertebrate flower visitors had a strong negative effect on plant reproduction across all studies, translating into an average reduction in fruit and seed production of 63% (confidence interval: –74.87 to –46.76) in the absence of vertebrate pollinators (Figure 2-4). The effect size differed according to the main type of flower visitor, with bats having the strongest effect on plant reproductive success. With respect to fruit and seed production, bat-pollinated plants, bird-pollinated plants, and rodent-pollinated plants exhibited an 83% decline, a 46% decline, and a 49% decline (combined lnR), respectively (Figure 2-4a). The breadth of flower visitors did not have a significant effect on plant reproductive success when vertebrate pollinators were excluded. Plants pollinated by vertebrates only were subject to a 59% reduction in reproductive success and those pollinated by both vertebrate and invertebrate pollinators had a 61% reduction (Figure 2-4b). The exclusion of vertebrate pollinators negatively affected plants reproductive success to varying degrees by region (Figure 2-4c) and across latitudes, where the success was reduced by 71% and 45% in the tropical and extra-tropical climatic domains respectively (Figure 2-4d). With regards to the experimental design, the size of the negative effect of pollinator exclusion on plant reproductive success was higher when single flowers were manipulated (71%), than when inflorescences (42%) and whole-plants (40%) were the experimental unit (Figure 2-4e) although they did not differ significantly. Additionally, in terms of fruit production and seed production, proportional reductions in plant reproductive success were almost equal (58% and 61%, respectively)(Figure 2-4f).

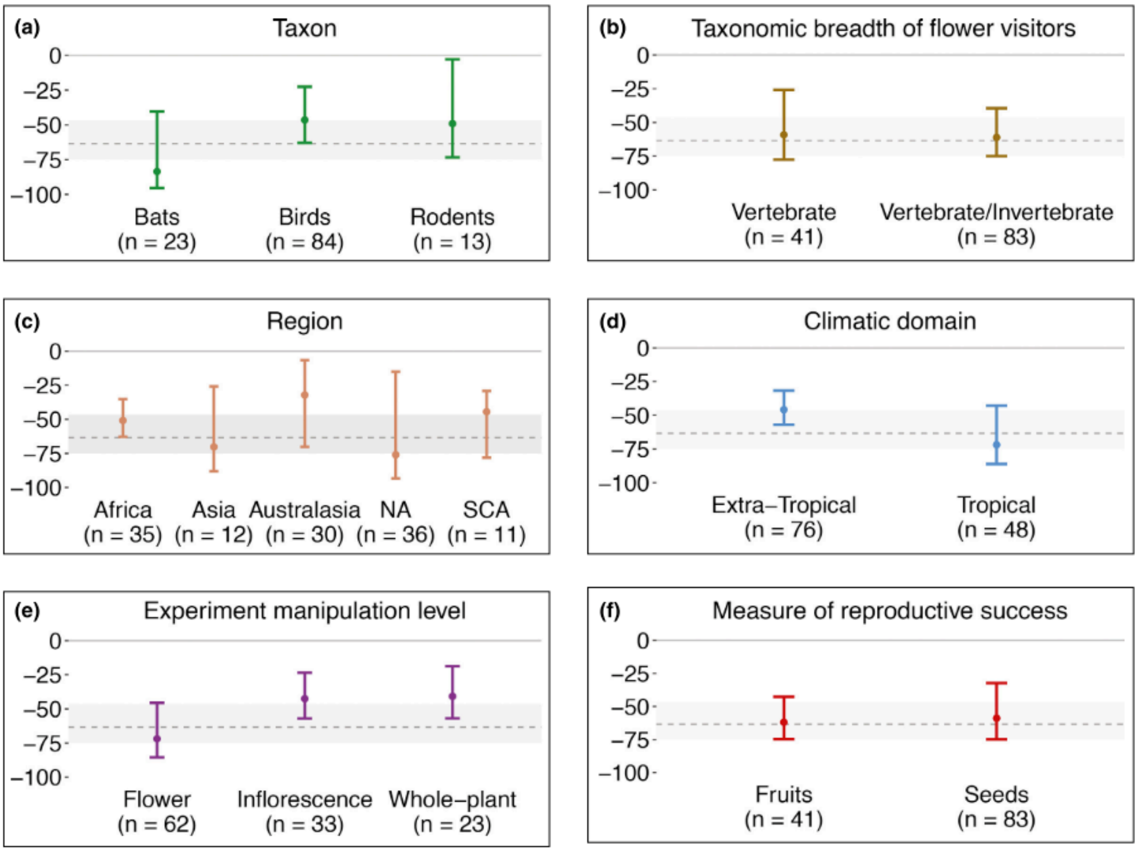

Figure 2-4 Changes in reproductive success when vertebrates were excluded expressed in percentages and 95% biased corrected confidence intervals grouped by from top left: pollinator taxon (a), taxonomic breadth of flower visitors (b), region (NA: North America; SCA: South–Central America), (d) climatic domain, (e) manipulation level of the exclusion experiment, and (f) measure used to estimate reproductive success. Categories in subgroups are shown at the bottom of graphs, and sample sizes are shown in parentheses. The overall mean percentage change in reproductive success is depicted as a dashed horizontal line with a 95% confidence interval (grey band).

Our model selection process inferred pollinator taxon and climatic domain to be the best predictors of the size of the effect of vertebrate pollination on plant reproductive success. Four moderators - pollinator taxon, climatic domain, taxonomic breadth of flower visitors and geographic region - all appeared in models with Δ $AIC_c < 6$, models for which there is considerable support (Burnham and Anderson 2002). Pollinator taxon was included in all the top-performing models and climatic domain in the best model and in one of the other five models with Δ $AIC_c < 6$ (Table 2-2a). Pollinator taxon and climatic domain were the only predictors that had a substantial effect on the observed effect sizes, with summed AIC weights > 0.3 (Newbold *et al.* 2013)(Table 2-2b). The taxonomic breadth of flower visitors, geographic region and type of exclusion experiment did not seem to affect the impact of vertebrate exclusion on the reproductive success of animal-pollinated plants.

Table 2-2 Explanatory variables included in the linear mixed models predicting the variation in reproductive success of plants in presence and absence of vertebrate pollinators; (b) Relative ability of each variable to explain observed responses of reproductive success to the exclusion of vertebrate pollinators. Explanatory power is expressed as the sum of AIC_c weights of variables featuring in models with Δ AIC_c <6.

(a)

Predictors in the model								
Model Rank	Climatic Domain	Pollinator Taxon	Taxonomic breadth of flower visitors	Region	d.f.	AIC_c	ΔAIC_c	weight
1	**+**	**+**			**9**	**550**	**0.00**	**0.52497**
2	**+**	**+**	**+**		**10**	**551**	**1.46**	**0.25327**
3		**+**			**8**	**553**	**3.53**	**0.08978**
4		**+**		**+**	**12**	**554**	**4.46**	**0.05657**
5		**+**	**+**		**9**	**555**	**5.80**	**0.02884**
6	+	+		+	13	556	6.39	0.02152
7		+	+	+	13	556	6.79	0.01763
8	+	+	+	+	14	558	8.52	0.00743

Notes: Models ranked by increasing AIC_c values, Best models, with Δ AIC_c <6, are shown in bold. The predictors featuring in each model are identified with the + symbol; d.f. represents degrees of freedom.

(b)

Variable	Sum of AIC_c weight
Pollinator taxon	**1.00**
Climatic Domain	**0.82**
Taxonomic breadth of flower visitors	0.29
Geographical Region	0.06

Notes: Variables with relative importance >0.3 have substantial effect on the reproductive success of plants (Newbold *et al.* 2013).

2.5 Discussion

Our results show that bat-pollinated plants are more severely affected by pollinator loss than those dependent on birds or rodents. The majority of plants (69%) that yielded no fruit/seed production at all in vertebrate exclusion experiments were bat-pollinated species. This could be because bats are more effective than birds at moving pollen from one flower to another. Many bat-pollinated plants produce very large amounts of pollen and Muchhala *et al.* (2007) demonstrated that at similar visitation rates, bats can transfer up to four times more pollen than transferred by birds. In comparison with feathers, fur has the capacity to hold and shed more pollen grains, making reliance on bats a more secure strategy in evolutionary terms relative to birds. Pollen can be transported over long distances, a feature that is important for plants such as cacti and agave species, which grow at low densities in arid zones (Fleming *et al.* 2009). These bat-adapted plants may represent an evolutionary "dead end" (Tripp and Manos 2008), where switching to an alternative pollinator becomes unlikely due to their inability to transport the large amount of pollen produced (Muchhala and Thomson 2010).

Our findings indicate that birds and rodents are important pollen vectors for many plants. However, we may have underestimated the magnitude of rodents' impact on plants' sexual reproduction for two reasons. First, studies on rodent pollinators were conducted predominantly in South Africa (and with some exceptions in Australia), resulting in a wide knowledge gap for other geographical regions. Second, our meta-analysis included only one rodent family, the Muridae (rats and mice). We consider this dataset insufficient to generalize about the global importance of non-flying mammalian pollinators on the reproductive success of animal-pollinated plants, because it excludes empirical data on many other known mammalian pollinators such as non-human primates (including lemurs), possums, and squirrels.

The second most important factor that explains the impact of vertebrate pollinators on plant reproductive success was climatic domain. Vertebrate-pollinated plants inside the tropics are more dependent on pollinators than vertebrate-pollinated plants outside the tropics, conceivably due to a higher degree of plant specialization near the Equator (Olesen and Jordano 2002; Dalsgaard *et al.* 2011; Trøjelsgaard and Olesen 2013). For example, columnar cacti pollination systems range from exclusively bat-pollinated species in the tropics to species with more generalized pollinator interactions involving both diurnal and nocturnal pollinators outside the tropics (Munguía-Rosas *et al.* 2009). When plants are more specialized (that is, visited by a narrower range of pollinators), then the removal of one pollinator species or group might be expected to have a larger impact on those plants. Dalsgaard *et al.* (2011) found higher specialization in the tropics among plant–hummingbird pollinator networks.

2.5.1 Pollinator dependence and pollen limitation

Our meta-analysis of exclusion experiments measures the degree of pollinator dependence in plants pollinated by vertebrates. This measure reflects the 'value' of existing vertebrate pollination, in the current contexts where the experiments took place (Figure 2-5), and highlights the importance of vertebrate pollinators for fruit and seed production in natural ecosystems. We recognize that experimental exclusion of vertebrate pollinators depicts a worst-case scenario of total pollinator loss for those plants relying on vertebrate pollen vectors. There is, as yet, no documented example of an animal-pollinated plant species that is at risk due to the disappearance of its dominant vertebrate pollinator. Nevertheless, the bleak scenario detailed above is plausible at the scale of individual sites. Local extinctions are known to have occurred for bees and hoverflies (Biesmeijer *et al.* 2006). The long-term survival of a plant species could conceivably be threatened when their vertebrate pollinator communities decline.

Given that we relied on exclusion experiments and not hand pollination comparisons, our results cannot be used to determine how much pollen limitation already exists in the open-pollinated 'controls', due to deficits in the pollination services being provided by vertebrates when the experiments took place. The extent of pollen limitation is measured by the enhancement in plant reproductive success that can be achieved by maximizing pollination (by hand), as if pollinator populations had increased. Previous research has shown that pollen limitation is widespread (Larson and Barrett 2000; Ashman *et al.* 2004). Tropical regions may be more prone to pollen limitation than temperate regions, for several reasons, including the higher incidence of animal-pollinated species in the tropics (Ollerton *et al.* 2011), as well as a positive correlation between high biodiversity and pollen limitation (Vamosi *et al.* 2006). It is not clear whether this observed pollen limitation is a result of ongoing or previous pollinator declines, or whether it reflects the ecological contexts in which the plant-pollinator interactions evolved. If the plants in the pollinator exclusion studies analysed here were already experiencing pollen limitation due to pollinator decline, then the overall negative impact of vertebrate decline on fruit and seed production could be higher than we estimated.

Finally, resource reallocation at a plant level (where plants are manipulated at a flower or inflorescence scale) could potentially bias the experiment results by overestimating the magnitude of the impact of vertebrate exclusion (Knight *et al.* 2006). However, the absence of significant difference in reproductive success among studies subjected to different experiment manipulation level showed that our estimated magnitude of the effect of pollinator loss on plant reproductive success is robust. Nevertheless, future studies could investigate this further by developing standardised methodologies across exclusion experiment studies.

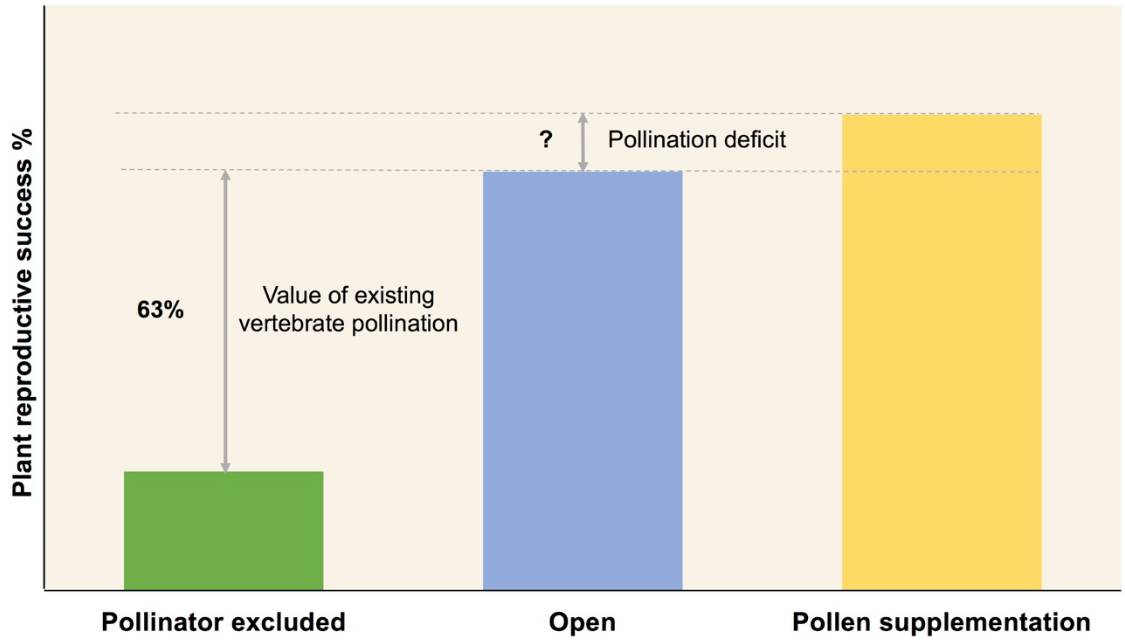

Figure 2-5 A conceptual illustration of results from an experiment testing the impact of both pollinator exclusion and pollen supplementation (usually by hand pollination) on plant reproductive success. This illustrates the difference between pollen limitation caused by lack of pollinators or pollen donors in the environment (leading to pollination deficit) and the value of existing open pollination in the given environment. Here we measure the value of existing pollination service to plant reproductive success.

2.5.2 Implications for human well-being and ecosystems

Our review emphasizes the importance of conserving vertebrate pollinators, particularly in the tropics. Vertebrate pollinator-dependent crops are an important component of our tropical cultivated goods (e.g. pitayas, agave, durian), and declining pollination services may result in substantial losses of revenue. Despite their reduced species richness, bat-pollinated plants have substantial economic and social value. The loss of pollinating bats, for instance, would have profound consequences for the reproduction of plants such as agave and columnar cacti, which yield high monetary-valued goods - mezcal and pitayas - in the Mexican agricultural market. Furthermore, durian (*Durio zibethinus*), which depends on bats and flying foxes for pollination (Bumrungsri *et al.* 2009) is an extremely popular and economically relevant fruit in South-East Asia. A loss of fruits and seeds of this magnitude, especially in tropical areas, would likely have an adverse impact on animals that depend on these resources, including birds, bats, rodents and primates, as well as many granivorous or frugivorous invertebrate species.

In the tropics, vertebrate pollinators may play important roles not only in the regeneration and restoration of degraded natural systems but also in the long-term maintenance of both natural and agricultural systems. However, because many of these roles are poorly understood (such as the consequences of reduced fruit/seed sets on recruitment in future generations of plants), community-level empirical data on the pollination system of plants and their vertebrate pollinators are urgently needed. Future research should also attempt to identify the habitat preference of and potential threats to dominant vertebrate pollinator taxa.

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2.7 Co-Authors contribution

Contributor	Contribution
FR	Formulated the original research question and study design, performed systematic review and data extraction, statistical analysis and write-up
BS	Performed phylogenetic meta-analysis and advised on statistical analysis write-up
RS	Advised on statistical analysis and write-up
VZ-G	Performed literature search in Spanish, advised on write-up
MM	Advised on study design and write-up
JCM	Advised on study design and write-up
GMP	Advised on write-up
LD	Formulated the original research question and study design, advised on statistical analysis and write-up
KSHP	Formulated the original research question and study design, advised on statistical analysis and write-up

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Chapter 3 : A dataset of the degree of dependence of wild and crop plants on vertebrate pollination

This chapter is formatted for submission in the natureresearch journal 'Scientific Data'

3.1 Abstract

Vertebrate pollinators have experienced a substantial decline in the last decades and a recent meta-analysis revealed that excluding vertebrate pollinators from the plants they pollinate, reduces fruit and/or seed production by an average of 63%. Information on the production dependence of plants on their vertebrate pollinators is crucial to fully understand their importance for food production and the maintenance of natural ecosystems, particularly in the tropics, and to better inform conservation actions. Based on a comprehensive literature review, here I present a dataset for degree of production dependence of wild and crop plants on vertebrate pollination based on field exclusion experiments. The database includes information on 126 sites for 29 countries and 90 plants species. I also documented site details, plant information and flower visitors information. A major reuse value of the dataset is in using the production dependence data to enable economic valuations of pollination services provided by vertebrates, especially for economically and socially important plants.

Design Type(s)	Database creation objective
Measurement Type(s)	Reproductive success data (i.e. seed and fruit production)
Technology Type(s)	Data item extraction from journal article
Factor Type(s)	
Sample Characteristic(s)	Earth (Planet) - Vertebrate pollinated plants

3.2 Background & summary

Biotic pollination plays a vital role in the reproduction of many plant species. Globally, almost 90% of the world's flowering plant species depend, to some extent, on animal pollination (Ollerton *et al.* 2011). Over three quarters of the leading global crops species rely to some degree on animal pollination for yield quality and quantity (Klein *et al.* 2007). Although the majority of pollinators are insects, pollinators exist in many vertebrate taxa such as birds, bats and other non-flying mammals as well as reptiles. Chapter 2 (Ratto *et al.* 2018) demonstrated that the exclusion of vertebrates from plants visited by both insects and vertebrate pollinators may reduce fruit and seed production by as much as 63%. This meta-analysis also revealed that tropical plants are more reliant on vertebrate pollination than their temperate counterparts, and bat-pollinated plants are more dependent on vertebrate pollination than those pollinated by other vertebrates.

Vertebrates, especially bats, are particularly crucial for the reproduction of some economically important crop species including *Hylocereus undatus* (dragon fruit) *Durio* spp.(Durian) and *Parkia* spp. (beans) (Ortiz-Hernández and Carrillo-Salazar 2012), Bumrungsri *et al.* 2008, 2009), which are an important component of our tropical cultivated goods (e.g. pitayas, agave, durian). Consequently, a decrease in pollination services due to a decline in vertebrate pollinator taxa may result in substantial losses of revenue in some parts of the world. Furthermore, a severe loss of fruits and seeds, particularly in tropical areas, could potentially affect animals such as birds, bats, rodents and primates, as well as many granivorous or frugivorous invertebrate species that depend on these resources. Therefore, it is crucial to establish the degree of dependence of animal pollinated plants on their vertebrate pollinators, to better understand our reliance on vertebrate pollination for food production and to guide conservation actions and management options. The degree of reliance of plants on animal pollination can be expressed as a dependency ratio (DR), defined as the proportional magnitude of improvement in production, which is attributable directly to animal pollination; this can also be expressed as a percentage of increased production in the presence of biotic pollination. Field experiments comparing seed and fruit production between plants excluded and open to animal pollination have been conducted globally for the past decades. However, there is no global dataset available of these plants' degree of dependence on vertebrate pollination. The only global review of the degree of dependence of plant reproduction on pollination is provided by Klein *et al.* (2007), which exclusively focus on crop plants and primarily on insect pollination. To date, Ollerton *et al.* (2011) provide the best global-scale information available about the degree of dependence of wild plants on their pollinators, however it is not based on empirical data on plant reproductive success.

Here, I describe a database constructed by compiling information on studies selected through systematic review methodologies, which aimed at conducting a meta-analysis on the importance of vertebrate pollinators on plants' reproductive success (Chapter 2). For each study, a wealth of information was collected in addition to mean seed and fruit production in the presence and exclusion of vertebrate pollinators. I extracted reproductive success data from 69 published studies; the total number of geographic site locations is 126 spanning 29 countries around the world in both tropical and temperate biomes. Eleven studies were from South and Central America, 37 from Africa, 36 from North America, 30 from Australasia and 12 from Asia. There are 126 entries in this database, each reporting the degree of production dependence of a plant species on a vertebrate pollination taxon (ratio and percentage) and other attributes such as site location, information on the study plant and information on the pollinator taxa. The magnitude of the improvement in production when pollinated by vertebrates is scored into five classes following the classification in Klein *et al.* (2007)(see section 3.3.3. for details).

This dataset can be used to enable economic valuations of pollination services provided by vertebrate taxa, especially for plants that have a commercial value. The dataset can also be used in future studies and meta-analyses to investigate the extent to which non-insect pollinators contribute to crop production. In addition, this production dependence data can be incorporated into a larger and comprehensive datasets of wild and crop plants' production dependence on animal pollination.

3.3 Methods

3.3.1 Literature search and data extraction

An extensive systematic literature review was conducted to search for studies that looked at the relationship between vertebrate pollinators' visitation and plant sexual reproduction (see Chapter 2 Section 2.3.1 for full details on the search). The selected articles meeting all the criteria were 389 (Fig 2.2, Chapter 2). The full text of each article was screened and all relevant information was extracted (Table 3.1): Reference, Site location, Site details, Plant information, Pollinator information, Measure of reproductive success, impact of vertebrate pollination on seed and fruit production.

3.3.2 Code availability

The dataset is saved in a xlsx. file (see Appendix B.1 for an extract, and here for full dataset) that is easy to access by Microsoft Excel or other data processing software such as R (https://www.r-project.org). There are 126 entries with information in 16 columns (Table 3.1) within the dataset. Each entry represents an exclusion experiment on one plant species, where the seed or fruit production is compared between plants excluded from vertebrate pollination by mean of bagging or caging and those of unmanipulated plants (open pollination). No custom computer code was used to generate the data described in this chapter.

Table 3-1 Description of the attributes and columns in the dataset

Attribute	Column	Column Name	Unit	Note
1. Reference	1	ArticleID	-	Author names and publication year
2. Site location	2	Country	-	Country where the study site was located
	3	Site name	-	Name of the site (e.g. state, region, province, county)
	4	Number of Sites	-	Number of sites where exclusion experiments were carried out
3. Plant information	5	Plant Family	-	Family of study plant
	6	Plant Species	-	Scientific name of study plant
	7	Breeding System	-	Plant breeding system as reported in the study
	8	Crop/Wild	-	Cultivated or wild plant
4. Flower visitors information	9	Pollinator Family	-	Family of the main plant flower visitors. Pollinator group excluded from the plant in the study
	10	Main flower visitors	--	Species names of main flower visitors as observed in the study
	11	Other flower visitors	-	Less frequent flower visitors as observed in the study
5. Impact of vertebrate pollination	12	Measure of reproductive success	-	Fruit set, seed set, fruit number, seed number, fruit weight, seed weight
	13	DR	ratio	Dependency ratio
	14	% of increase in production	%	Dependency ratio expressed as a proportion (DR*100)
	15	Impact by animal pollination		The increase in production is grouped in categories based on those used in Klein *et al.* 2007.

3.3.3 Data records

The data compiled are available in an easy to access xlsx. file, which consists of three sheets: the “Data” file, which is the main dataset, the “Glossary” file, which provides definitions and explains categories and abbreviations, and the “Reference list” file with full references. Data records are reported in a single spreadsheet consisting of 128 rows (including headings) and 16 columns. Each row represents a single measure of proportional change in reproductive success attributable to vertebrate pollination. Each column represents a variable describing location, information on plants, information on flower visitors and on the impact of vertebrate pollinators on the plant’s reproductive success. The names of the columns are grouped in categories denoted as “attributes” (Table 3.1).

Attribute 1 “Reference” contains a single column “ Article ID” reporting the number code of the publication from which the data was extracted. The full citation with author names, title, year of publication and journal name can be found in the file “References list”. Some entries have the same article ID as more than one data point was extracted from a single study. This was due to the study having more than one study plant, more than one study site or because the impact of more than one vertebrate taxon on the same plant species was measured in the study (e.g. birds and bats).

Attribute 2 “Site Location” contains three columns:

- “Country” reports the nation where the study was conducted
- “Site name” indicates the name of the study site when reported, which was often the name of the region, state or county.
- “Number of sites” identifies the number of separate experimental sites in the study

Attribute 3 “Plant information” contains four columns:

- “Plant Family” is the family to which the study plant belongs
- “Plant Species” indicates the scientific name of the study plant
- “Breeding system” of the study plant
- “Crop/wild” indicates whether the plant is cultivated or found in the wild

Attribute 4 “Flower visitors information” consists of three columns:

- "Pollinator Family" reports the family to which the main flower visitors belong. The pollinators in this family are those prevented from contacting the study plant's flowers in the exclusion experiments
- "Main flower visitors" indicates the scientific species names of the most frequent flower visitors as observed in the study or reported in the study from previous published literature.
- "Other flower visitors" reports the species scientific names of less frequent visitors to the study plants, including legitimate and non-legitimate visitors (e.g. nectar robbers)

Attribute 5 "Impact of vertebrate pollination" contains four columns:

- "Measure of reproductive success" indicates the unit of reproductive success used in the study to measure the change in production due to exclusion of vertebrate pollinators (e.g. fruit and seed set, fruit and seed number, fruit and seed weight)
- "DR" indicates the Dependence Ratio defined as the proportional magnitude of improvement in production, which is attributable directly to animal pollination (in this case, vertebrate pollination)
- "% of increase in production" reports the dependence ratio as a percentage (DR*100)
- "Impact by animal pollination" contains scores of the degree of production dependence on vertebrate pollination. The categories were assigned following the classification system in Klein *et al.* (2007), which assigns the degree of production dependence into five classes: (i) **Essential** (production reduction by 90% or more without flower visitors), meaning that animal pollination is required for production (ii) **High** (between 40% and <90% reduction in production), (iii) **Modest** (between 10% and <40% reduction), (iv) **Little** (greater than 0 to less than 10% reduction), and (v) **No reduction**

Some cells in the columns have no values, which is due to the information not being available or not reported in the original article.

3.4 Technical validation

Each original article that met the inclusion criteria was read at least twice. The first time to extract the general information such as site information and a second time to extract the data for the meta-analysis and to make sure that nothing had been missed. All the records included in the dataset originate from published material on peer-reviewed journals and therefore the majority of the data is deemed reliable. Mean data and dispersion values of reproductive success for pollinator-excluded and open-pollinated plants were extracted from tables or line text and checked twice for accuracy. When mean data was presented in figures, the data was extracted using DataThief software (Tummers 2006), which is widely used and allows to accurately measure mean and dispersion values data from reported figures. When these data were not reported at all in the original article, I obtained them from the authors and thus am confident in their reliability. Overall, this dataset provides high-quality open access information on the dependence of wild and crop plants on vertebrate pollination for their reproduction.

3.5 Usage notes

This global dataset contains production dependence data for 91 plant species spanning 35 families. The majority of studies (67%) investigated bird pollinators, 21% flying mammals (bats), 10% non-flying mammals (rodents) and 2 studies reptiles. The flower visitors reported in the column "main flower visitors" are those recorded by the authors in the study site, thus have been determined by field observations. Therefore, although it is reasonable to assume they may be the most effective pollinators, this has not been empirically assessed (e.g. through pollen deposition or pollen load experiments). Furthermore, the classes of production dependence provided in this dataset are categorical and therefore do not take into account variations across varieties and hybrids. However, the exact DR is available in the database to use for more accurate estimates; furthermore most plants in the dataset are wild and have not be subject to artificial selection or hybridization. The calculation of the production dependence scores are based on few primary studies, in many instances on one exclusion experiment only. Therefore, variations in dependence across latitudes, sites and habitats may not be reflected in this dataset, which needs to be taken into account, especially when the data is used for plants occurring in a region different from the original study. The paucity of studies on reptile and rodent pollinators inevitably limits the scope of this dataset, which principally reports data on bats and birds. However, the data were collected up to 2016; field exclusion experiment studies are conducted every year so it is reasonable to expect this database could be updated in the future for the same plant species and for new vertebrate pollinated plant species.

A major reuse value of the dataset is in using the production dependence data to carry out economic valuations of the pollination services provided by vertebrates, particularly for economically and socially important plants such as cacti and durian. Research on economic valuation of pollination services has heavily focussed on market values of invertebrate pollinators, specifically bees. This dataset provides a tool for future studies to elucidate the extent to which non-insect pollinators contribute to crop and wild plants reproduction, which will help support pollinator conservation and inform management strategies. In addition, by coupling this dataset with IUCN data on threatened pollinator species, it will be possible to identify regions and plants species with higher vulnerability to the loss of their vertebrate pollinator and prioritise conservation actions.

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Chapter 4 :A practical tool for assessing pollination services at a site level: tool development and first application at Noar Hill SSSI, UK

4.1 Abstract

The substantial decline of managed and wild pollinators is linked to land-use intensification and habitat loss, and it is accepted knowledge that pollinator visitations to flowers reduce with isolation from natural and semi-natural habitat. However, information on plants degree of dependence on biotic pollination and the contribution of small remnants of natural habitat to the delivery of pollination services is still scant. Currently available ecosystem services assessment tools that include pollination services (e.g. ARIES, InVEST), operate at broad scales or rely on high technical expertise. Accessible and practical tools to enable decision making at the operation level (i.e. a nature reserve) are still lacking. Here, I addressed this research gap by (a) developing a novel, rapid and inexpensive toolkit for the assessment of pollination services at a site-scale, and (b) quantifying the pollination service provided by a small nature reserve in the UK (Noar Hill SSSI) by piloting the newly developed methods (objective (a)). Expert elicitation techniques were used to develop this pollination protocol: an online forum with 20 pollination experts and a 2-day workshop with 12 pollination experts. The resulting protocol consists of three sets of methods: desk-based methods (red standard), field surveys (amber standard) and exclusion experiments (green standard). The latter two methods were piloted in three sampling locations of oilseed rape and field beans located along a 1 km radius from the reserve and another three sampling locations outside the 1km buffer. In each field, the contribution of insect pollination to seed yield and market value was assessed in a block exclusion experiment with three replicates and two treatments: (1) total pollinator exclusion (flowers enclosed in tulle net bags), and (2) open pollination. The methods provide a comparison between a site in its current state and an alternative state, defined as a state to which the site might plausibly change as a result of different management decisions (e.g. a patch of natural habitat converted to cropland). Despite the different levels of confidence, the three methods unanimously show that Noar Hill contributes animal pollination services to the oilseed rape and field beans in the adjacent farmlands. The results show that the annual net economic value of pollination service delivered by Noar Hill in the current state was greater than the alternative state by between £111 and £151 ha^{-1} $year^{-1}$ depending on the method adopted. Under the alternative state of the site crop production is reduced, which demonstrates the potential consequence of losing pollination services provided by the nature reserve. These findings highlight the importance of conserving small nature reserves in highly modified landscapes for both the maintenance of biodiversity and the demands of future crop production.

4.2 Introduction

Intensive land-use changes with large areas of natural grassland being converted to agricultural use, occurred in the UK after the Second World War, following the *Agriculture Act 1947* to ensure food security. As a consequence, a substantial proportion of the natural grasslands and woodlands have been cleared for intensive farming use (Robinson and Sutherland 2002). The Utilised Agricultural Area (UAA) eventually reached 17.4 million hectares in 2017, covering 71% of UK land (Defra 2017a). The total area of natural habitat, including natural grasslands and woodlands, currently stands at approximately 30% of total land cover (Rae 2017), yet only about 1 million hectares, which represents approximately 8% of the total land area of England, is protected under national and international law (Defra 2017b). As large areas of England have been converted to farmland or urbanised, small areas of natural and semi-natural habitat such as small nature reserves, represent very important remnants of biodiversity, which provide resources for wildlife and connectivity across highly modified landscapes.

Intensive land management and the policy-driven changes in agricultural practice are by far the greatest drivers of decline in UK biodiversity (Burns *et al.* 2016). The main negative factors are, amongst others, the abandonment of mixed farming systems, an increase in the use of pesticides and fertilisers and the reduction of marginal habitats, such as hedgerows and ponds (Hayhow *et al.* 2016). According to the modern Red List criteria, approximately 56% of UK species declined in the past four decades, and 15% are extinct or threatened with extinction (JNCC 2014). Particularly, land use intensity and habitat loss have been identified as major drivers of pollinator decline and consistently linked to the drastic decrease in pollinator species richness (Kennedy *et al.* 2013; Vanbergen *et al.* 2013). This is due to intensely cultivated landscapes being deprived of natural habitat which provides foraging and nesting resources to pollinators (Kennedy *et al.* 2013). Research indicates that at a European scale, the loss and fragmentation of semi-natural habitat affect pollinator community composition and lead to a decline in bees diversity (Carré *et al.* 2009). Equally, the higher proportion and intensity of agricultural land adversely affect pollinator abundance and richness (Scheper *et al.* 2015) which may influence the stability in the delivery of pollination services to both crop and wild plants (Klein *et al.* 2003c; Fontaine *et al.* 2006).

In Britain, animal pollination contributes to over 80% of crop production which includes, in addition to oilseed rape and field beans, orchard fruits such as apple and pear and strawberry (Boatman 2012). The overall estimated economic value of pollination services to the UK agriculture ranges between £186 and £567 million per year (Boatman 2012). The

UK is the largest producer of oilseed rape in Europe, accounting for approximately 8% of total EU production (Defra 2017a). The total land use for oilseed rape production was about 590,000 ha in 2017 with a production value of £502 million (Defra 2017c). Oilseed rape is grown predominantly for its oil-rich seeds, for the production of vegetable oil and it is also being used as biodiesel. Although the benefits of insect pollination to oilseed rape yield and quality are dependent on the variety (Steffan-Dewenter 2003; Hudewenz *et al.* 2014), Bommarco *et al.* (2012) estimated the overall contribution of insect pollination to the total yield to be approximately 18%. Furthermore, the UK has the largest area in Europe for field beans production with the single largest share of 27.2% (Eurostat 2017), this area has increased to 192,000ha in 2017 with a production value of circa £172 million (Defra 2017c). Although early studies indicated a moderate effect of pollination on the reproductive success of field beans (Free 1993), more recent evidence revealed that the production in terms of the number of pods per plant and developed beans per pod is substantially affected by insect pollination (Aouar-sadli *et al.* 2008).

Despite such substantial economic benefits delivered by wild and managed pollinators to the UK agriculture, the contribution of natural habitat to the provision of pollination service remains unquantified. A review by Holland *et al.* (2017) found that that semi-natural habitat in Europe had a positive effect on pollinators by providing them with food resources. However, they found that most studies investigated pollination by measuring the number of pollinators (i.e. using transect counts, flower-visiting observation, pan trap or netting). Studies measuring metrics of pollination such as fruit and seed set, quality and pollen deposition remain sparse. Furthermore, although a wealth of pollination research in the past decade has increased our understanding of the benefits provided by animal pollination to crop yield (Garibaldi *et al.* 2011b, 2013), information on the contribution of pollinator communities to yield and crop quality in the UK is still surprisingly scant. A review by Klein *et al.* (2007) is currently the best available source on crop dependence on animal pollination, though it is a categorical approach and does not take into account variations across different regions and varieties (Bartomeus *et al.* 2014). For instance, the dependence of oilseed rape on pollinators has been shown to vary between 0 and 30% across different varieties (Stanley *et al.* 2013; Garratt *et al.* 2014b).

Although in recent years some studies have focused on quantifying the contribution and economic value of insect pollination to a number of British crops such as apples (Garratt *et al.* 2014a), courgettes (Knapp and Osborne 2017) and oilseed rape (Stanley *et al.* 2013), these studies did not account for the yield variation due to the contribution of pollination services from nearby natural habitat. Additionally, the UK still lacks empirical evidence on how variation in the abundance of pollinators may influence crop pollination and the consequent economic impact (Vanbergen *et al.* 2013). To enhance pollination services in agroecosystems, it is fundamental to assess the consequences of losing natural habitat on pollinator abundance and their delivery of pollination services. This information could be used by NGOs and site managers to provide additional evidence for the conservation and management of small natural sites within agroecosystems and to support the implementation of sustainable finance mechanisms for site conservation, such as payments for ecosystem services. Evidence on the importance of natural habitat to adjacent crop productivity may also help to justify expenditures for effective mitigation measures such as agri-environment schemes (Entry-High Level Stewardships, Natural England 2013a,b).

Here, I address the research gaps by (i) developing a set of rapid, inexpensive and accessible methods for the assessment of pollination services at a site-scale, to enable local decision-making. The unique features of the TESSA toolkit (section 1.4.4.1) fit with this aim, and it was therefore chosen as a framework for developing a set of protocols for measuring pollination services; (ii) investigating pollination services provided by Noar Hill, a protected area embedded in a predominantly agricultural landscape in Hampshire, UK. In order to elucidate the contribution of pollination services provided by the nature reserve to the surrounding agriculture production, I carried out a comparative assessment for the pollination service provisions by the site managed for nature conservation and its hypothetical state where the protection status had not been established and the land was converted into agricultural farmland. To achieve this, I piloted the new pollination protocol developed for objective (i). This study represents the first application of the new pollination tool, which is available in TESSA 2.0 (Peh *et al*. 2017).

4.3 Materials and Methods

4.3.1 Protocol development

The protocol development took place in six consecutive phases. Initially, this process was started by implementing two successive approaches: an online expert forum and an expert workshop. The information gathered from these approaches was subsequently collated and synthesised into a draft protocol and submitted for peer review. Finally, the protocol was finalised, piloted in the field and published in TESSA V2.0 (Figure 4.1).

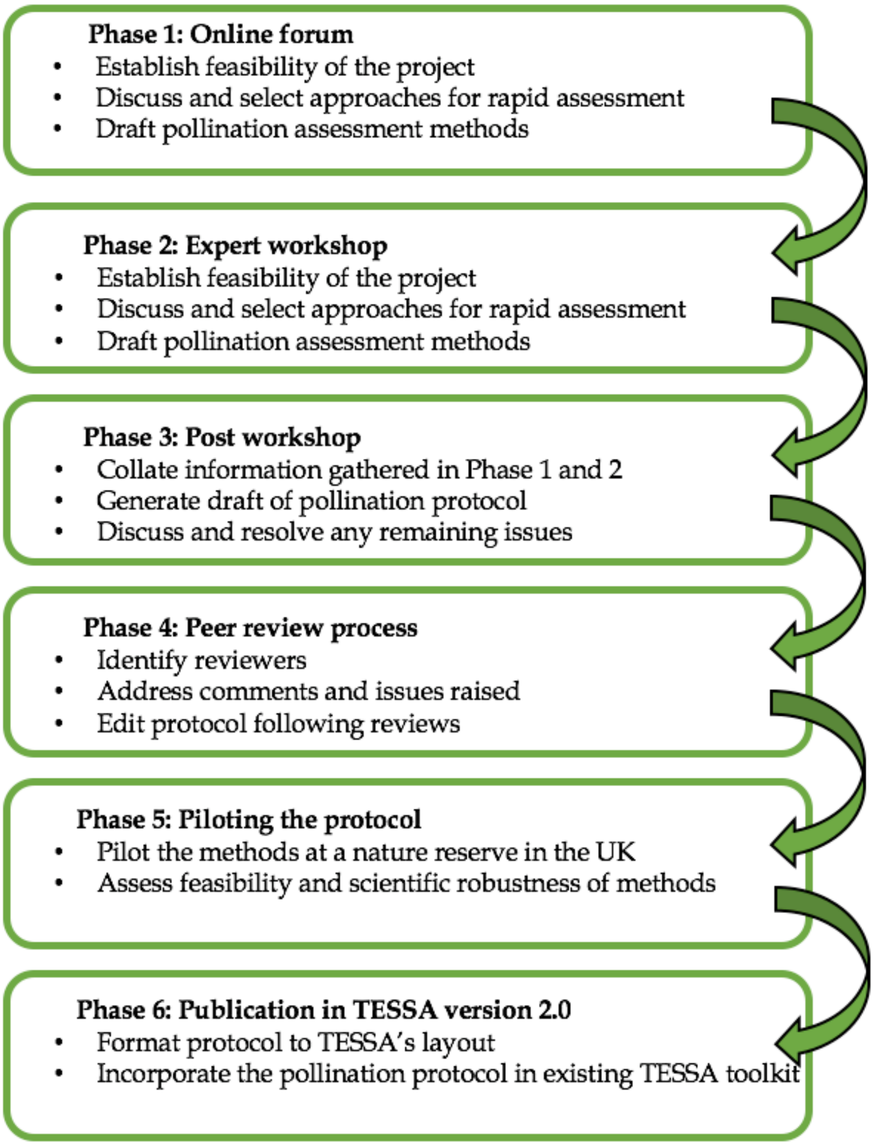

Figure 4-1 Flowchart showing the protocol development steps.

4.3.1.1 PHASE 1 & 2: Online Expert forum and expert workshop

Expert elicitation is a technique used to synthesise expert opinions, which has been used for a number of decades in fields such as social sciences, economy, political sciences and risk-assessment sector (De Vaus 2002; Garthwaite *et al.* 2005; O'Hagan *et al.* 2006). More recently, expert-based approaches are increasingly used in conservation biology studies and ecological studies and assessments (Halpern *et al.* 2007; Donlan *et al.* 2010; James *et al.* 2010; Krueger *et al.* 2012; Schneiders *et al.* 2012; Drescher *et al.* 2013; Sutherland *et al.* 2013). These approaches are also commonly used in ecosystem services studies (Vihervaara *et al.* 2010, 2012; Kaiser *et al.* 2013) as they are particularly suited for transdisciplinary assessments such as integrated ecosystem service assessments (Jacobs *et al.* 2014).

The first phase of protocol development started with an online expert forum as a remote interaction is less time demanding for the participants (Drescher *et al.* 2013), and the discussion can be conducted for a longer period of time. The web-based approach provides participants with more flexibility to reflect on the topic and contribute in their own time and allows engagement with a broader range of international experts. The forum was created in March 2015 and ran until August 2015 on Lefora (https://www.lefora.com).

Although the online forum stimulated discussions and provided key ideas and suggestions for the protocol development, it was not active for long enough to achieve the objectives of this study in full. Therefore, an experts' workshop was chosen as another form of expert elicitation. Face-to-face meetings are typically more enjoyable than remote interactions and generate enthusiasm to communicate the value of the work (Drescher *et al.* 2013). Furthermore, dynamic group discussions such as workshops enable experts to share more recent information about the topic of interest and to discuss issues more freely. They also generate more information and insight into a topic than those revealed by individual interviews or surveys (Kitzinger 1994, Morgan 1993). The two-day workshop was held at the headquarters of the UNEP-WCMC (World Conservation Monitoring Centre) in Cambridge on 19th -20th September 2016 and comprised fourteen participants which included twelve experts and two facilitators.

Detailed information on the protocol development phases are available in Appendix C.1 to C.14.

4.3.1.2 Phase 3 & 4: Post-workshop and Peer-review process

Building on the outcome of the workshop, I expanded on the concepts and methodologies suggested in the previous phase and created a comprehensive document, following the format and specifications of TESSA. The final version was peer-reviewed by a number of pollination experts who did not take part in the workshop. I selected four reviewers, two with knowledge of invertebrate pollinators in temperate regions and two with expertise on tropical ecosystems and vertebrate pollination.

4.3.1.3 PHASE 5 & 6: First application of the protocol and publication in TESSA Version 2.0

This phase required the identification of a suitable site for piloting all the methods that had been developed I identified Noar Hill SSSI in the UK as an appropriate site for the pilot study as it is a small remnant of semi-natural habitat isolated in a landscape of crop production. This was achieved by liaising with HIWWT (Hampshire and Isle of White Wildlife Trust), GWCT (Game and Wildlife Conservation Trust), FWAG South East (Farming and Wildlife Advisory Group). These organisations advised me on potentially suitable sites in the Hampshire area and put me in contact with the SLP (Selborne Landscape Partnership). The fieldwork was carried out between April-September 2017 (see Section 4.3.2).

The peer-reviewed version of the protocol was formatted to comply to TESSA's layout by myself and the TESSA coordinator, Ms Jennifer Merriman at BirdLife international, and was published on 20th December 2017 as the Pollination module in TESSA version 2.0 (Peh *et al.* 2017)(Appendix C.15 to C.23).

4.3.2 Protocol pilot: first application at Noar Hill SSSI

4.3.2.1 Study area and site selection

Noar Hill (hereafter 'the reserve') is a nature reserve of approximately 63 ha, comprising an unimproved species-rich calcareous grassland, scrub mosaic with old pits, bare ground and semi-natural broadleaved woodland around the site fringes (51° 04′ 18N, 0° 55′ 59W)(Sanderson 2000). This reserve sits within the South Down National Park and it is surrounded by a matrix of the agriculturally dominated landscape. Oilseed rape (*Brassica napus)* and field beans (*Vicia faba*) were grown on the land immediately surrounding the site in 2017 but no crop is grown within its boundaries at any time. Approximately, 85 per cent of the South Downs National Park is farmland and two-thirds of it is managed through various kinds of the agri-environment scheme, which support land managers who implement a farming practice that also benefits wildlife and the environment. Farmers in the area surrounding Noar Hill are joined into a 'farm clusters', groups of farmers and land managers working together to secure funding and benefit the environment.

Management regime of the reserve includes rabbit and sheep grazing for controlling rank grasses invasion and maintain the close-cropped turf on which several insects and plants depend. Coppicing of hazel trees is also regularly carried out to preserve the scrubby habitat of the reserve (Sanderson 2000). Originally, Noar Hill was a site of medieval chalk-workings – chalk was extracted and spread as fertilizer on nearby fields, leaving an irregular network of pits and hollows. Due to the ground unevenness, the site remained unploughed for centuries and only used for grazing. The area was declared a nature reserve in 1982, and it is currently managed by the Hampshire and Isle of Wight Wildlife

Trust (HIWWT). Noar Hill is designated as a Site of Special Scientific Interest (SSSI) and a Special Area of Conservation (SAC) based on its biodiversity values.

Currently, the reserve is one of the best examples of chalk grassland and scrub mosaic in the UK. It is floristically very rich with over a dozen species of orchid, including a nationally important colony of musk orchids (*Herminium monorchis*), and populations of scarcer species such as early gentian (*Gentianella anglica*) and hairy rock-cress (*Arabis hirsuta*). Due to the diverse flora, Noar Hill supports over 35 species of butterflies including the declining duke of burgundy (*Hamearis Lucina)*, the brown hairstreak (*Thecla betulae*) and the rare Silver-washed fritillary (*Argynnis paphia*). This nature reserve represents a key area of interest for local communities for its invertebrate diversity, particularly butterflies, wildflowers and the historical interest as medieval chalk workings. Furthermore, Noar Hill is valued by people for its remoteness and the peaceful walks it offers.

4.3.3 Measuring pollination services

To explore the contribution of Noar Hill to the pollination services for the surrounding agricultural landscape, I selected three concentric buffer areas radiating out from the reserve (Figure 4-2). The innermost buffer was adjacent to the reserve and the outermost buffer area was no more than 1 km from the perimeter of the reserve. Each buffer area was approximately 350 metres wide (Figure 4.2). Areas of OSR (*Brassica napus*) and FB (*Vicia faba*) were identified in each buffer area. There is no cultivated or harvested wild goods found within the reserve.

Figure 4-2 Noar Hill SSSI site (red) surrounded by three buffer areas (yellow lines: Close, Medium, Far) within a 1km radius (yellow) from the reserve. The red triangles represent the sampling locations in oilseed rape (yellow fields), the green triangles represent the sampling locations on field beans (brown fields).

Figure 4-3 Location of sampling points at a finer scale in the Close buffer. The red triangles represent the sampling locations in oilseed rape (yellow fields), the green triangles represent the sampling locations on field beans (brown fields).

First, I assessed the pollination service values for the surrounding farmland within 1 km from the reserve. Then data from adjacent farmland beyond 1 km from the reserve was used to estimate what the pollination service value of this reserve would be if it were under crop cultivation. In this study, I used the pollination service assessment methods from TESSA v. 2.0 (Peh *et al.* 2017) developed in Chapter 3. TESSA guides local non-experts through a selection of three relatively accessible methods for measuring pollination services. These methods are colour-coded to reflect their resource (including time and expertise), requirement and the level of confidence of their resulting data. These include primary data collection by (1) using desk-based approach based on existing databases and studies but yielding results with lower degree of confidence (Red standard); (2) conducting field surveys of pollinator visitation frequency (Amber standard); and (3) carrying out field exclusion experiments and yielding results with high confidence level (Green standard)(See Appendices C.15, C.17 and C.19).

I conducted questionnaire interviews with the local farmers (Appendix C.24) to obtain information on the highest locally achievable yield in the area (expressed in t ha^{-1}) for both crops and total area (ha) of both crops which grow within a 1 km buffer of the reserve. The questionnaire also provided information on the farmgate prices (£ t^{-1}) of both crops (net value of the crop when it leaves the farm after marketing costs have been subtracted) and annual production costs (i.e., costs attributable to crop production, expressed in £ ha^{-1}). Estimates of annual management costs for the reserve (e.g., labour, staff, contractors, volunteer expenses, fuel and transport for grazing and scrub cutting) were obtained from the site manager at HIWWT.

4.3.3.1 Desk-based method using published results (Red standard)

I estimated the value of pollination services provided by the reserve to both oilseed rape and field bean crops within a 1 km buffer from the reserve perimeter using the rapid desk-based method, most suitable when resources do not permit field data collection (Peh *et al.* 2017). To use this method, I determined the dependency ratio (DR; the proportional magnitude of improvement in production attributable directly to animal pollination) of both oilseed rape and field bean from the existing literature (Klein *et al.* 2007). This method is based on a decay curve showing an exponential relationship between distance from the reserve and visitation frequency of pollinators from the reserve, constructed from a global synthesis (Ricketts *et al.* 2008). This method, using a decay function based on published results, assumes that (1) the decline with distance from the reserve is equal for all pollinator species, crops and habitat types; and (2) the crop production immediately outside the reserve always attains maximum achievable yield and it would decline exponentially following the decay function.

To estimate the pollinator visitation frequency in each buffer areas at the distance at which the crops occurred (oilseed rape: 60 m, 440 m, and 850 m; field bean: 66 m, 388 m and 896 m), and at 1 km from the site, I used the following formula: $\mathbf{y(d) = a*e^{kd}}$ where y(d) is the value of visitation frequency at distance d; a is the value of visitation frequency at the start (inside the reserve); k is the rate of decay (μβ in Table 4-1); and d is the given distance.

For each crop type, the value of each visitation frequency was estimated along the distance gradient from the reserve by assuming that the highest pollinator visitation frequency corresponds to maximum achievable yield. The latter was multiplied by DR to obtain the proportion of yield that is attributable to animal pollination. This value was subsequently multiplied by the crop price (£ $tonne^{-1}$) to obtain the value of pollination (£ ha^{-1}) and then deducted by the estimated pollination value at 1 km to exclude the baseline pollination (i.e., pollination provided by pollinators that persist in the agricultural matrix). Finally, these three values of each crop were averaged to obtain a mean economic value of pollination. The sum of the values of oilseed rape and field beans represents the total economic value of pollination services provided by Noar Hill.

Table 4-1 Estimates of overall decay rate for pollinator visitation rate extracted from Ricketts *et al.* (2008).

Variable	N	μβ*	Point of 50% decay (m)**
Visitation rate	22	-0.00104	668 (395-1727)
Temperate	11	-0.00053	1308 (437-13849)
Tropical	11	0.00118	589 (296-8186)

*Posterior probability that overall decay rate () is less than zero.
** Distance at which variable is 50% of the maximum value at distance = 0, along with 90% credible interval.

4.3.3.2 Field Surveys (Amber standard)

The value of pollination services delivered by the reserve to both oilseed rape and field bean crops within a 1 km buffer from the reserve boundary was assessed by conducting field survey of the pollinator visitation rate, based on the perception that the visitation frequency of pollinators to flowers is a strong proxy for pollination services (Winfree *et al.* 2015). For this method, I assume that (1) all flowers do not receive more visitations from pollinators than they need; (2) the highest visitation rate provides 100% of the requirements of a crop adjacent to the reserve resulting o the maximum achievable yield; (3) all flower visitations provide pollination services; (4) every visit and every pollinator is equal; and (5) the crop area is evenly distributed across the 1 km buffer. This method is suitable when some financial resources and time could be devoted to ground data collection (Peh *et al.* 2017).

For both oilseed rape and field beans, I identified three sampling locations within each buffer areas at the distance whereby the crop occurred (i.e., the same distances as in the desk-based methods). At each sampling location, I established three plots, each measuring 1 m × 1 m. Hence, a total of nine sampling locations and 27 plots for each crop type. Each plot was located at least 50m away from field edge to minimise edge effect and as far as possible from patches of semi-natural habitat to minimise influx of pollination services provides by those patches. All visits to flowers inside each plot were counted and all flower visitors were recorded for 15 minutes. I also counted the number of open flowers within each plot. The observed flower visitors were classified as honey bees (*Apis mellifera* L.), bumblebees (*Bombus spp.*), solitary bees (*Andrenidae* and *Halictidae*), hoverflies (*Syrphidae*), other flies (*Anthomyiidae* and *Muscidae*) and others (including Lepidoptera, Coleoptera, Diptera and Hymenoptera). Observations were performed between 1000 and 1600 hours during dry, sunny weather with temperatures ≥ 13°C (Pollard and Yates 1993) and wind speed below 5 on the Beaufort scale. These field surveys were carried out during the peak of the flowering seasons of both crops: from 17 April 2017 to 21 April 2017 for oilseed rape; and 19 June 2017 and 23 June 2017 for field beans.

Average visitation frequency (expressed in terms of number of visits flower^{-1} minute^{-1}) was calculated across the 9 plots within each buffer area and these three values for visitation frequency at three increasing distances from the reserve were then used to calculate the value of pollination services (£ ha^{-1}) provided by the reserve. Same calculations as in the desk-based method were performed but using the observed visitation frequencies collected in the field instead. The same sampling effort was applied beyond the 1km buffer for each crop for estimating the value of pollination under the alternative state. This estimated value of pollination services beyond 1 km was the baseline pollination provided by pollinators which inhabit within the agricultural matrix. Therefore, the value of pollination services provided only by the reserve was derived by a deduction of this baseline measure.

4.3.3.3 Exclusion Experiments (Green standard)

I measured the value of pollination services delivered by the reserve to the surrounding cropland within 1 km from the reserve perimeter by carrying out exclusion experiments which involve placing mesh bags over plants to exclude pollinators. Although this method is more time consuming, labour-intensive and expensive than the previous two methods, it produces more accurate results as it enables the measurement of marginal crop yield that is the direct result of animal pollination. To enhance the accuracy of exclusion experiments and to prevent the effect of bagging on seed/fruit development, bags were placed on the plants for as short a time as possible and removed at the end of the flowering period.

Three sampling locations within each buffer zone were chosen for each crop type (approximately at the same sampling locations used for pollinator visitation frequency surveys). At each sampling location, five plants were randomly selected. On each oilseed rape plant, I identified two flower units (racemes) that were similar in length, position and number of flowers. These were randomly assigned for two treatments: (1) unmanipulated racemes where flowers were accessible to wind, insect and self-pollination (control treatment [C]); and (2) racemes enclosed in a 60 cm x 40 cm tulle net bag (N) to prevent access to insect pollinators. The experiments consisted of 15 plants per distance zone, each plant had one bagged raceme and one unbagged raceme as control. The racemes in each treatment were identified with a garden tag featuring plant and treatment code. In total, there were 45 bagged racemes and 45 unbagged racemes across the distance gradient. I did not bag the entire oilseed rape plants due to the time and resources constraints. To investigate potential compensation due to resource reallocation to unbagged parts of the plant, I tagged an additional control raceme (C2) in a nearby plant and statistically compared the yield resulting from these racemes with that obtained from the other control racemes (unbagged racemes; C1) using a Student's t-test. A total of 45 bagged racemes and 45 unbagged racemes on 45 randomly selected plants was also set up in the area beyond 1 km from the reserve to represent the alternative state.

An identical experimental design was applied to field beans, though on this crop type the entire plants were bagged. This experiment consisted of 30 experimental plants (15 bagged plants and 15 control plants) per distance zone; hence, a total of 90 experimental plants across the distance gradient. Due to time constraint, I reduced the number of experimental plants in the area beyond 1 km from the reserve–that represents the alternative state–to 15 bagged and 15 control plants; hence the same sampling effort as in each distance zone.

Bags were placed before the flowering onset and removed at the end of the flowering period to minimise the effect of bags on exposure to pests and diseases. On OSR, plants parts with no flowers on were left outside the bags to minimise any microclimatic effect as in Bommarco (2012). I visited the plants twice over the flowering period and adjusted the bags to allow the stems more room to grow. At the end of the flowering period, I removed the bags and left the tags on until the end of the ripening period.

At harvest, the number of pods per stem and number of seeds per pod on ORS were counted; the number of pods per plant, number of beans per pod and number of seeds per plant were noted on field beans. I measured the individual dry seed weight in ORS plants and the weight of dry seeds per plant in field beans. For each plant, I divided the yield of bagged flowers by the yield of unbagged flowers - the resulting ratios estimated the proportion of yield that is due to self-pollination. The proportion of yield that is due to insect pollination was obtained by using the formula 1-(self-pollination) for each plant and then averaged to obtain a pollination dependence value for each buffer zone. These values were averaged again to obtain a final pollination dependence value (DR) for each crop type.

The economic value of pollination provided by Noar Hill was calculated with the following formula: **PS = A*Y*DR*FP,** where PS is the value of pollination services (£); A is the area under crop production (ha); Y is the annual quantity of the crop produced (t ha^{-1} $year^{-1}$); DR is the mean dependency ratio for the crop; and FP is the farmgate price of the crop.

In addition to the pollination protocol, Analysis of variance was used in the field surveys method to analyse the effect of pollinator taxa on visitation rate. If a significant effect was found, a Tukey Honest Significant Difference test was used to assess significant differences between pollinator taxa as in Garratt *et al.* (2014b). I used a two-way ANOVA on the whole dataset to test the effect of treatment and distance on OSR seed weight and on number of seeds per pod, number of pods per plant and number of seeds per plant in field beans. Data of response variables were log n+1 transformed to improve normality and homogeneity of variance.

For all three methods, the estimated value of pollination services beyond 1km was used as the background measure of pollination services provided by pollinators inhabiting the agricultural matrix. Therefore, this background measure was deducted so that the final values represent pollination services provided by the assessment site only.

4.4 Results

The total area (ha) of crops growing within a 1km buffer from the reserve was 43.1 hectares for oilseed rape and 48.5 hectares for field beans. Maximum locally achievable yield at the study site was 3.75 tonne/ha for oilseed rape and 3.875 tonne/ha for field beans. Farmers at Noar Hill sell oilseed rape at a farmgate price of £330 per tonne and field beans at £155 per tonne.

4.4.1 Desk-based method (Red standard)

Oilseed rape

The exponential decay curve, based on the desk-based assessment, showed a decrease in the value of pollination services from the innermost buffer (nearest to the reserve) estimated at £309 ha^{-1} yr^{-1} to the outermost buffer at £136 ha^{-1} yr^{-1} (Figure 4-4). After deducting the baseline value, the value of pollination services ranged from £193 ha^{-1} yr^{-1} in the buffer nearest to the reserve to £19 ha^{-1} yr^{-1} in the outermost buffer. The average value of pollination services for the oilseed rape production within the 1 km buffer from the reserve was estimated at £102 ha^{-1} yr^{-1}.

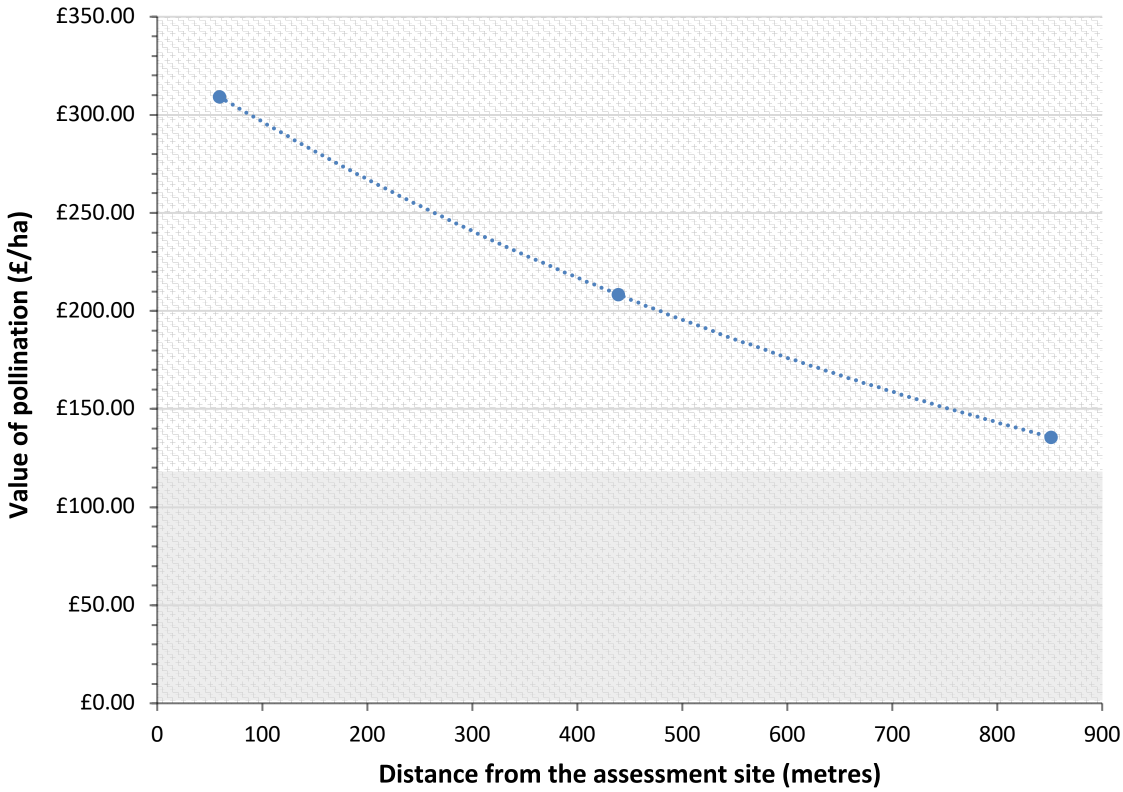

Figure 4-4 Desk-based method: Distance decay curve of the value of pollination service for oilseed rape within 1 km from the reserve under the current state. The grey shading represents the value of pollination beyond 1 km provided by pollinators which inhabit within the agricultural matrix.

Beyond 1 km from the reserve (baseline pollination), the value of the baseline pollination for oilseed rape was estimated at £116 ha^{-1} yr^{-1} (Figure 4-4). The value of pollination services provided by the alternative state is £0.

Field beans

The exponential decay curve derived from the desk-based assessment showed that there was a decline in pollination services for field beans along the 1 km radius from the reserve from an estimated value of £150 ha^{-1} yr^{-1} to £63 ha^{-1} yr^{-1} (Figure 4-5). After deducting the baseline value, the value of pollination services ranged from £93 ha^{-1} yr^{-1} in the innermost buffer to £6 ha^{-1} yr^{-1} in the outermost buffer. The average value of pollination services for the field bean production within the 1 km buffer area from the reserve, after deducting the baseline value, was estimated at £50 ha^{-1} yr^{-1}.

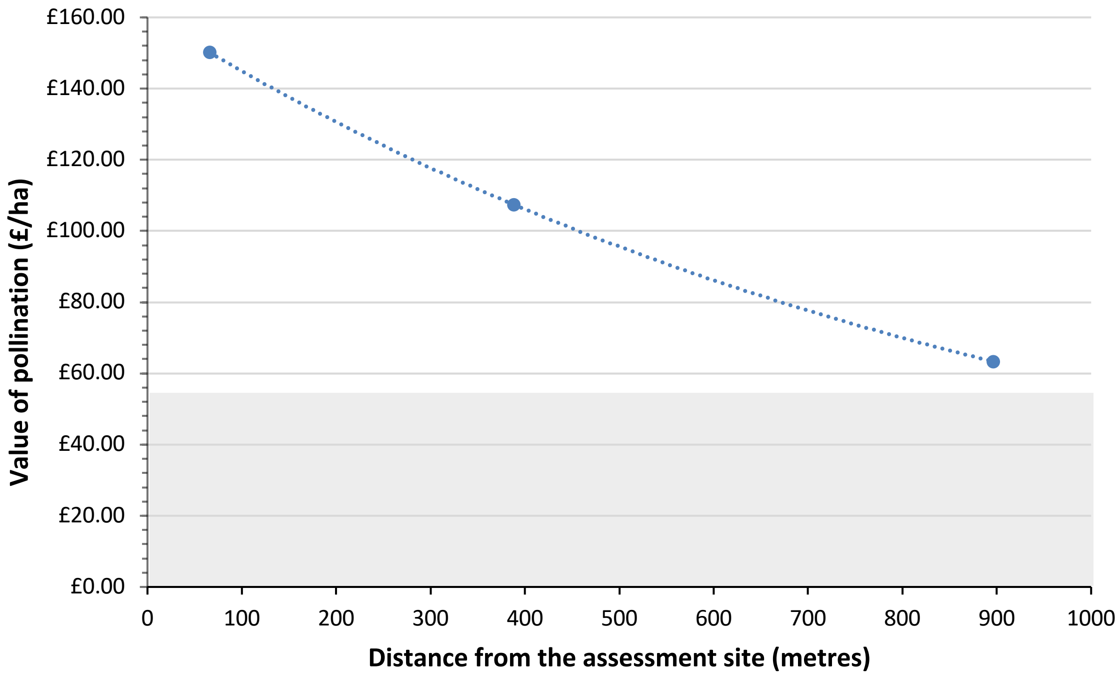

Figure 4-5 Desk-based method: Distance decay curve of the value of pollination service for field beans within 1 km buffer from the reserve under the current state. The grey shading represents the value of pollination beyond 1 km provided by pollinators which inhabit within the agricultural matrix.

The decay curve showed that the value of the baseline pollination for field beans in the area beyond 1 km from the reserve was £57 ha^{-1} yr^{-1} (Figure 4-3). The value of pollination services provided by the alternative state is £0.

4.4.2 Field survey (Amber standard): Effect of pollinator visitation rate on oilseed rape and field beans yield

Oilseed rape

Under both the current (within 1 km buffer from the reserve) and alternative (beyond 1 km from the reserve) states, the vast majority of the visits to oilseed rape flowers were carried out by common flies (*muscidae spp.*) followed by honey bees (*Apis mellifera* L.); other taxonomic groups were rarely observed (Figure 4-6). There was a significant effect of pollinator taxon on visitation rate for the current state ($F_{1,34}$ = 8.072 p=0.007). Under the current state, pollinator visitation frequency declined sharply along the 1 km radius, from 0.0058 visits $flower^{-1}$ min^{-1} (nearest to the reserve) to 0.0016 visits $flower^{-1}$ min^{-1} (in the outermost buffer area). This indicates a detectable influence of the reserve on the provision of pollination services to the adjacent crops. Based on the published dependency ratio (0.25; Klein *et al.* 2007), the value of pollination services from the reserve declined along the distance gradient from £309ha^{-1} yr^{-1} (nearest to the reserve) to £87ha^{-1} yr^{-1} (in the outermost buffer)(Figure 4-7). After deducting the baseline value, the value of pollination services ranged from £223 ha^{-1} yr^{-1} in the buffer nearest to the reserve to £0.5 ha^{-1} yr^{-1} in the outermost buffer. The average value of the pollination service for the oilseed rape production within 1 km buffer from the reserve, after deducting the baseline value, was estimated at £76 ha^{-1} yr^{-1}.

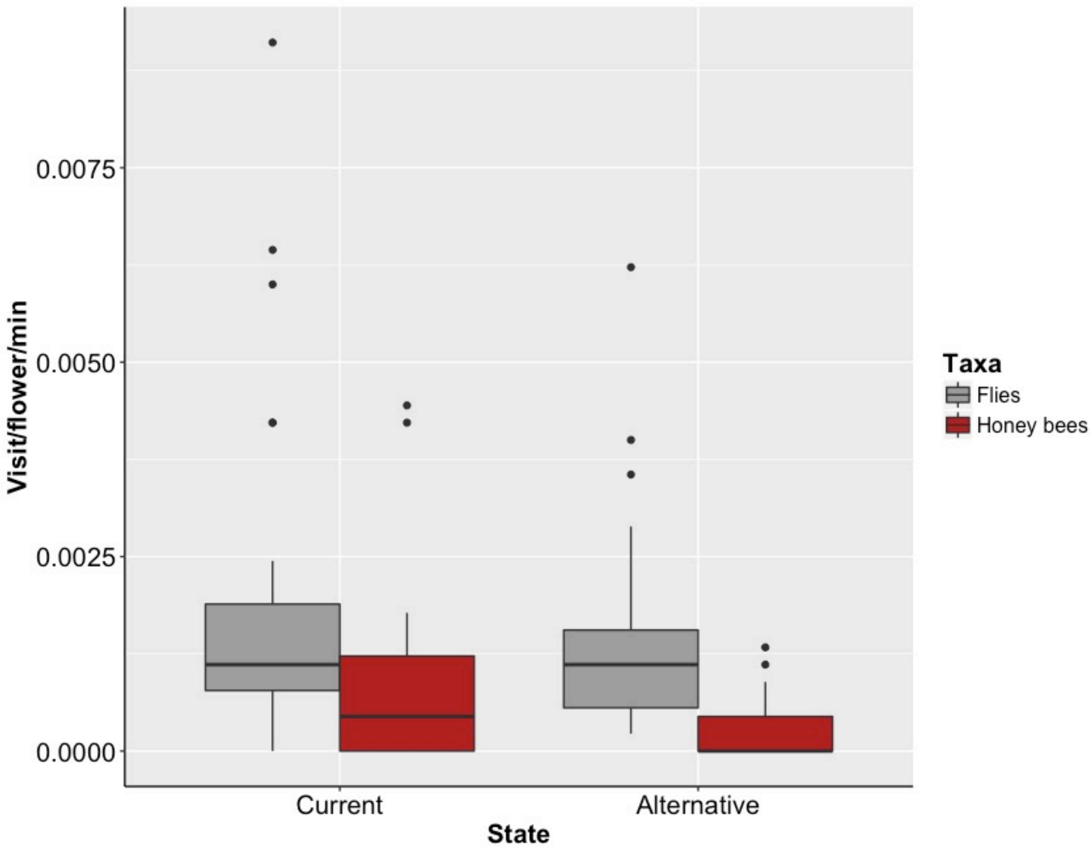

Figure 4-6 Visitation frequencies (visits $flower^{-1}$ min^{-1}) carried out by legitimate pollinator taxa on oilseed rape flowers within 1 km buffer from the reserve under the current state and beyond 1 km from the reserve, representing the alternative state (i.e. conversion of the reserve to cropland). The medians, 1st and 3rd quartiles for flies (grey boxes) and honeybees (red boxes) are shown. Error bars represent upper and lower quartiles.

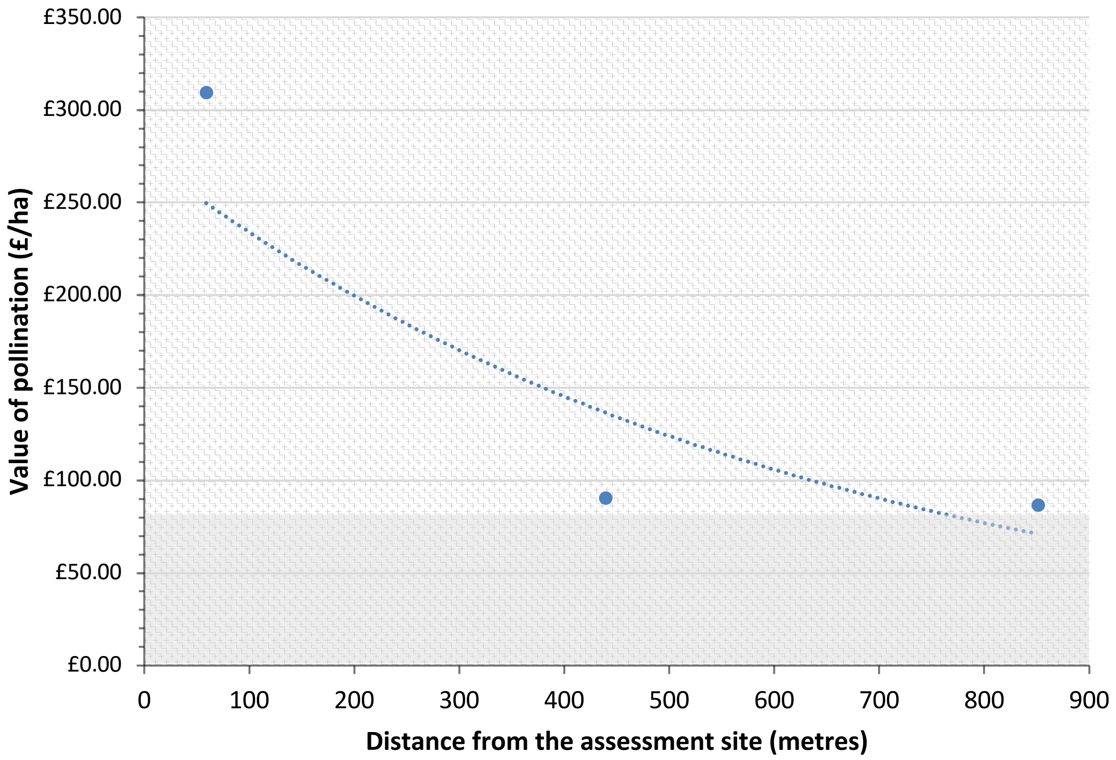

Figure 4-7 Field surveys method: Distance decay curve of the value of pollination service for oilseed rape within 1 km buffer from the reserve under the current state. The grey shading represents the value of pollination beyond 1 km provided by pollinators which inhabit within the agricultural matrix.

Beyond 1 km from the reserve (baseline pollination), pollinator visitation rate ranged between 0.0012 and 0.0020 visits flower^{-1} min^{-1} . The average value of this baseline pollination for oilseed rape was estimated at £86 ha^{-1} yr^{-1}. The value of pollination services provided by the alternative state is £0.

Field beans

Field beans flowers in Noar Hill were predominantly visited by bumblebees (*Bombus spp.*) followed by honey bees (*Apis mellifera* L.) and hoverflies (*Syrphidae*)(Figure 4-8) but there was no significant difference in visitation rate between taxa ($F_{2,51}$ = 0.401, p=0.66).

Under the current state, pollinator visitation frequency declined from 0.0028 visits flower^{-1} min^{-1} in the buffer area nearest to the reserve to 0.0008 visits flower^{-1} min^{-1} in the outermost buffer from the reserve; the visitation rate reduced by half at approximately 500 m from the reserve. The value of pollination services for field beans was estimated at £150 ha^{-1} yr^{-1} in the buffer area nearest to the reserve and £48 ha^{-1} yr^{-1} in the outermost buffer from the reserve (Figure 4-9), based on the published dependency ratio in Klein *et al*. (2007). After deducting the baseline value, the value of pollination services ranged from £102 ha^{-1} yr^{-1} in the innermost buffer to £0.14 ha^{-1} yr^{-1} in the outermost buffer. The average value of the pollination services for the field bean production within 1 km buffer area from the reserve, after deducting the baseline value, was estimated at £37ha^{-1} yr^{-1}.

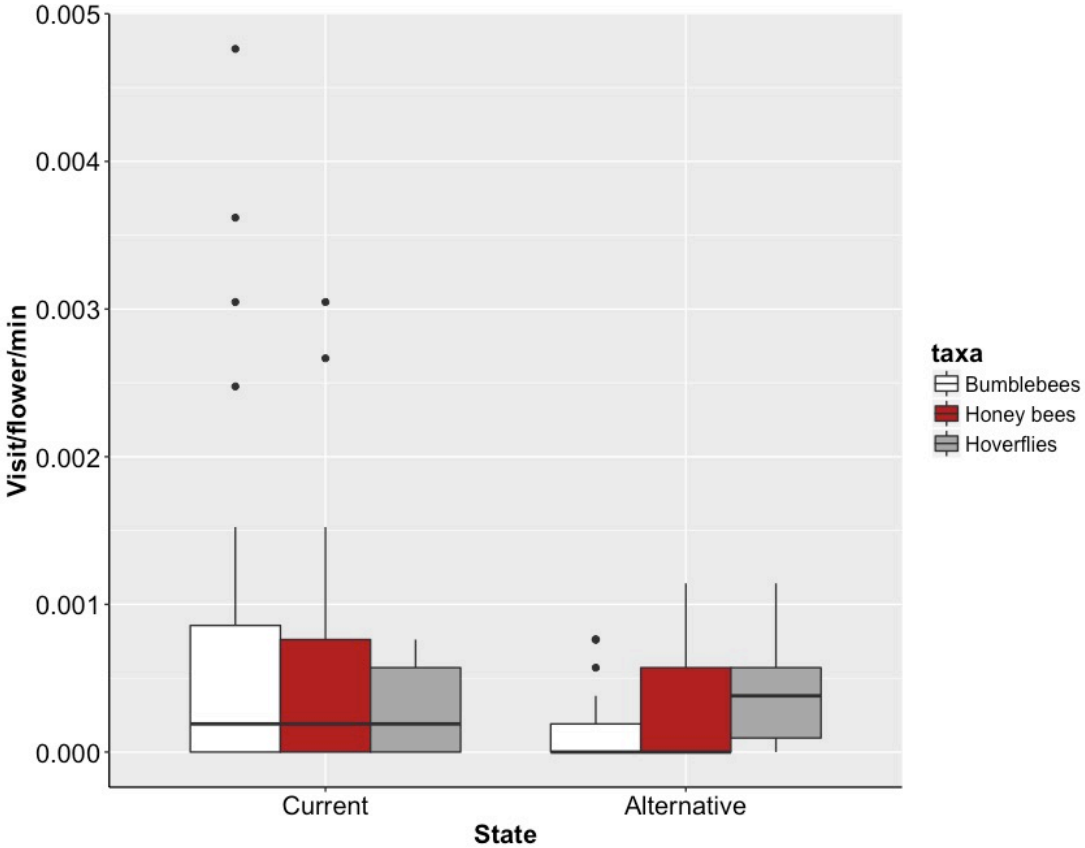

Figure 4-8 Visitation frequencies (visits flower^{-1} min^{-1}) carried out by legitimate pollinator taxa on field bean flowers within 1 km buffer from the reserve under the current state, and beyond 1 km from the reserve representing the alternative state (i.e. conversion of the reserve to cropland). The medians, 1st and 3rd quartiles for bumblebees (white boxes), honeybees (red boxes) and hoverflies (grey boxes) are shown. Error bars represent upper and lower quartiles.

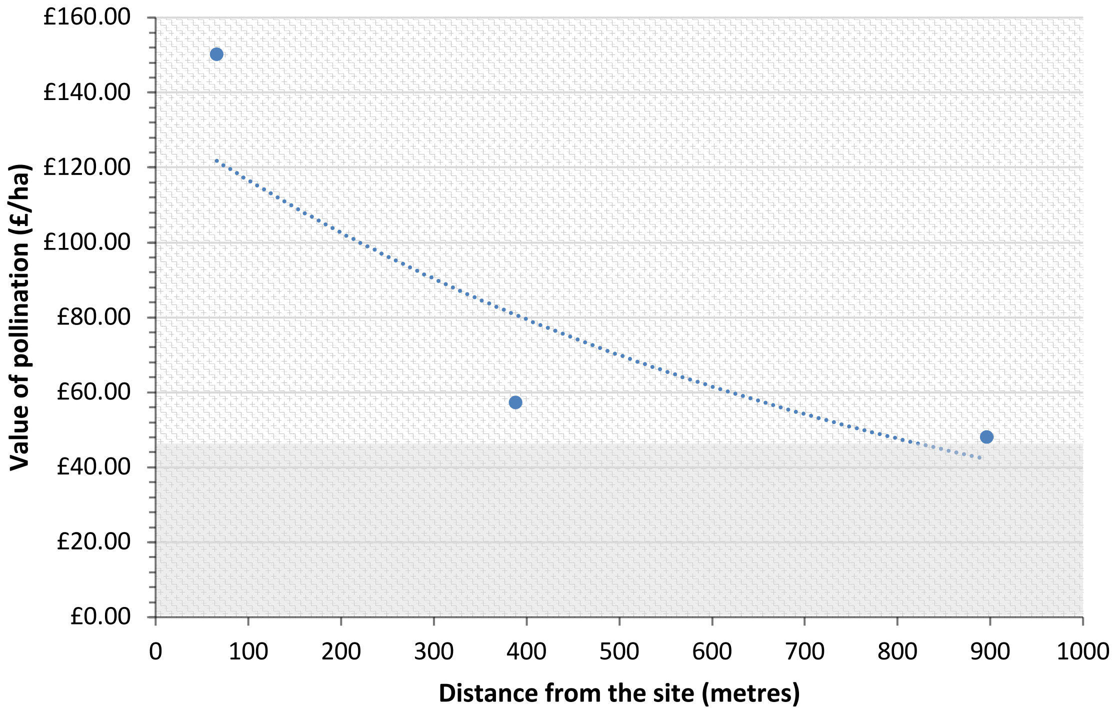

Figure 4-9 Field surveys method: Distance decay curve of the value of pollination service for field beans within 1 km buffer from the reserve under the current state. The grey shading represents the value of pollination beyond 1 km provided by pollinators which inhabit within the agricultural matrix.

Beyond 1 km from the reserve (baseline pollination), pollinator visitation rate ranged between 0.0006 and 0.0012 visits flower^{-1} min^{-1}. The average value of this baseline pollination was estimated at £48 ha^{-1} yr^{-1}. The value of pollination services provided by the alternative state is £0.

4.4.3 Exclusion experiments (Green standard)

Oilseed rape

There was no significant difference in individual seed weight between the two sets of control oilseed rape racemes (t = -0.191, d.f. 45, P= 0.85), confirming the absence of resource reallocation within the experimental plants. Under the current state, individual seed weight of oilseed rape was lower in the bagged racemes than the unbagged ones across all distances. There was a significant effect of treatment on seed weight at the close buffer ($F_{1,4}$ = 14.431, P = 0.019); and distance had a significant effect on the seed weight from the unbagged racemes ($F_{3,8}$ = 9.149, P = 0.005) (Figure 4-10). Dependence ratios decreased from 0.36 in the buffer nearest to the reserve to less than 0.5 in the buffer furthest from the reserve (Figure 4-11), hence the mean dependency ratio (DR) for oilseed rape was 0.19. After deducting the baseline value, the mean DR was 0.10 and the value of pollination services for the oilseed rape production within the 1 km buffer from the reserve was estimated at £111 ha^{-1} yr^{-1}.Beyond 1 km from the reserve, the mean baseline DR value for oilseed rape was 0.10. The value of pollination services provided by the reserve under the alternative state is £0.

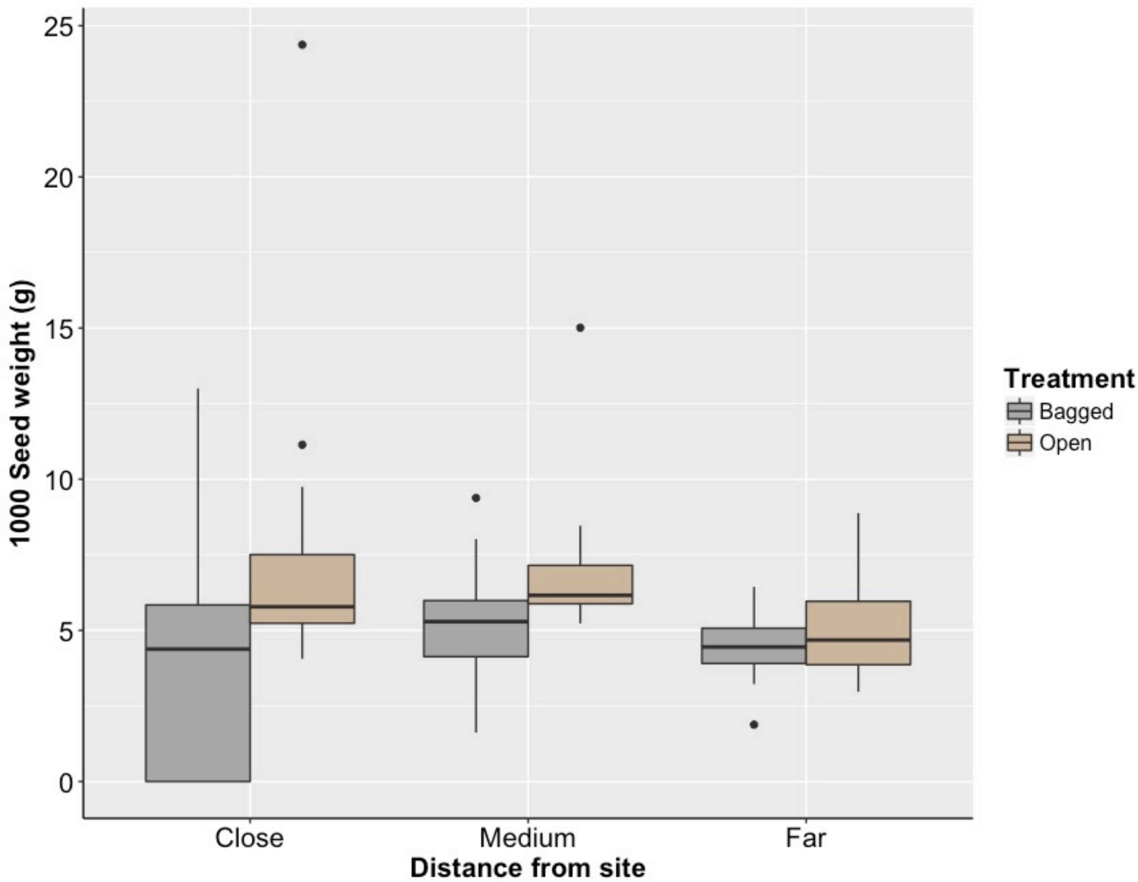

Figure 4-10 Median individual seed weight in the three buffer areas ("Close", "Medium", "Far") at increasing distances from the reserve, in oilseed rape racemes excluded from insect pollination (Bagged) and racemes exposed to natural pollination (Open). The medians, 1st and 3rd quartiles for Bagged (grey boxes), and Open (bisque boxes) are shown. Error bars represent upper and lower quartiles.

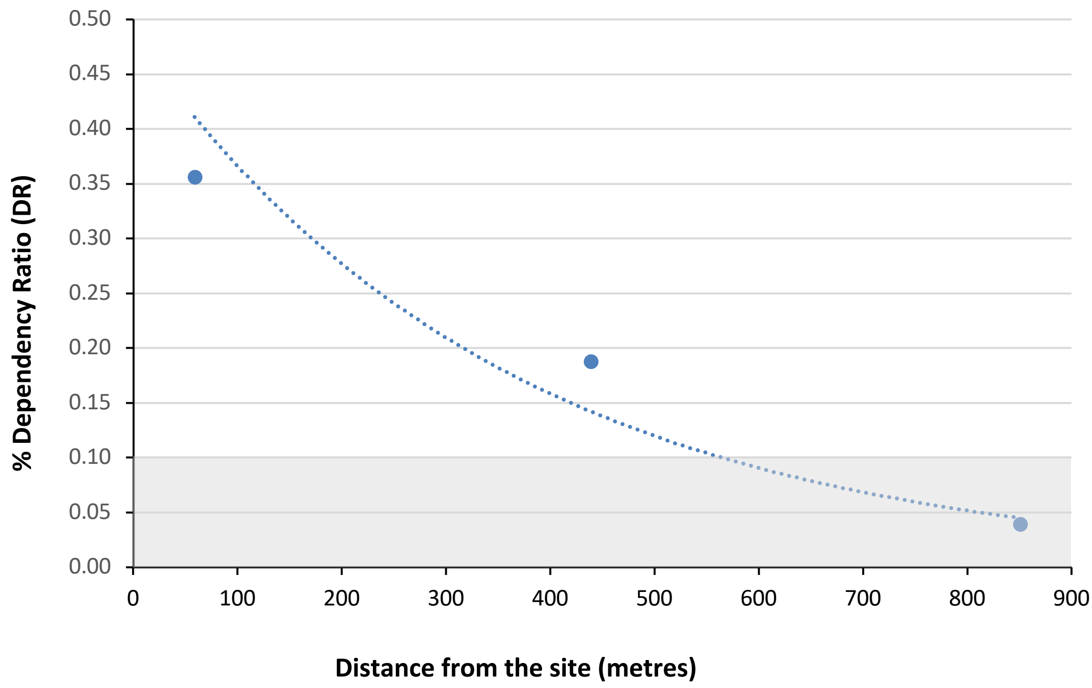

Figure 4-11 Exclusion experiments method: DR of oilseed rape on insect pollination at increasing distance from the reserve under the current state. The grey shading represents the value of pollination beyond 1 km provided by pollinators which inhabit within the agricultural matrix.

Field beans

Under the current state, the number of seeds per pod was significantly affected by the pollinator exclusion at all distances from the reserve (Close: $F_{1,4} = 9.233$, $P = 0.038$; Medium: $F_{1,4} = 13.322$, $P = 0.021$; Far: $F_{1,4} = 9.695$, $P = 0.035$)(Figure 4-12). The number of seeds per plant was consistently lower in plants excluded from animal pollination, though the effect of treatment was not significant ($P > 0.05$)(Figure 4-13). Equally, treatment had no significant effect on the number of pods per plant at any distance ($P > 0.05$) (Figure 4-12).

Dependency ratios ranged between 0.12 and 0.18 within the 1 km buffer from the reserve with no explicit decay curve with distance from the site (Figure 4-15). Beyond 1 km from the reserve, the mean DR for field beans was 0.21. There was no pollination service for field beans provided by the current state and the average baseline DR value was 0.17 with an estimated pollination value of £102 ha^{-1} yr^{-1}.

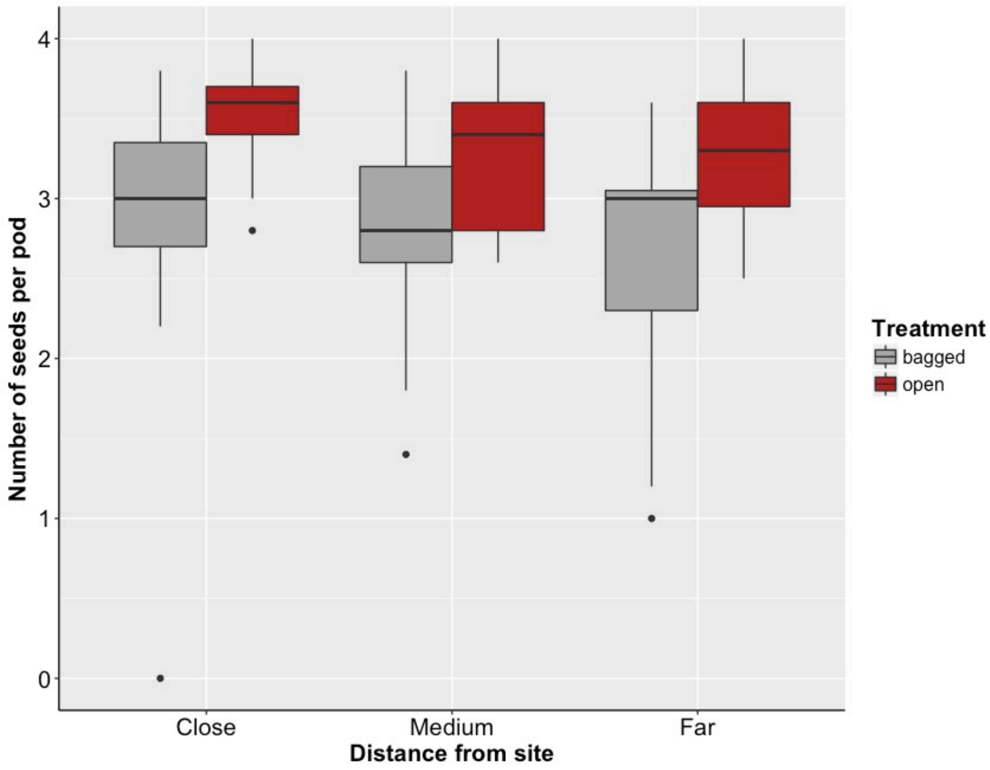

Figure 4-12 Median number of seeds per pod in the three buffer areas (“Close”, “Medium”, “Far”) at increasing distances from the reserve, in field bean plants excluded from insect pollination (Bagged) and plants exposed to natural pollination (Open). The medians, 1st and 3rd quartiles for Bagged (grey boxes) and Open (red boxes) are shown. Error bars represent upper and lower quartiles.

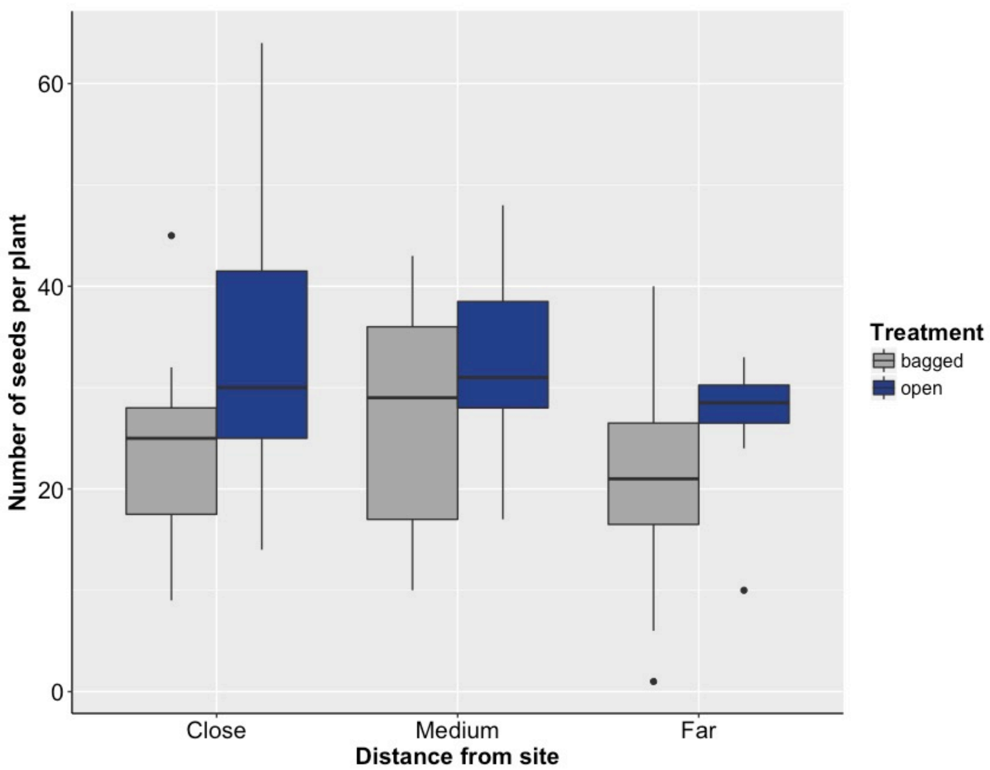

Figure 4-13 Median number of seeds per plant in the three buffer areas (“Close”, “Medium”, “Far”) at increasing distances from the reserve, in field bean plants excluded from insect pollination (Bagged) and plants exposed to natural pollination (Open). The medians, 1st and 3rd quartiles for Bagged (grey boxes) and Open (blue boxes) are shown. Error bars represent upper and lower quartiles.

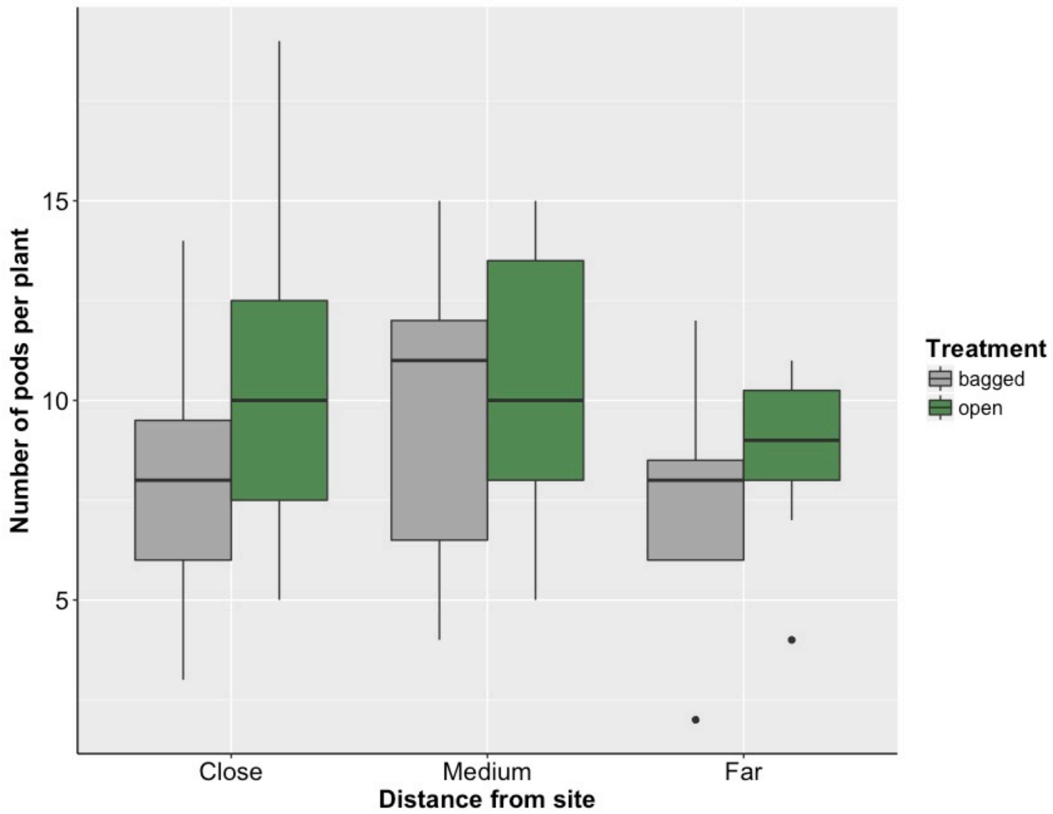

Figure 4-14 Median number of pods per plant in the three buffer areas (“Close”, “Medium”, “Far”) at increasing distances from the reserve, in field bean plants excluded from insect pollination (Bagged) and plants exposed to natural pollination (Open). The medians, 1st and 3rd quartiles for Bagged (grey boxes) and Open (green boxes) are shown. Error bars represent upper and lower quartiles.

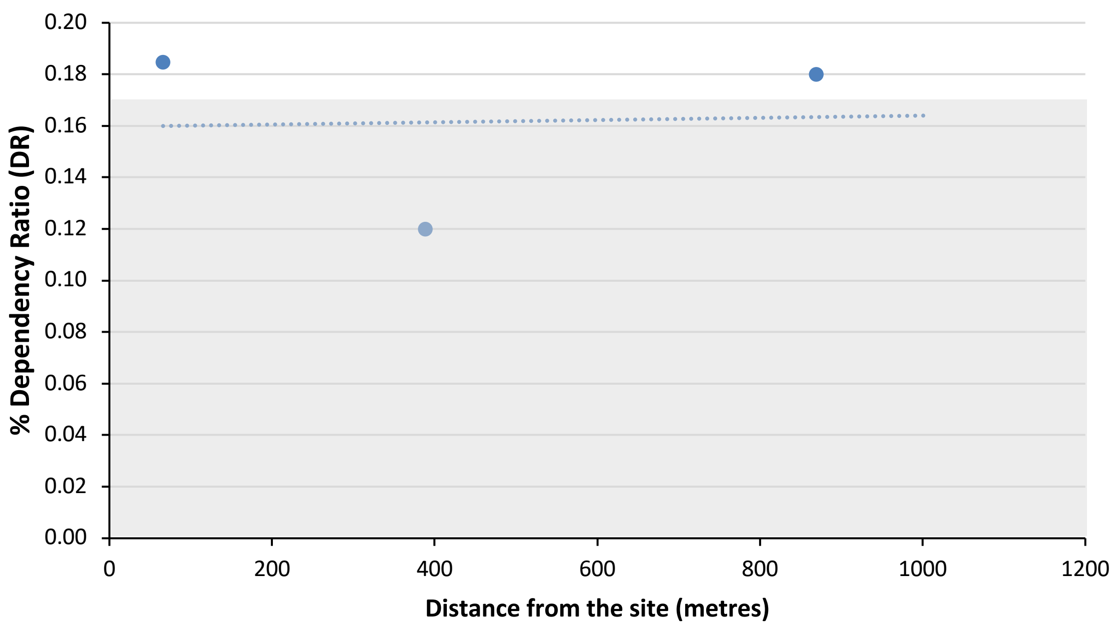

Figure 4-15 Exclusion experiments method: DR of field beans on insect pollination at increasing distance from the reserve under the current state. The grey shading represents the value of pollination beyond 1 km provided by pollinators which inhabit within the agricultural matrix.

4.4.4 Overall summary of results

Overall, the economic value of pollination service in the current state of Noar Hill was greater than the alternative state by between £111 and £151 ha^{-1} $year^{-1}$ depending on the method adopted (Figure 4-16)(Table 4-2).

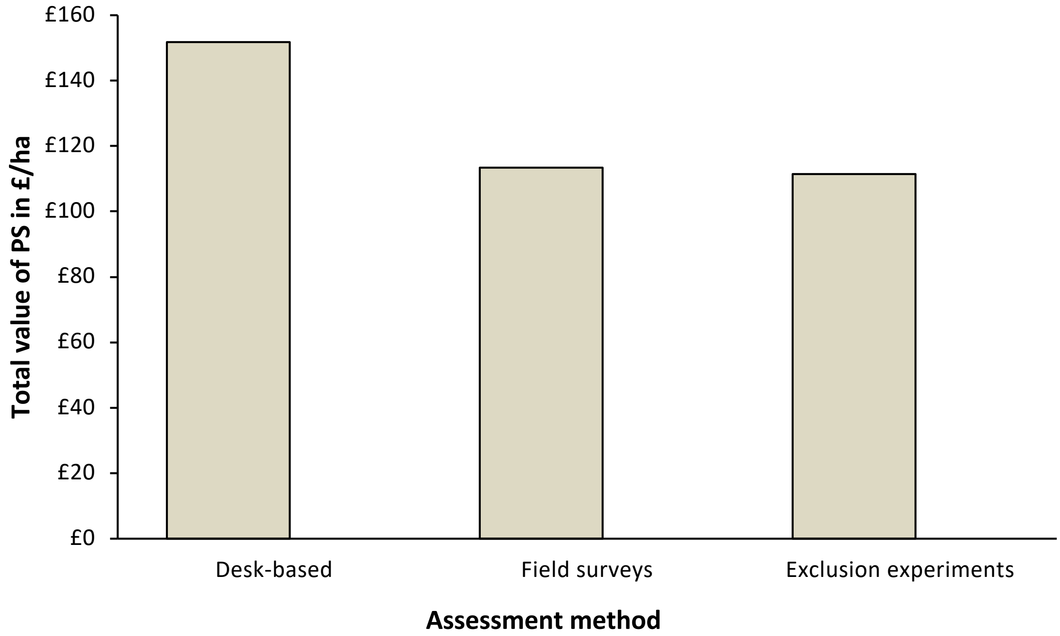

Figure 4-16 Comparison across the three assessment methods of the annual economic value of pollination services provided by Noar Hill under the current state.

Table 4-2 Estimated value of pollination services (£ ha^{-1}) provided to oilseed rape and field beans by the reserve under the current and alternative states.

Method	Crop type	Current State (within 1km from the reserve)	Alternative State (beyond 1km from the reserve)	Difference in £ revenue
Desk-based method (Red standard)	Oilseed rape	£101.57	£0.00	£101.57
	Field beans	£50.13	£0.00	£50.13
	Total value of pollination	**£151.70**	£0.00	£151.70
Field surveys method (Amber standard)	Oilseed rape	£76.12	£0.00	£76.12
	Field beans	£37.20	£0.00	£37.20
	Total value of pollination	**£113.32**	£0.00	£113.32
Exclusion experiments method (Green standard)	Oilseed rape	£111.38	£0.00	£111.38
	Field beans	£0.00	£0.00	£0.00
	Total value of pollination	**£111.38**	£0.00	£111.38

Based on the results of the exclusion experiments, the total value of ecosystem services derived from crop production on the 91.6 ha of arable land in the current state (OSR and field beans) was estimated to be £80,302 y^{-1} (£1,788 ha^{-1} y^{-1}), offset by management costs of £37,620 y^{-1} (£835.86 ha^{-1} y^{-1}) including production costs, pesticides, adjuvants and seeds (Appendix C.25) and conservation costs including labour (staff, contractors and volunteers), fuel and transport (Reserve manager pers. comm.). In the alternative scenario, where the reserve was converted to cropland, crop production was estimated to be £123,000 y^{-1} offset by management costs of 63,949 y^{-1} but with no conservation costs (Figure 4-17).

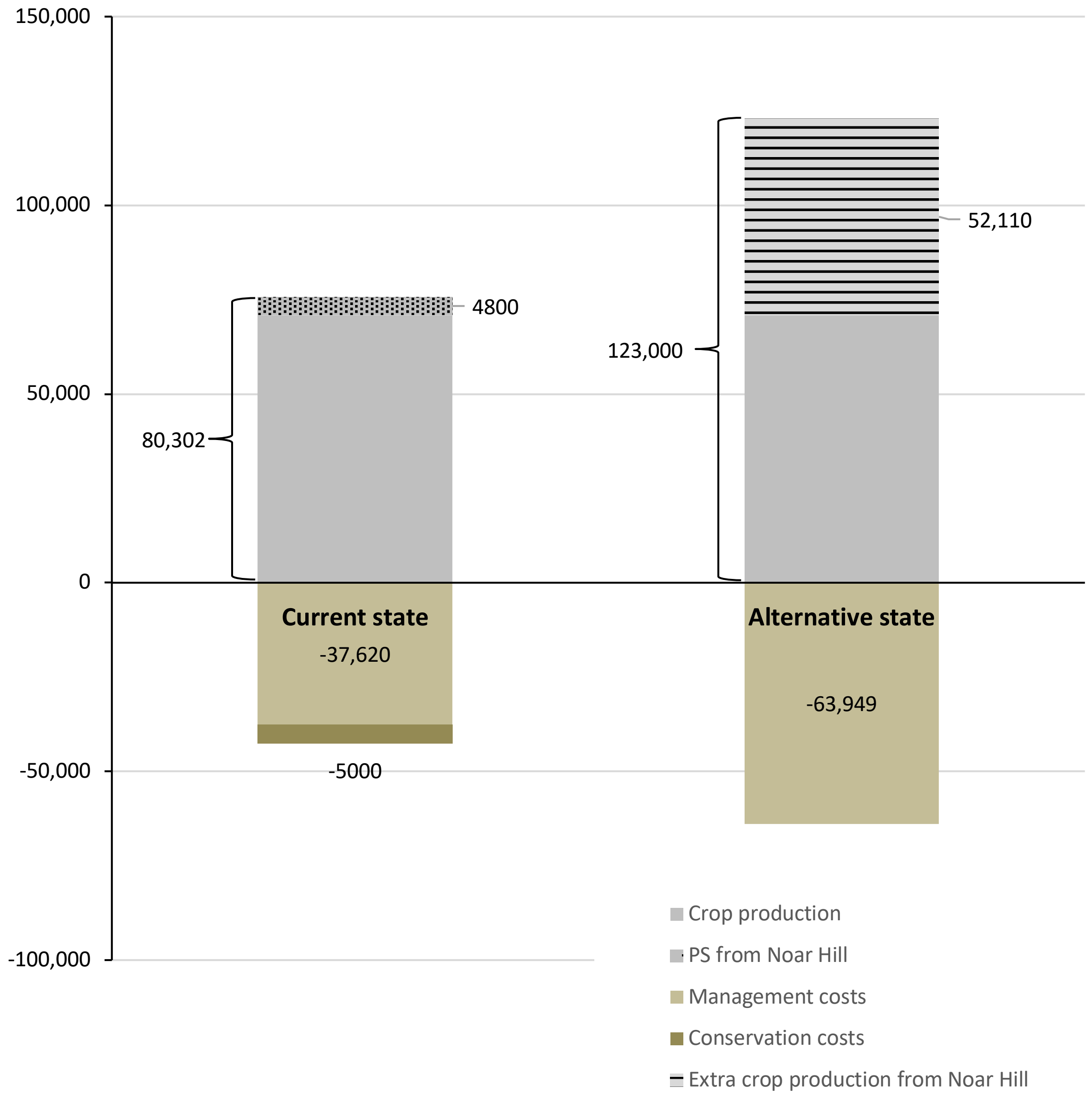

Figure 4-17 A comparison of the pollination service values and management costs within 1 km buffer area (in £ for 91.6ha y[1] of cropland) from the reserve and of the same land if the reserve was converted into cropland (154 ha y[1] of cropland).

On the whole, the estimates for the costs and benefits of the ecosystem services provided by Noar Hill in terms of arable production suggests that net value would be higher in the alternative state by approximately £22,051 y^{-1}.

4.5 Discussion

This study represents the first field application of a newly developed pollination protocol, which rapidly assessed the capacity of a small protected area to provide pollination services to the nearby intensive agricultural landscape. This research provides evidence that the conservation of a small nature reserve in a highly modified agricultural landscape can result in a net monetary benefit of approximately £4800 y^{-1} (£111 ha^{-1} y^{-1})(Figure 4-15), from the pollination services. These estimates are based on three pollination assessment methods of varying resource requirement in terms of resources (workforce, finances), time and expertise. The resulting data obtained from these three methods also have a varying degree of confidence level ranging from low to high, which corresponds with their resource and time requirement. Nonetheless, their results unanimously show that Noar Hill has been contributing animal pollination services to the oilseed rape and field bean in the adjacent farmlands. A conversion of the nature reserve to cropland could reduce economic gain from the additional animal pollination provided by those natural habitats within the reserve.

4.5.1 Noar Hill's contribution to oilseed rape production

All the three methods in this study show that the loss of oilseed rape pollination provided by the reserve could potentially reduce the production by £102 per ha (based on the desk-based method), £76 per ha (based on field surveys) and £111 per ha (based on exclusion experiments). The estimate obtained from exclusion experiments is the most robust due to the high degree of confidence level, though it did not substantially differ from the results of field surveys. Nevertheless, these values should be considered as conservative as the methodology used did not account for other benefits of pollinators such as a reduced crop blooming period (Sabbahi *et al.* 2006) and enhanced quality in terms of higher oil content and lower chlorophyll concentration (Bommarco *et al.* 2012b).

The sharp decline in visitation rate on OSR flowers at increasing distance from the site, which is not detectable in the alternative state, indicates a spill over of service from Noar Hill with a steep decline within the first 500 metres. These findings are in line with previous studies (e.g., Woodcock *et al.* 2016) and confirm that isolation from natural and semi-natural habitat would have the consequence of fewer pollinator visitations (Garibaldi *et al.* 2011). The calculated mean dependence ratio in the current state showed a modest positive impact of animal pollination, consistent with the Klein *et al.* review (2007) and in line with previous studies (Bommarco *et al.* 2012b; Stanley *et al.* 2013; Bartomeus *et al.* 2014). These results can inform farmers on how to manage their land to maximise the production of animal-pollinated crops. Farmers could restore or preserve small natural areas across the landscape strategically, so that pollinator-dependent crops are grown within 1 km from these natural areas.

Visitation frequency surveys revealed that the predominant pollinator visiting oilseed rape at the Noar Hill site were non-syrphid flies (*muscidae*) followed by honey bees. Although non-syrphid flies have been observed to visit OSR flowers in the UK (Garratt *et al.* 2014b), studies have shown that the main visitors were bumblebees, honey bees (Hayter and Cresswell 2006) and solitary bees (Woodcock *et al.* 2013). Hoverflies appear to be efficient pollinators of oilseed rape (Jauker and Wolters 2008b; Jauker *et al.* 2012) and the visitation rate of non-syrphid flies has been considered in previous studies (Mudssar *et al.* 2011). However, the contribution of these groups to oilseed rape yield have not been sufficiently investigated. The results from this study provide novel insight that this group may be an important pollinator of oilseed rape in the UK.

4.5.2 Noar Hill's contribution to field bean production

The three methods in this study show that the loss of field bean pollination provided by the reserve could potentially reduce production by £50 per ha (based on the desk-based method), £37 per ha (based on field surveys) and £0 per ha (based on exclusion experiments). The number of pods per plant and seeds per pod was found to be positively impacted by insect pollination, which is consistent with previous studies (Garratt *et al.* 2014b). The results derived from the exclusion experiments method reveal no detectable distance decay in the dependence of field beans on animal pollination. This suggests that there will be no change in field beans productivity if pollinator-friendly habitats in the Noar Hill site were lost, despite other studies showing that open pollination significantly increases yield in field beans (e.g., Bartomeus *et al.* 2014). This may be due to variation in the level of self–compatibility between different varieties, though research on this is still sparse. Furthermore, pollination efficiency has been predominantly related to the abundance of flower visitors (Garibaldi *et al.* 2013); more studies measuring reproductive success (e.g. Marzinzig *et al.* 2018) are needed to clarify the level of dependence of field bean varieties on insect pollination.

Visitation frequency surveys revealed that the majority of visitation to field bean flowers was carried out by bumblebees (*Bombus spp.)* followed by honeybees (*Apis mellifera*). This finding is consistent with other studies in the UK (bumblebee: Bartomeus *et al.* 2014; Garratt *et al.* 2014b) (honey bee: Kendall and Smith 1975). Previous research shows that the proportion of semi-natural habitat and floral resources determine pollinator activities on field beans (Nayak *et al.* 2015) and that bumblebee density and species-richness is significantly enhanced by experimentally planted nectar-rich sources in agriculture landscapes (Carvell *et al.* 2015). Consistent with these findings, this study found that insect visitation to field beans flowers decreased sharply with distance from Noar Hill.

4.5.3 First application of the pollination assessment methods: lessons from the Noar Hill pilot

The main aim of the pollination assessment methods was to provide rapid and accessible methodologies for pollination services assessment, which inherently entailed a trade-off between rapidity, simplicity, low-cost and accuracy. A number of assumptions underpin each method, which allow the protocol to be less time consuming, although it has some limitations.

The desk-based method, which uses a published estimate of distance decay rate (Ricketts *et al.* 2008), inevitably generalises the relationship between pollinator visitation frequency and distance from natural habitat, providing a less accurate estimate of the value of pollination to a focal crop yield. Indeed, the effect of distance on crop flower visitation frequency depends on the crop key pollinators and their foraging range, which varies amongst taxonomic groups and different body sizes (Greenleaf *et al.* 2007). Users could increase accuracy by using local pollinator visitation data if available, and the buffer radius (suggested at 1km) may be adjusted according to the approximate foraging range of the pollinator of interest. Despite a relatively high level of uncertainty, this method enables users with very limited resources to obtain a reasonable estimate of the pollination value for a particular crop at virtually no cost (time and resources).

The application of the field surveys and exclusion experiments methods in OSR indicated similar economic values and comparable differences in economic return between the current and the alternative state, confirming the robustness of these methods for this crop type. Conversely, the two methods produced substantially different results for field beans, resulting in an overestimation of the service value when using the field surveys method. Recent research indicates considerable variation in pollinator visitation rate between days, which could potentially affect the results of studies using one-day observations due to environmental noise (Fijen and Kleijn 2017). Currently, the field surveys method requires about 8-9 person-days of data collection at very little cost as no field equipment is needed. Therefore, the accuracy of this method can be improved by increasing the sampling effort (e.g. repeating observation across three or more days depending on the resources available), allowing a more robust estimate of visitation rate.

The exclusion experiments method provides a true measure of plant's dependence on animal pollination. However, the time required to carry out the exclusion experiments varies considerably amongst crop types. For example, the dense nature and rapid growth of oilseed rape made the adjustment and removal of the exclusion bags more laborious. Furthermore, the processing of oilseed rape seeds to calculate reproductive success is also time-consuming. In this study, the exclusion experiments method required 20 person-days for oilseed rape and 13 person-days for field beans to implement. These resource requirements may become challenging within a rapid assessment framework, especially when measuring up to five plant types. However, users are advised to adapt the methods to their circumstances, for example, by focusing on the three most important crops if it is too expensive to measure all five crop types. Labour time can be mitigated by making mesh bags that can be used on different crop types to reduce preparation time. Furthermore, the protocol can be modified to reduce the sampling effort on the alternative state to 15 treatment plants (as piloted in field beans) as opposed to the 45 currently suggested.

The new methods were piloted in a temperate region of Europe, in a highly heterogeneous habitat. More pilot studies are needed in different climatic regions, with various degrees of heterogeneity (e.g. in tropical regions, vast monocultures) to test the robustness and generalizability of the methods for different habitats. Finally, this protocol focused predominantly on insect pollination and, although it presents adaptations to vertebrate pollinators, future efforts should focus on the development of more robust methodologies for the rapid assessment of pollination services provided by vertebrate pollinators.

4.5.4 Comparison with landscape-scale approaches

Approaches to address spatial effects on pollinators and their ability to deliver ecosystem services have looked at different spatial scales, particularly farm and landscape scale (e.g. Kasina *et al.* 2009; Ricketts 2004). Specifically, landscape-scale approaches have been widely used to determine the pollination service delivered by natural and semi-natural areas to cropland and the attached economic value of the increased crop production (Steffan-Dewenter & Tscharntke 1999; Greenleaf & Kremen 2006; Carvalheiro *et al.* 2010, 2011; Kremen *et al.* 2002, 2004; Winfree *et al.* 2007; Winfree *et al.* 2011). Pollination services are delivered by landscape processes due to the high mobility of pollen vectors, which rely on foraging and nesting resources in habitats of different size and quality, including the agricultural matrix. Therefore, a landscape perspective is key when assessing and measuring pollination services especially in landscapes of high complexity. The methods developed in this chapter, in line with the above studies, rely on the established knowledge that flower visitation and fruit set decline with isolation from natural habitat (Garibaldi *et al.* 2011). However, unlike landscape-scale approaches, it changes the perspective to a local, site-based scale with the aim to measure the contribution of a single reserve to the pollination of surrounding crops. By doing this, the methods present limitations that may affect the accuracy of the results. This is because insect pollinators are affected by the whole landscape matrix, the elements of which are interdependent (Pufal *et al.* 2017). Therefore, nearby non-crop habitats could also impact on the yield of crops surrounding the targeted reserve.

4.5.4.1 Landscape-scale modelling tools

A broadly used landscape-scale modelling approach that includes pollination services (Lonsdorf model, Lonsdorf *et al.* 2009) is the InVEST model (see section 1.4.3.2). This model confers the value of pollination services delivered by non-crop habitat to agriculture within the relevant foraging ranges of the known crop pollinators (Sharp *et al.* 2018). Unlike the TESSA pollination methods, InVEST applies a landscape-scale approach and allocates pollination value to any non-crop habitat within a set radius, rather than to a specific reserve, thus taking into account the entire landscape matrix surrounding the crop land. Furthermore, the radius of influence of natural habitat on agriculture is adjusted according to the foraging range of the main pollinator of a crop of interest, which makes estimations of pollination services more accurate. On the other hand, the nesting and foraging potential of the non-crop habitat is entirely based on land-cover maps and not real data from the ground, which Cunningham *et al.* (2018) found created a discrepancy between the results of model based on literature data versus field based data. This highlights the importance of real data collection on the ground that the pollination methods can generate for rapid assessments and for use in methods such as InVEST and more in-depth broad scale estimations.

4.5.4.2 Landscape-scale empirical studies

A wealth of broad-scale empirical studies have quantified pollination services delivered by natural habitat to a number of important crops such as coffee (Klein *et al.* 2003a,b) and oilseed rape (Morandin & Winston 2005). This was done by either measuring the contribution of pollinators to crop production at a linear distance gradients from the natural habitat (Steffan-Dewenter & Tscharntke 1999; Ricketts 2004; Greenleaf & Kremen 2006; Carvalheiro *et al.* 2010, 2011) or at varying proportions of natural habitat within a given radius from crop fields (Kremen *et al.* 2002, 2004; Winfree *et al.* 2007; Winfree *et al.* 2011).

For example, Klein *et al.* (2003) measured pollinator abundance on coffee fields and fruit set at increasing distances from old-growth rainforest and found that fruit set decreased steadily within 900m from the forest. Pollinator abundance responded to either distance or farm management depending on the pollinator taxon. In another study on sunflowers, Carvalheiro *et al.* (2011) found that both distance from natural habitat and within-field wild flowers affected pollinator abundance and crop yield. These types of study test the impact of landscape heterogeneity on the delivery of pollination services to agriculture and show how landscape and local intensification might disrupt pollination processes (Nabhan & Buchmann 1997; Klein *et al.* 2003a,b). The strength of such approaches in comparison with methods included in the TESSA pollination protocol, is again a broader scale perspective that captures the value of all suitable natural habitat surrounding the crop fields. This is achieved by measuring the distance from the study plants to the closest patch of natural habitat instead of to a targeted reserve as done in the pollination protocol. Furthermore, these studies benefit from greater sampling efforts, which increase the robustness of results.

In comparison, to detect the pollination overspill from a single reserve, the pollination protocol developed here, advises to set the sampling transects beyond the range of influence of other nearby patches of natural habitat. However, I recognise that in highly heterogenous landscapes it may not be possible to lay transects far enough from other non-crop patches to elude a spill-over of the service onto the sampling buffer area. This could, in some instances, overestimate the value of pollination services provided by the reserve of interest. The pollination protocol partly controls for the effect of the landscape by deducting the pollination services value at 1km (baseline value), which removes a portion of the service that can be attributed to the agricultural matrix and other non-crop habitats in the landscape. However, to increase the accuracy of results, it may be necessary to increase the number of transects radiating from the site to cover the entire buffer area. This could be added as an additional step in the protocol when dealing with highly heterogenous landscapes, defined as those containing >20% non-crop habitat (Tscharntke *et al.* 2005). An increased sample size would produce a more accurate distance decay curve to take into account the landscape complexity.

In addition, the buffer radius could be decreased to 500m to reduce the area over which the reserve is assumed to exert an influence. Although foraging ranges have shown to be shorter in more complex landscapes (Steffan-Deweter & Khun 2003), a smaller buffer area could reduce the risk of wrongly allocating the pollination service provided by social species with large foraging ranges (e.g. bumblebees) entirely to the reserve. Furthermore, the methods currently suggest to exclude managed bees from the analysis only when all pollinators are supplied to the farms. However, the effect of the surrounding landscape could be further controlled by always excluding managed pollinators from the analysis. Honeybees have been shown to travel beyond 5km (Hagler *et al.* 2011) with median distances of around 1.5km travelled to collect nectar (Steffan-Dewenter & Kuhn, 2003). Therefore their presence on the study crop may be less likely to be attributable solely to the reserve.

Most agricultural landscapes are largely dominate by crop land and sustain small remnant of natural habitats, mainly woodland and old grassland. In these dynamic habitats, where local extinction is a widespread process, immigration of pollinators can be of extreme importance for long-term sustainability of the services generated by these ecosystems (Tscharntke *et al.* 2005). Unlike landscape-scale approaches, the pollination protocol provides a snapshot of the provision of pollination services by the two contrasting counterfactuals at a fixed spatial radius of 1km from the reserve. Therefore, this protocol does not allow the exploration of the resilience of the pollination service provided by sites of interest to assess long-term delivery and sustainability. This would require long-term collection of data (over multiple years), which is not feasible within the scope of a rapid assessment.

4.5.5 Future testing of the TESSA pollination module

To formally test the robustness of the new TESSA pollination module and to ensure that these methods show the dependence of pollinators on a single reserve, a number of more in-depth studies should be implemented and their results compared to those of the pollination protocol. Such studies could implement the same experimental design as the pollination protocol to other no-crop areas within a 5km radius for the reserve, to test if they exert any influence on the yield of the crop surrounding the reserve. The information generated by a sufficient number of pilot studies could be used to make inferences on threshold minimum patch sizes under which the non-crop area can be deemed negligible in terms of pollination overspill. Equally, these data could be used to determine a patch size over which a nearby reserve should always be tested.

Another in-depth approach could involve substantially increasing the number of sampling transects along the 1km gradient, using phytometers in non-cultivated fields to cover the whole buffer area surrounding the reserve. This would provide a more accurate estimation of the current and potential contribution of the reserve to nearby crop production. Furthermore, the pollination protocol could be replicated over a number of years, to compare how a snapshot in time provided by a TESSA type assessment compares with the results of studies that explore temporal variability. Formal testing of the developed methods should also include piloting them on a substantial number of case-study sites, covering different habitat types and land-use change scenarios. This step is fundamental to assess the generalizability of the methods and unearth potential caveats or issues that may not have been evident during the development phase.

Woodcock *et al.* (2016) demonstrates that the visitation rate of bumblebees and solitary bees declines with distance from oilseed rape field margin. Currently, the protocol instructs the user to set sampling plot at least 50m from the field margins, but not to use a fixed distance from the field edges. Therefore, the distance gradient detected along the 1km buffer may reflect a reduction in pollination services towards the centre of each individual field rather than showing a reduction in pollinator visitation from the reserve. This could bias the results when sampling in fields that differ substantially in size and in farms that implement agri-environment schemes. To minimise edge effect and local management, future testing of the protocol should consistently place sampling plots at the same distance from the field edge in all fields across the buffer area and the alternative state.

Ultimately, TESSA is a living document, which can be changed and improved for future versions. TESSA V2.0, which includes the pollination module, is freely available to download anywhere in the world. Therefore, users worldwide can help to further refine the pollination methods by providing feedback and publishing the case studies of their applications.

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Chapter 5 General discussion and conclusions

"Our vision is to see pollinators thrive, so they can carry out their essential service to people of pollinating flowers and crops, while providing other benefits for our native plants, the wider environment, food production and all of us." The National Pollination Strategy 2014

The underlying issue addressed in this thesis originates from the knowledge that human activities have a negative impact on pollinator populations and thus on the ecosystems services they provide. The overall aim was therefore to improve understanding as to how pollinator decline affects the delivery of pollination services and the benefits they provide to humans. Particularly, I paid special interest in estimating the consequence of such a decline on the reproductive success of plants. Chapter 1 (Section 1.3) describes four areas of importance of pollinators to human well-being: (a) agricultural production and its economic value, (b) essential micronutrients provision, (c) support to biodiversity, (c) socio-cultural values. For this dissertation research, I focused specifically on agricultural production (Chapter 4), support to biodiversity (Chapter 2/3) and economic valuations (Chapter 3/4) (Figure 5-1).

This thesis adds novel insight on the potential effects of the decline of pollinator taxa in different regions by assessing variations in the reproductive success of wild and crop plants at a global and local scale. This adds knowledge of the extent to which flower-visiting animals, both invertebrates and vertebrates, enhance the reproduction of flowering plants. This was achieved through systematic review methodologies and meta-analysis, expert elicitation techniques, field surveys and observations, and field-level experimental manipulations. In Chapter 2, I collated existing data on the contribution of vertebrate pollinators to plants reproductive success and explored how such contribution varies across vertebrate pollinator taxa, taxonomic breadth of flower visitors, geographical regions, and climatic domains. Chapter 3, uses the data collated for the meta-analysis carried out in the previous chapter and builds the first dataset for degree of production dependence of wild and crop plants on vertebrate pollination. Chapter 4, addressed the need for a practical, accessible tool for the site-scale assessment of pollination services and developed a novel set of methods to suit different levels of technical expertise and resource availability. Here, I also examined the contribution of a small natural area to the provision of pollination services to surrounding agricultural landscape by piloting the methods developed. This chapter aims at synthesising the key results of the thesis in the context of existing research and outline overall limitations. Here, I also examine the implication of the results for policy and decision-making, for the conservation of pollinators and pollination services, and makes suggestions for future research.

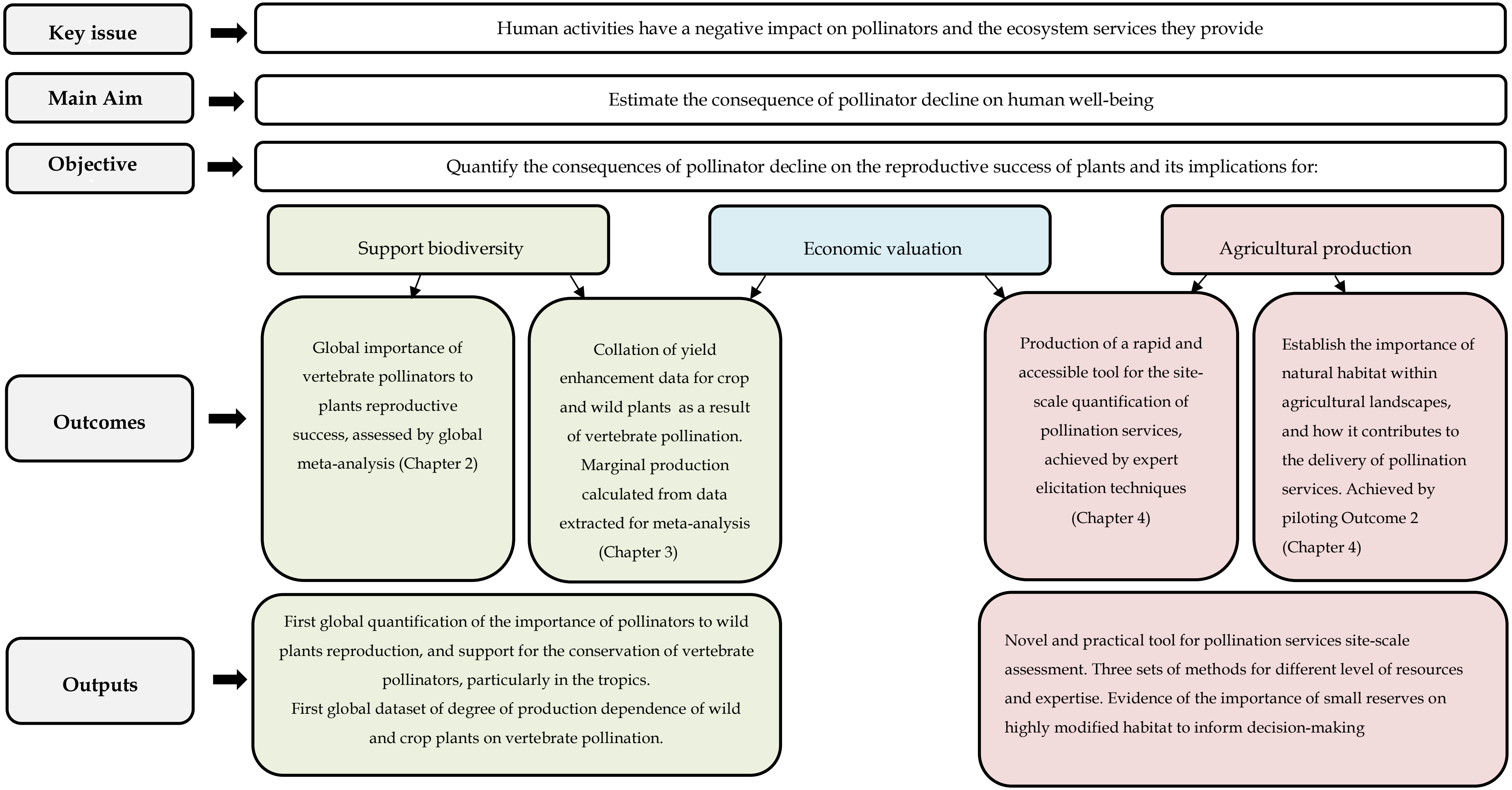

Figure 5-1 Hierarchical framework of thesis estimating the consequences of losing pollination services.

5.1 Summary and synthesis

The following are the main findings from three previous chapters with respect to how they contribute to our knowledge of the impact of pollination service loss on human well-being.

5.1.1 The global importance of vertebrate pollinators to plant reproductive success and first global dataset of vertebrate pollinator dependency of plants

Vertebrate pollinators are important for the reproduction of many plant species and are known to be essential for the reproduction of some economically important crop species such as *Hylocereus undatus* (Dragon fruit) (Ortiz-Hernández and Carrillo-Salazar 2012), and *Durio* spp. (Durian) (Bumrungsri *et al.* 2009). Global scale meta-analyses have examined the extent of pollen limitation in relation to local and regional biodiversity patterns (Vamosi *et al.* 2006) and the efficacy of pollination syndromes in predicting effective pollinators (Rosas-Guerrero *et al.* 2014). However, the evaluation of the importance of current pollination to plant populations, communities and ecosystems had not been addressed.

Chapter 2 (Ratto *et al.* 2018) demonstrated that excluding vertebrate pollinators from plants visited by both insects and vertebrate pollinators, may reduce fruit and seed production by 63%. The impact of their decline on plant reproductive success varies across taxa, region and climatic domain, and taxonomic breadth of flower visitors (Chapter 2 Figure 2-4). Bat-pollinated plants were found to be more dependent on pollinators than bird-pollinated plants with a reduction in fruit/seed production of approximately 84% when bats were being excluded, compared to 46% when birds were excluded. Furthermore, the dependence on vertebrate pollinators for plant reproductive success was found to be greater in the tropics than at higher latitudes.

These findings suggest that the ongoing decline of vertebrate pollinators could have important adverse effects on vertebrate pollinator-dependent crops such as tropical cultivated goods (e.g. pitayas, agave, durian), and cause substantial revenue loss. It is likely that the loss of fruits and seeds of this magnitude, especially in tropical areas, could also have an adverse effect on many granivorous or frugivorous species including birds, bats, rodents, primates and invertebrate species. Effective conservation action for threatened flower-visiting vertebrate species should, therefore, be a priority, and future research should focus on how vertebrate pollinator decline might affect wider ecosystems.

Chapter 3 presents a dataset for degree of production dependence of wild and crop plants on vertebrate pollination based on field exclusion experiments. The database includes information on 126 sites for 29 countries and 90 plants species and provides information on study sites, plant and flower visitors information. This is the first dataset providing dependence ratios of plants on vertebrate pollinators and build on previous literature which mainly focused on crop plants and insect pollinators (Klein *et al.* 20017). A major reuse value of the dataset is in using the production dependence data to enable economic valuations of pollination services provided by vertebrates, especially for economically and socially important plants. The information provided by this dataset is a crucial to fully understand the importance on vertebrate pollinators for food production and the maintenance of natural ecosystems, particularly in the tropics, and provides data for potential future economic valuation of ecosystem services delivered by these taxa.

5.1.2 A novel tool for pollination services site-scale assessment and Site-scale provision of pollination services

In the past few decades, there has been an increased interest in measuring and valuing ecosystem services, and a number of tools are currently available for the measurement and evaluation of pollination services (Neugarten *et al.* 2018). Chapter 4 developed a set of methods for the assessment of pollination services, providing a novel, rapid and accessible framework that enables an evaluation of pollination services provision at a site-scale under different land management decisions. A main output of Chapter 4 is a new tool that provides three sets of methods to suit different levels of technical expertise and resource availability: Red, Amber and Green standard methods (Appendix C15 to C23). This is achieved by adopting desk-based, observational and experimental methodologies respectively. These methods enable the comparison of the pollination services provision currently provided by a site and the provision of an alternative state of the site resulting from different land-use management decisions. The integration of the pollination methods in TESSA Version 2.0 (Peh *et al.* 2017) allows the identification of synergies and trade-offs between pollination and other ecosystem services and the implementation of a simple, and yet robust cost-benefit analysis.

The results of the case study in a UK agricultural region (Chapter 4), in line with previous findings, show that pollinator visitation to both oilseed rape and field beans flowers declines with increasing distance from the nature reserve. Proximity to the nature reserve increases the yield of oilseed rape plants but not that of field beans. The comparison with the hypothetical alternative state of the site (where the protected area had not been established and was used for farming) revealed that the overall annual net economic value of pollination service in the current state was greater than the alternative state by between £111 and £151 ha^{-1} $year^{-1}$ depending on the method adopted. Chapter 4 also represents the first field application of the newly developed pollination protocol (Ratto *et al.* 2017).

5.2 Bridging knowledge gaps between invertebrate and vertebrate pollination services

The overall goal of this research thesis was to increase understanding of the potential consequences of losing pollination services that are essential to human well-being and to provide tools to measure the value of this service to inform biodiversity conservation, both in agro and natural ecosystems. A substantial focus has been to address the evident knowledge gaps in the role of non-insect pollinators for the reproduction of crop and wild plants and the development of a rapid pollination services assessment tool. Taken forwards, the combination of results from this research can help to bridge the knowledge gaps between invertebrate and vertebrate pollination services by increasing research on the latter.

5.2.1 Application of the TESSA tools for vertebrate pollinators

The TESSA pollination tool developed here is largely adapted to insect pollination, owing to the much greater understanding we have of these taxonomic groups compared to vertebrate pollinator taxa. However, these methods can be adapted to aid the measurement and evaluation of vertebrate pollination services, so that conservation of vertebrates and the plants they pollinate can be better informed. This is possible in principle, yet there are a number of challenges associated with the implementation of such a tool to vertebrates. The global meta-analysis presented in Chapter 2, revealed a wealth of research on the impact of some vertebrate pollinator taxa on plant reproductive success. However, large scale syntheses to detect general patters of the landscape effect on pollination services (see Garibaldi *et al.* 2013; Ricketts *et al.* 2008) are still lacking for vertebrate pollinators. Furthermore, information on the production dependence of many crops is surprisingly sparse and virtually inexisting for wild plants, which hinders potential economic evaluations, especially of pollination delivered by vertebrates. Therefore, a key aspect of the pollination protocol, such as the distance decay rate extracted from Ricketts *et al.* (2008), does not apply to vertebrate pollinators as it is entirely based on insect studies. Equally, the 1km buffer area is not adequate for vertebrate pollinators, especially highly mobile taxa such as bats, with much greater foraging ranges (Meyer *et al.* 2005; Loayza and Loiselle 2008; Zeale *et al.* 2012).

Potentially, the exclusion experiments approach (Green standard method) could be adapted to vertebrates by discarding the distance decay approach. The value of any increased crop yield would be allocated entirely to the reserve if the pollinators are known to utilise its resources for nesting and foraging. Pollinators may also rely on other non-crop areas for resources, however increasing the buffer area would also increase its heterogeneity, thus confounding the provision of pollination services by the assessment site. Also, this would significantly increase the amount of financial and human resources required. Exclusion experiments can easily be adapted to vertebrates by making exclusion bags with chicken wire instead of tulle mesh, which prevents larger pollinators from accessing the plants but not insects, providing an accurate measure of increased production due solely to vertebrate pollination.

The desk based (Red standard) and visitation rate methods (Amber standard) are more challenging to adapt to vertebrate pollination due to paucity of available data on the production dependence of plants on these pollinator groups. Therefore, the dependence ratio would have to be measured empirically in most cases, using exclusion experiments. However, the dataset created in this theses (Chapter 3), is a step toward filling this knowledge gap and could be incorporated as an appendix in a TESSA type assessment tool for vertebrate pollination and be regularly updated. Methods to measure visitation rates would also need to be adapted to the vertebrate group of interest. Camera-traps are a widely used technique for flying mammals such as bat and flying foxes (e.g. Aziz *et al.* 2017) and non-flying mammals such as rodents (e.g. Steenhuisen and Johnson 2012). However, this requires more resource to be implemented, hence a very rapid yet robust method to assess vertebrate pollination services may be difficult to achieve.

Other available pollination assessment tools such as InVEST and ARIES are not designed for vertebrate pollination, partly because the main focus of these assessment is crop pollination. This reveals a definite need for pollination research to increase efforts beyond crop pollination services delivered by insects. This would allow to quantify the value of pollination services not only for food production but also for the reproduction of wild plants, the maintenance of natural ecosystems as well as the social and cultural values of pollinators.

5.2.2 The need to increase knowledge of pollinator contribution to plants yield and accuracy of economic valuations

Throughout this research project, a common factor that impacted on the accuracy of results and the ability to make broader inferences, was the availability of accurate information on the on the proportion of plant yield due to pollinator activity. For example in Chapter 2, the lack of available data on the contribution of non-flying mammals to plants reproductive success was not sufficient to generalise on the impact of their loss on plants output. Equally, the quicker assessment methods in the new TESSA pollination tool (Red and Amber methods) can only be implemented when the dependence ratio (DR) of the plant of interest is known. This limits their applicability to major crop plants for which the pollinator dependence is well studied such as oilseed rape (Bommarco et al. 2012) and coffee (Klein *et al*. 2003a/b; Ricketts 2004). Furthermore, even when the dependence ratio is known, it is often extracted from the Klein *et al.* (2007) review. This dated synthesis is limited in scope as it focuses solely on leading crops, and limited in accuracy as it provides categorical values of DR, which miss the nuances of specific regional contexts and crop varieties. Furthermore, dependence ratios are a key component of formulas that have been heavily used to estimate pollination economic value (Hanley *et al.* 2015, Breeze *et al.* 2016). The majority of published global and national scale economic valuation of pollination services (e.g. Gallai *et al.* 2009; Leonhardt *et al.* 2013; Smith *et al.* 2011; Vanbergen *et al.* 2014) used values of dependence ratios extracted from Klein *et al.* (2007). Yet, these values were originally collated to determine what proportion of agricultural output relied on pollinator activities and not for economic valuation (Melathopoulos *et al.* 2015), which limits the accuracy of existing and future economic valuations of pollination services.

It is only by generating more accurate and exhaustive databases on plants dependence on pollinators that we can expect to produce more robust estimations of the value of pollinators to crop and wild plants reproduction and fully appreciate the consequences of their decline for our well-being. This can be addressed by expanding the scope of literature syntheses such as the one done in Chapter 2, to all pollinator taxa and collate context specific yield analysis studies that produce more accurate estimates of pollinators benefits (Breeze *et al.* 2016). TESSA type pollination assessments can help with this by rapidly generating field-based data on dependence ratio of plants that are region specific. Irrespective of the dependence on a single reserve, the data generated by the Green standard method provides the most direct measure of pollinators contribution to seed set

(Ne'eman *et al.* 2010), which is locally relevant, thus enabling more locally-appropriate policy and conservation advice.

5.3 Implications for biodiversity and ecosystem services conservation

5.3.1 Biodiversity conservation

Pollinators are important in both natural and agricultural ecosystems for the services they provide to wild plants and crop plants alike, thus it is necessary to sustain them in these habitats. The results of this research can provide a number of suggestions for conserving pollinators, with further implications for both wild and crop plants.

5.3.1.1 Conservation of vertebrate and invertebrate pollinators

Flower-visitors are found in many vertebrate taxa, pollinate socially and economically important crops and are potentially crucial for the maintenance of ecosystems, especially in the tropics. My research provides an initial global picture of the importance of pollinators to wild plant reproduction and the crucial role they play in the ecosystems they inhabit. Almost two-thirds of fruit and seed production of the studied plants, on average, would be lost in the absence of vertebrate pollinators, giving a measure of the potentially catastrophic consequences of their loss. Therefore, findings from this thesis should provide more impetus for conservation actions, especially in the rapidly disappearing tropical ecosystems that have shown to be more vulnerable to the loss of vertebrate pollinators.

The results from Chapter 4 give an indication of how proximity to a small nature reserve enhanced both visitation frequency and yield to some of the surrounding crops, which strengthens the argument for conservation action to maintain areas of natural habitats in intense agricultural landscapes. However, Kleijn *et al.* (2015) show how focusing conservation efforts based on the ecosystem services argument may not be enough to protect wider biodiversity as a small percentage of common species delivers the majority of pollination to crop. Furthermore, enhanced crop pollination can be achieved from small patches of semi-natural areas whereas biodiversity conservation requires large areas of intact landscapes (Chan *et al.* 2006). Therefore, focusing on agricultural pollination services may be beneficial for a small number of resilient more generalist species (Senapathi *et al.* 2015) but miss rare species higher conservation concern as well as larger biodiversity conservation targets. However, very few species are found in abundance away from natural habitat as all pollinators rely on such habitat for the provision of floral and nesting resources (Ricketts *et al.* 2008; Garibaldi *et al.* 2011b). Conservation of a wider range of species can be achieved through the implementation of agri-environment schemes including measures for enhancing floral resources that will benefit more diverse flower-visitor communities (Grass *et al.* 2016). Furthermore, agricultural values have been shown to be positively associated with the richness of high conservation-value species in the UK (Anderson *et al.* 2009). In this context, the evidence generated by using this assessment tool, although focusing on crop production, provides opportunities to raise awareness across decision makers and encourage habitat management of broader flower-visitor communities.

5.3.2 Conserving ecosystem services at a site-scale

In the past decade, international conservation policy has shifted targets for the conservation of ecosystem goods and services by adopting the Aichi Targets included in the Conference of the Parties to the CBD (18–29 October 2010, Nagoya, Aichi Prefecture, Japan). These targets re-focused biodiversity conservation policy and legislation on ecosystem services, providing better integration of biodiversity conservation in other policy sectors that may not have been as receptive to traditional biodiversity conservation targets (Eastwood *et al.* 2016). In order to integrate ecosystem services into site conservation programmes, considerations have to be made on how the ecosystem processes align with the beneficiaries of the services and the scale of service flows. This is particularly relevant to relatively small sites in human-dominated areas, where the distribution of many ecosystem service benefits affect a smaller spatial scale (Hein *et al.* 2006). Ecosystem services where the ecological process that underpins them and the beneficiaries align at a local scale may be effectively managed on a single-site basis. For instance, some cultural services such as the recreational or spiritual value often depend on a particular site rather than a type of place (Stålhammar *et al.* 2017). In this case the beneficiaries are often the local communities which makes a site-based conservation approach more appropriate.

Some ecosystem services such as carbon capture and storage, are produced at a local scale, but the benefits accrue to people at a global scale (Raudsepp-Hearne and Peterson 2016). Although it is important to measure the capacity of small sites to deliver climate regulation services, it may not be appropriate for it to be the focus of conservation strategies for a single site, as its loss may not have an impact on climate regulation at a larger, more significant scale. Also, it could potentially divert the focus from other ecosystem services that are more relevant at smaller spatial scales (e.g. harvested wild goods).

Landscape characteristics influence the scale at which conservation targets for pollination services are set as well as the targeted pollination taxa. For example, pollinating bats and flying foxes in tropical and subtropical areas may form large permanent colony roosts in patches of rain forest (e.g. Abdul-Aziz *et al.* 2017). In this case, a site-based conservation strategy may be sufficient for securing the maintenance of pollinator services to the area. Conversely, in agroecosystems, agricultural intensification affects biodiversity at two spatial levels: more intensive farming practises (e.g. high levels of chemical inputs) affect biodiversity at a local level, while at a landscape scale, enlarged field size causes the reduction of non-crop habitat (Tscharntke *et al.* 2005). In these ecosystems, conservation strategies should be designed on multiple scales to protect biodiversity and the delivery of pollination and pest control services, as both local and landscape scale processes impact on invertebrate abundance and species richness (Gonthier *et al.* 2014). For example, a single site focus could benefit the conservation of less mobile pollinator taxa such as hoverflies and other diptera and natural enemies such as ground beetles, which have been observed to decline along two hundred metres towards the centre of crops fields (Woodcock *et al.* 2016). Thus, site-based conservation strategies could benefit the delivery of these services into the immediate surrounding cropland.

However, the development of the dynamics of meta-population (Hansky 1999,2001) and metacommunities (Leibold *et al.* 2004) in ecological theory, have supported a shift into landscape-scale management approaches regarding biodiversity conservation, such as metapopulation management (Rouquette & Thompson 2007). Such theories have highlighted the importance of landscape processes such as species migration, colonization and dispersal, to ensure the persistence of species forming ecological communities (Turner 2005). These include highly mobile social insects that utilise resources at a larger spatial scale, and also natural enemies have been shown to positively respond to landscape complexity (Chaplin-Kremen *et al.* 2011). Furthermore, observation and measurement of ecosystem services at a single scale may not allow the identification of trade-offs between ecosystem services at a larger spatial scale, which is essential for the sustainable management of ecosystem services (Carpenter *et al*. 2009, Bennett *et al.* 2015). For example, advising farmers to place pollinator dependent crops all around Noar Hill to maximise the pollination services delivered and increase production, could have an adverse effect on water quality at a landscape scale (Raudsepp-Hearne and Peterson 2016).

Assessment tools such as TESSA can help build a stronger case for site conservation by highlighting the value of the ecosystem services provided by a site and can rapidly generate locally-relevant data on the benefits and value of ecosystems services. However, they should be used to build part of the picture rather than being the only tools. The integration of such tools into bigger scale assessments is essential to inform larger scale conservation planning. This is especially important for ecosystem services delivered by landscape processes, to ensure the provision of recolonization sources in case of large or small scale disturbances. This approach is needed to safeguard the long-term support of these services, which in the case of pollinators can only be obtained through a mosaic of connected non-crop habitat within agricultural landscapes (Bengtsson *et al.* 2003).

5.4 Implications for policy and decision-making

Agricultural ecosystems are the most human-modified and managed ecosystems, dominating global land surface (Ellis *et al.* 2010). In this extremely productive ecosystem, pollinators and pollination services yield high monetary value, but it is also where they are potentially subject to the greatest threats (Lautenbach *et al.* 2012; Potts *et al.* 2016). Conservation and policy-actions for pollinators in agroecosystems are therefore a high priority at the national and international level (Defra 2014; FAO 2018). This thesis presents a new pollination assessment protocol that has potential implications for policy by generating evidence that can inform decision-making, support the conservation of a site and inform mitigation strategies for pollinator decline and the associated pollination service.

To inform decision-making, especially at a site-scale, it is essential to integrate the pollination assessment in a more comprehensive ecosystem services assessment to establish the full benefits and costs of maintaining a site for its current purposes. The benefits of maintaining a nature reserve for pollinators might not prove a strong enough argument when compared to the potential economic gain of conversion to recreational uses (e.g. a golf course) or to agriculture. For example, in the case study presented in Chapter 4, incorporating the values and costs of pollination services with those of agricultural production, results in a minimal economic gain of maintaining the site for biodiversity (See Figure 4-17). However, management decisions should be made on a complete assessment of ecosystem services delivered by a site to fully appreciate trade-offs and synergies between them. For example, enhanced wildflowers in agricultural landscape support a suite of invertebrate taxa (e.g. non-syrphid Diptera) that can provide additional ecosystem services such as pest control (Holland *et al.* 2008). Furthermore, by assessing pollination services alone, we will miss out other significant services such as climate-regulating services, nature-based recreation and tourism.

At a national level, the toolkit developed here can assist government bodies such as Natural England (NE) with planning, development, and land management decisions. NE currently use the Defra Biodiversity Metric to assess the biodiversity value of a site and quantify compensations (in land and money) required for loss of biodiversity due to development (DEFRA 2012). The Defra Biodiversity Metric is now being developed to expand the scope to other ecosystem services (NE Sustainable Development Lead Advisor 2018, pers. comm., 14 June), which demonstrates the timely potentials for applications of the newly developed protocol to inform government level decision-making.

At an international level, the pollination assessment methods can help address some identified weaknesses in evidence on the effect of semi-natural habitat on pollination at a European level (Holland *et al.* 2017). This can provide much-needed valuation tools to increase knowledge and assist decision making. This tool can help the design of agri-environment schemes by assessing the effect of variations in the availability of semi-natural habitat on the delivery of pollinations services in agricultural landscapes.

5.5 Suggestions for future research

Here I highlight some potential areas for future research as informed by the results and limitations of my study.

In Chapter 2, I investigated the importance of vertebrate pollination on the reproductive success of plants, which has helped to increase the understanding of the contribution of animal pollination to fruit and seed production, especially in wild plants. However, more research is still needed on the extent to which the reproduction of wild plants is enhanced by a wider range of flower-visitor taxa. Worldwide, the majority of pollination is carried out by insects and other invertebrates. Future work to quantify the potential impact of insect pollination loss on seed and fruit production in wild plants would be beneficial. This will help to fully appreciate the impact of pollinator decline on global biodiversity and natural ecosystems.

This study produced a set of methods for the rapid assessment of pollination services at a site-scale (Chapter 4). These methods are mainly adapted to invertebrate pollination in terms of experimental design and underlying assumptions. Future developments of this protocol should focus on improving methods for the assessment of vertebrate pollination services to expand the scope and applicability of this toolkit. This will enable its implementation in a broader range of regions and habitats, such as the tropics where dependence on vertebrate pollination is greater.

The methods developed in this thesis address the benefits provided by pollination in terms of marginal increase in crop yield quantity. However, pollination provides several more direct and indirect benefits to people. It would be useful to develop rapid methods to assess other aspects of pollination services starting with its contribution to agricultural production in terms of quality of crops. Furthermore, future work to complement existing pollination methods with rapid methodologies to measure indirect benefits of pollination such as cultural and social benefits would be beneficial. This would extend the scope of the pollination assessment and provide a more holistic valuation of pollination services.

Semi-natural habitats support flower-visiting insects but also a number of other invertebrates that may deliver benefits beyond pollination to the surrounding arable land. It would be useful for the next version of TESSA to develop methods for measuring other ecosystem services delivered by crop visiting insect such as biological pest control.

Chapter 4 provided insight on the importance of non-syrphid flies (*muscidae*) for oilseed rape pollination. Visitations of flies to oilseed rape have been observed in previous studies in UK (Garratt *et al.* 2014b), yet the importance of this group to oilseed rape and other crop types is still not clear. Therefore more work on this insect taxon would be useful to determine the potential benefits of these flower visitors to crop production. Expanding from this, a greater research effort should focus on less recognised pollinator groups such as non-bee invertebrates and vertebrate, particularly on their plant-pollinator interaction and their contribution to plant reproduction.

This thesis has shown a negligible effect of insect pollination field beans yield in contrast with previous research (Bartomeus *et al.* 2014). Future studies on the degree of dependence of different varieties of field beans and other crop types on animal pollination would be beneficial. Most of the economic valuation of pollination services use the level of dependence presented in the Klein *et al.* (2007) review, which is not a comprehensive source. Further research on the level of dependency of many crop types, measured through yield analysis, is still needed. This can provide more accurate estimates of crop dependence on biotic pollination and improve future economic valuations.

In Chapter 4, I presented the first pilot of the newly developed pollination assessment methods, the results of which were integrated with cultivated goods services. However, a number of other ecosystem services are likely to be delivered by the pilot site. It would be useful to implement the entire TESSA toolkit to the pilot site to gain a full picture and reveal trade-offs and synergies between ecosystem service for a more holistic management approach.

This thesis contributed to generating empirical evidence on the importance of semi-natural habitat in highly modified landscapes (Chapter 4). Remnants of natural habitat in intensely human-altered ecosystems provide essential foraging and nesting resources for pollinators. For example, riparian corridors have been shown to be important habitat for pollinators, impacting on the reproduction of bees nesting on farms (Williams and Kremen 2007) and influencing native bees in their ability to pollinate crop (Kremen *et al.* 2004). Riparian vegetation infiltrates modified landscapes such as agricultural and urban land, often providing the only continuous natural habitat in these systems, yet they are not well studied. Therefore, it would be interesting to investigate the benefits provided by riparian corridors, perhaps by applying the methods developed in this thesis to rapidly generate data on their ability to deliver pollination services.

5.6 Concluding remarks

Biotic pollination is an essential function in most terrestrial ecosystems, yet pollinator populations are under great pressure due to a number of drivers of decline (Vanbergen *et al.* 2013), the greatest of which is probably habitat loss (Bartomeus and Dicks 2018). Animal pollination represents a crucial ecosystem service that delivers key benefits to humans through the maintenance of natural ecosystems (Aguilar *et al.* 2006; Ollerton *et al.* 2011) as well as agricultural productivity (Klein *et al.* 2007; Ricketts *et al.* 2008). Paradoxically, the aims of wildlife conservation and food production have historically been perceived as incompatible, even though the productivity of many crops highly depends on pollinators abundance and diversity (Bartomeus and Dicks 2018). Although in the past decades efforts have been made to reconcile these goals through a multifunctional view of landscape uses (Senapathi *et al.* 2017).

This research has highlighted the potential devastating impact of vertebrate pollinator loss on the reproductive success of wild plants globally and produced a robust set of methods for assessing pollination services at a fine scale. I have demonstrated the feasibility of these methods in the field and the robustness of their results, and shown the potential important role of remaining patches of natural habitat, in human-dominated landscapes, for pollination services provision.

These methods can be useful to scientists, governments, land managers and conservationists in providing rapid and accessible means to generate robust data to inform decision-making, at an operational scale and in various regions, ecosystems and socio-cultural contexts. The decline of pollinators, their conservation and the implications for food security and human well-being is a complex, multifaceted issue, involving every layer of society that we can only aspire to effectively address through a multi-disciplinary, integrated, evidence-based approach.

5.7 Literature cited

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Appendices

Appendix A Supporting information for Chapter 2

Appendix A.1 Search string for all databases used for the systematic review. First searches were performed in March 2015. A final search was performed in February 2016. After this, we sought unpublished data from researchers and checked databases alerts until mid 2016.

ENGLISH SEARCH
First search performed on Web of Science on 02/03/2015
pollinat* OR "flower* OR visit* OR "pollen deposit*" AND bird* OR bats OR bat OR avian OR chiroptera* OR lorikeet* OR flowerpecker* OR honeyeater* OR whiteeye* OR warbler* OR hummingbird* OR sunbird* OR "diurnal pollinator*" OR nectariv* OR “nocturnal pollinator*” OR “nectar feeding” OR “flying fox*” OR lemur* OR possum* OR lizard* OR squamata OR iguania OR gekkota OR gecko* OR rodent* OR gerbil OR mammal* OR Acrobatidae OR Aotidae OR Atelidae Burramyidae OR Callaeatidae OR Callithricidae OR Cardinalidae OR Cebidae OR Cercopithecidae OR Cheirogaleidae OR Coerebidae OR Coliidae OR Columbidae OR Corvidae OR Cotingidae OR Cracidae OR Cricetidae OR Dasyuridae OR Daubentoniidae OR Dicaeini OR Didelphidae OR Emberizidae OR Fringillidae OR Furnariidae OR Galagidae OR Giraffidae OR Gliridae OR Icteridae OR Irenidae OR Lemuridae OR Lepilemuridae OR Loriinae OR Lorisidae OR Lybiidae OR Macroscelididae OR Marsupialia OR Meliphagidae OR Mimidae OR Mohoidae OR Muridae OR Mystacinidae OR Nectariniidae OR Nectariniini OR Paridae OR Parulidae OR Petauridae OR Phalangeridae OR Phelsuma OR Phoeniculidae OR Platacanthomydae OR Pycnonotidae OR Phyllostomidae OR Picidae OR Ploceidae OR Procyonidae OR Promeropidae OR Pseudocheiridae OR Psittacidae OR Pteropodidae OR Ptilocercidae OR Scincidae OR Scincomorpha OR Sciuridae OR Strigopidae OR Sturnidae OR Sylvidae OR Tarsipedidae OR Thinocoridae OR Thraupidae OR Trochilidae OR Troglodytidae OR Tupaiidae Turdidae OR Tyrannidae OR Vespertilionidae OR Vireonidae OR Viverridae OR Zosteropidae AND Pollen OR fruit* OR seed* Returned 2527 results
First search performed on CAB Abstract on 02/03/2015
(This database accepts the same format as Web of Science so the search was the same as the original) pollinat* OR "flower* OR visit* OR "pollen deposit*" AND

bird* OR bats OR bat OR avian OR chiroptera* OR lorikeet* OR flowerpecker* OR honeyeater* OR whiteeye* OR warbler* OR hummingbird* OR sunbird* OR "diurnal pollinator*" OR nectariv* OR “nocturnal pollinator*” OR “nectar feeding” OR “flying fox*” OR lemur* OR possum* OR lizard* OR squamata OR iguania OR gekkota OR gecko* OR rodent* OR gerbil OR mammal* OR Acrobatidae OR Aotidae OR Atelidae Burramyidae OR Callaeatidae OR Callithricidae OR Cardinalidae OR Cebidae OR Cercopithecidae OR Cheirogaleidae OR Coerebidae OR Coliidae OR Columbidae OR Corvidae OR Cotingidae OR Cracidae OR Cricetidae OR Dasyuridae OR Daubentoniidae OR Dicaeini OR Didelphidae OR Emberizidae OR Fringillidae OR Furnariidae OR Galagidae OR Giraffidae OR Gliridae OR Icteridae OR Irenidae OR Lemuridae OR Lepilemuridae OR Loriinae OR Lorisidae OR Lybiidae OR Macroscelididae OR Marsupialia OR Meliphagidae OR Mimidae OR Mohoidae OR Muridae OR Mystacinidae OR Nectariniidae OR Nectariniini OR Paridae OR Parulidae OR Petauridae OR Phalangeridae OR Phelsuma OR Phoeniculidae OR Platacanthomydae OR Pycnonotidae OR Phyllostomidae OR Picidae OR Ploceidae OR Procyonidae OR Promeropidae OR Pseudocheiridae OR Psittacidae OR Pteropodidae OR Ptilocercidae OR Scincidae OR Scincomorpha OR Sciuridae OR Strigopidae OR Sturnidae OR Sylvidae OR Tarsipedidae OR Thinocoridae OR Thraupidae OR Trochilidae OR Troglodytidae OR Tupaiidae Turdidae OR Tyrannidae OR Vespertilionidae OR Vireonidae OR Viverridae OR Zosteropidae

AND

Pollen OR fruit* OR seed*

Returned 1698 results

First search performed on Scopus on 02/03/2015

(Same search string. Used ALL as it is the most comprehensive one)

pollinat* OR flower* OR visit* OR "pollen deposit*"

AND

bird* OR bats OR bat OR avian OR chiroptera* OR lorikeet* OR flowerpecker* OR honeyeater* OR whiteeye* OR warbler* OR hummingbird* OR sunbird* OR "diurnal pollinator*" OR nectariv* OR “nocturnal pollinator*” OR “nectar feeding” OR “flying fox*” OR lemur* OR possum* OR lizard* OR squamata OR iguania OR gekkota OR gecko* OR rodent* OR gerbil OR mammal* OR Acrobatidae OR Aotidae OR Atelidae Burramyidae OR Callaeatidae OR Callithricidae OR Cardinalidae OR Cebidae OR Cercopithecidae OR Cheirogaleidae OR Coerebidae OR Coliidae OR Columbidae OR Corvidae OR Cotingidae OR Cracidae OR Cricetidae OR Dasyuridae OR Daubentoniidae OR Dicaeini OR Didelphidae OR Emberizidae OR Fringillidae OR Furnariidae OR Galagidae OR Giraffidae OR Gliridae OR Icteridae OR Irenidae OR Lemuridae OR Lepilemuridae OR Loriinae OR Lorisidae OR Lybiidae OR Macroscelididae OR Marsupialia OR Meliphagidae OR Mimidae OR Mohoidae OR Muridae OR Mystacinidae OR Nectariniidae OR Nectariniini OR Paridae OR Parulidae OR Petauridae OR Phalangeridae OR Phelsuma OR Phoeniculidae OR Platacanthomydae OR Pycnonotidae OR Phyllostomidae OR Picidae OR Ploceidae OR Procyonidae OR Promeropidae OR Pseudocheiridae OR Psittacidae OR Pteropodidae OR Ptilocercidae OR Scincidae OR Scincomorpha OR Sciuridae OR Strigopidae OR Sturnidae OR Sylvidae OR Tarsipedidae OR Thinocoridae OR Thraupidae OR Trochilidae OR Troglodytidae OR Tupaiidae Turdidae OR Tyrannidae OR Vespertilionidae OR Vireonidae OR Viverridae OR Zosteropidae

AND

Pollen OR fruit* OR seed*

Returned 249 results

Search performed on SCIELO on 16/09/2015

Search restricted to English and Spanish, Portuguese was excluded. We used all the terms at once

<u>Exposure:</u>

(poliniza* OR flor* OR visit* OR "deposici*n polen*")

AND

<u>Agent:</u>

(ave* OR murci*lago OR murci*lagos OR aviar OR chiroptera* OR quiroptera* OR periquito* OR picaflor* OR chupamiel* OR anteojito* OR ojiblanco* OR curruca* OR colibr* OR suimanga* OR nectarine* OR “p*jaro* sol” OR "polinizador* diurno*" OR nectariv* OR “polinizador* nocturno*” OR “alimentaci*n n*ctar” OR “zorro* volador” OR lemur* OR zarigüeya* OR lagartija* OR squamata OR iguania OR gekkota OR gecko* OR roedor* OR jerboa* OR mam*fero* OR Acrobatidae OR Aotidae OR Atelidae OR Burramyidae OR Callaeatidae OR Callithricidae OR Cardinalidae OR Cebidae OR Cercopithecidae OR Cheirogaleidae OR Coerebidae OR Coliidae OR Columbidae OR Corvidae OR Cotingidae OR Cracidae OR Cricetidae OR Dasyuridae OR Daubentoniidae OR Dicaeini OR Didelphidae OR Emberizidae OR Fringillidae OR Furnariidae OR Galagidae OR Giraffidae OR Gliridae OR Icteridae OR Irenidae OR Lemuridae OR Lepilemuridae OR Loriinae OR Lorisidae OR Lybiidae OR Macroscelididae OR Marsupialia OR Meliphagidae OR Mimidae OR Mohoidae OR Muridae OR Mystacinidae OR Nectariniidae OR Nectariniini OR Paridae OR Parulidae OR Petauridae OR Phalangeridae OR Phelsuma OR Phoeniculidae OR Platacanthomydae OR Pycnonotidae OR Phyllostomidae OR Picidae OR Ploceidae OR Procyonidae OR Promeropidae OR Pseudocheiridae OR Psittacidae OR Pteropodidae OR Ptilocercidae OR Scincidae OR Scincomorpha OR Sciuridae OR Strigopidae OR

Sturnidae OR Sylvidae OR Tarsipedidae OR Thinocoridae OR Thraupidae OR Trochilidae OR Troglodytidae OR Tupaiidae Turdidae OR Tyrannidae OR Vespertilionidae OR Vireonidae OR Viverridae OR Zosteropidae) AND <u>*Outcome:*</u> (Polen OR fruta* OR semilla*) Returned 152 results
First search performed on Google.com on 16/09/2015
Adapted to google settings, first 50 hits were reviewed, file format PDF, cookies deleted <u>All these words</u>: Polinizacion <u>Any of these words</u>: ave OR murcielago OR aviar OR periquito OR picaflor OR chupamiel OR anteojito OR ojiblanco OR curruca OR colibri OR suimanga OR pajaro sol OR lemur OR zarigüeya OR lagartija OR squamata OR iguania OR gekkota OR gecko OR roedor OR jerboa OR mamifero
First search performed on Google.Scholar on 16/09/2015
Adapted to Google-Scholar advance settings first 50 hits were reviewed, cookies deleted <u>With all the words</u>: Polinizacion <u>With at least one of the words</u>: ave murcielago periquito picaflor chupamiel anteojito ojiblanco curruca colibri suimanga lemur zarigüeya lagartija squamata iguania gekkota gecko roedor jerboa mamifero

Appendix A.2 Definition and formula for Fail-safe number

A fail-safe number is defined as the number of non-significant unpublished studies required to eliminate a significant overall effect size (Rosenberg 2005).

Results are considered robust to publication bias when the fail-safe number is equal to or greater than $5n+10$, where n is the number of studies. We found no evidence of publication bias with a weighted fail-safe number greater that $5n+10$

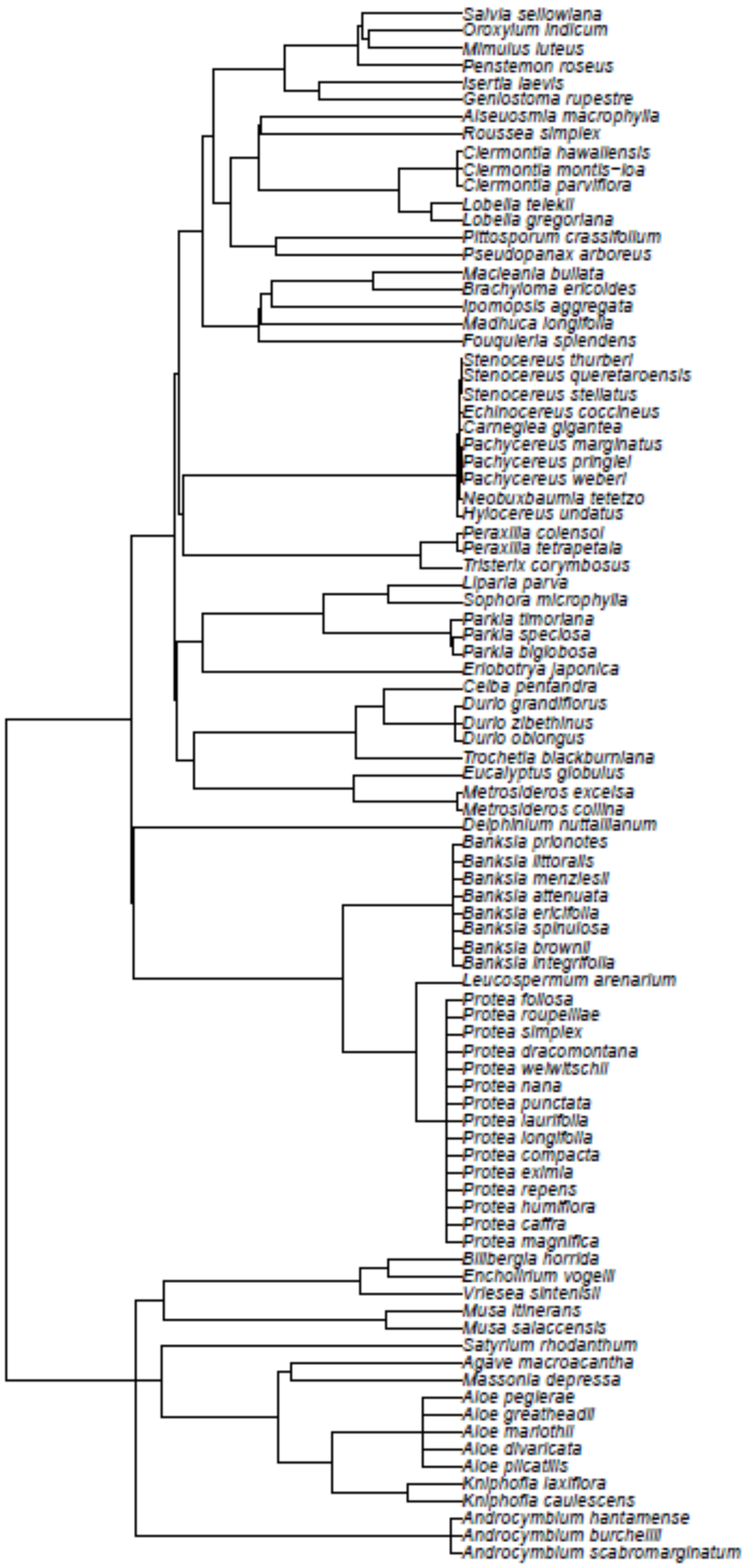
$n= 126$

$5*126 + 10= 640$

Computed Fail-safe number = 101018

< 101018

Appendix A.3 Phylogeny of plant species included in the meta-analysis



Appendix A.4 List of articles included in the final analysis

1 Aizen, M.A. (2005). Breeding system of Tristerix corymbosus (Loranthaceae), a winter-flowering mistletoe from the southern Andes. *Aust. J. Bot.*, 53, 357-361.

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Appendix A.5 List of plant species included in the analysis

Pant Species	Plant family	Crop or Wild
Aloe greatheadii var. davyana	Xanthorrhoeaceae	Wild
Agave Macroacantha	Agavaceae	Wild
Aloe divaricata	Liliaceae	Wild
Aloe marlothii	Xanthorrhoeaceae	Wild
Aloe peglerae	Xanthorrhoeaceae	Wild
Aloe plicatilis	Xanthorrhoeaceae	Wild
Alseuosmia macrophylla	Alseuosmiaceae	Wild
Banksia attenuata	Proteaceae	Wild
Banksia brownii	Proteaceae	Wild
Banksia ericifolia	Proteaceae	Wild
Banksia integrifolia	Proteaceae	Wild
Banksia littoralis	Proteaceae	Wild
Banksia menziesii	Proteaceae	Wild
Banksia prionotes	Proteaceae	Wild
Banksia spinulosa	Proteaceae	Wild
Billbergia horrida	Bromeliaceae	Wild
Brachyloma ericoides	Epacridaceae	Wild
Carnegiea gigantea	Cactaceae	Wild
Ceiba pentandra	Bombaceae	Crop/Wild
Clermontia hawaiiensis	Campanulaceae	Wild
Clermontia montis-loa	Campanulaceae	Wild
Clermontia parviflora	Campanulaceae	Wild
Colchicum coloratum	Colchicaceae	Wild
Colchicum hantamense	Colchicaceae	Wild
Colchicum scabromarginatum	Colchicaceae	Wild
Delphinium nelsoni	Ranunculaceae	Wild
Durio grandiflorus	Bombaceae	Wild
Durio oblongus	Bombaceae	Wild
Durio zibethinus	Bombaceae	Crop
Echinocereus arizonicus	Cactaceae	Wild
Encholirium vogelii	Bromeliaceae	Wild
Eriobotrya japonica	Rosaceae	Wild
Eucalyptus globulus	Myrtaceae	Wild
Fouquieria splendens	Fouquieriaceae	Wild
Geniostoma ligustrifolium	Loganiaceae	Wild
Hylocereus undatus	Cactaceae	Crop
Ipomopsis aggregata	Pomeliaceae	Wild
Isertia laevis	Rubiaceae	Wild
Kniphofia caulescens	Asphodelaceae	Wild
Kniphofia laxiflora	Asphodelaceae	Wild
Leucospermum arenarium	Proteaceae	Wild
Liparia parva	Fabaceae	Wild

Pant Species	Plant family	Crop or Wild
Lobelia telekii	Campanulaceae	Wild
Macleania bullata	Ericaceae	Wild
Madhuca longifolia	Sapotaceae	Wild/Crop
Marginatocereus marginatus	Cactaceae	Wild
Massonia depressa	Hyacinthaceae	Wild
Metrosideros collina	Myrtaceae	Wild
Metrosideros excelsa	Myrtaceae	Wild
Mimulus luteus var. luteus	Phrymaceae	Wild
Musa intinerans	Musaceae	Wild
Musa salaccensis	Musaceae	Wild
Neobuxbaumia tetetzo	Cactaceae	Wild
Oroxylum indicum	Bignoniaceae	Wild
Pachycereus pringlei	Cactaceae	Wild
Pachycereus weberi	Cactaceae	Wild
Parkia biglobosa	Fabaceae	Crop
Parkia speciosa	Mimosaeae	Crop
Parkia timoriana	Mimosaeae	Crop
Penstemon roseus	Plantaginaceae	Wild
Peraxilla colensoi	Loranthaceae	Wild
Peraxilla tetrapetala	Loranthaceae	Wild
Pittosporum crassifolium	Pittosporaceae	Wild
Protea caffra	Proteaceae	Wild
Protea compacta	Proteaceae	Wild
Protea dracomontana	Proteaceae	Wild
Protea eximia	Proteaceae	Wild
Protea foliosa	Proteaceae	Wild
Protea humiflora	Proteaceae	Wild
Protea laurifolia	Proteaceae	Wild
Protea longifolia	Proteaceae	Wild
Protea magnifica	Proteaceae	Wild
Protea nana	Proteaceae	Wild
Protea punctata	Proteaceae	Wild
Protea repens	Proteaceae	Wild
Protea roupelliae ssp. Roupelliae	Proteaceae	Wild
Protea simplex	Proteaceae	Wild
Protea welwitschii	Proteaceae	Wild
Pseudopanax arboreus	Araliaceae	Wild
Roussea simplex	Rousseaceae	Wild
Salvia sellowiana	Lamiaceae	Wild
Satyrium rhodanthum	Orchidiaceae	Wild
Sophora microphylla	Fabaceae	Wild
Stenocereus Queretaroensis	Cactaceae	Wild
Stenocereus queretaroensis var. Blanco	Cactaceae	Wild
Stenocereus queretaroensis var. Tenamaste	Cactaceae	Wild

Pant Species	Plant family	Crop or Wild
Stenocereus stellatus	Cactaceae	Crop
Stenocereus thurberi	Cactaceae	Wild
Tristerix corymbosus	Loranthaceae	Wild
Trochetia blackburniana	Malvaceae	Wild
Werauhia sintenisii	Bromeliaceae	Wild

Appendix B Supporting Information to Chapter 3

Appendix B.1 Extract from the dataset (.xlsx file) of the degree of dependence of wild and crop plants on vertebrate pollination

Plant Species	Pollinator Family	% of increase in production	Impact by animal pollination
Metrosideros collina	Drepanididae, Fringillidae	6	**Little**
Stenocereus stellatus	Trochilidae,Picidae	0	**No Increase**
Stenocereus stellatus	Trochilidae,Picidae	0	**No Increase**
Stenocereus stellatus	Trochilidae,Picidae	6	**Little**
Stenocereus stellatus	Phyllostomidae	100	**Essential**
Stenocereus stellatus	Phyllostomidae	100	**Essential**
Stenocereus stellatus	Phyllostomidae	100	**Essential**
Banksia ericifolia	Dasyuridae, Petauridae, Muridae	17	**Modest**
Massonia depressa	Muridae, Gerbidae	90	**Great**
Macleania bullata	Trochilidae	100	**Essential**
Banksia ericifolia	Birds	55	**Great**
Banksia spinulosa	Meliphagidae	2	**Little**
Durio grandiflorus	Nectarinidae	100	**Essential**
Durio oblongus	Nectarinidae	100	**Essential**
Banksia attenuata	Meliphagidae	0	**No Increase**
Banksia littoralis	Meliphagidae	57	**Great**
Banksia menziesii	Meliphagidae	100	**Essential**
Lobelia keniensi	Nectariniidae, Muscicapidae, Sturnidae	31	**Modest**
Lobelia telekii	Nectariniidae, Muscicapidae, Sturnidae	48	**Great**
Banksia menziesii	Meliphagidae	77	**Great**
Banksia integrifolia	Burramyidae, Dasyuridae,Acrobatidae	19	**Modest**
Banksia integrifolia	Meliphagidae	37	**Modest**
Musa salaccensis	Nectariniidae	94	**Essential**
Ceiba pentandra	Pteropodidae	100	**Essential**
Aloe divaricata	Nectariniidae	83	**Great**
Neobuxbaumia tetetzo	Phyllostomidae	100	**Essential**
Banksia brownii	Meliphagidae	32	**Modest**
Pachycereus weberi	Phyllostomidae	100	**Essential**
Macleania bullata	Trochilidae	42	**Great**
Peraxilla colensoi	Meliphagidae	75	**Great**
Peraxilla tetrapetala	Meliphagidae	54	**Great**
Peraxilla tetrapetala	Meliphagidae	94	**Essential**
Agave Macroacantha	Phyllostomidae	50	**Great**
Carnegiea gigantea	Phyllostomidae	0	**No Increase**
Carnegiea gigantea	Birds	0	**No Increase**
Carnegiea gigantea	Phyllostomidae	4	**Little**
Carnegiea gigantea	Birds	37	**Modest**

Plant Species	Pollinator Family	% of increase in production	Impact by animal pollination
Pachycereus pringlei	Birds	0	**No Increase**
Pachycereus pringlei	Phyllostomidae	0	**No Increase**
Stenocereus thurberi	Birds	31	**Modest**
Stenocereus thurberi	Phyllostomidae	51	**Great**
Protea humiflora	Muridae	55	**Great**
Musa intinerans	Macroglossinae	7	**Little**
Musa intinerans	Nectarinidae	9	**Little**
Pseudopanax arboreus	Meliphagidae,Notiomystidae, Psittaculidae, Callaeidae	58	**Great**
Sophora microphylla	Meliphagidae,Notiomystidae, Psittaculidae, Callaeidae	98	**Essential**
Geniostoma ligustrifolium	Meliphagidae,Notiomystidae, Psittaculidae, Callaeidae	50	**Great**
Metrosideros excelsa	Meliphagidae,Notiomystidae, Psittaculidae, Callaeidae	52	**Great**
Pittosporum crassifolium	Meliphagidae,Notiomystidae, Psittaculidae, Callaeidae	62	**Great**
Isertia laevis	Meliphagidae	0	**No Increase**
Brachyloma ericoides	Meliphagidae	5	**Little**
Eucalyptus globulus	Meliphagidae	15	**Modest**
Werauhia sintenisii	Trochilidae	0	**No Increase**
Tristerix corymbosus	Trochilidae	64	**Great**
Stenocereus Queretaroensis	Phyllostomidae	78	**Great**
Peraxilla colensoi	Trochilidae	45	**Great**
Peraxilla tetrapetala	Trochilidae	0	**No Increase**
Peraxilla tetrapetala	Trochilidae	0	**No Increase**
Marginatocereus marginatus	Phyllostomidae	0	**No Increase**
Marginatocereus marginatus	Trochilidae	7	**Little**
Mimulus luteus *var.* luteus	Trochilidae	22	**Modest**
Trochetia blackburniana	Gekkonidae	64	**Great**
Hylocereus undatus	Phyllostomidae	0	**No Increase**
Parkia speciosa	Pteropodidae	77	**Great**
Parkia timoriana	Pteropodidae	100	**Essential**
C. coloratum	Muridae	73	**Great**
C.hantamense	Muridae	0	**No Increase**
Colchicum scabromarginatum	Muridae	95	**Essential**
Penstemon roseus	Trochilidae	52	**Great**
Penstemon roseus	Trochilidae	83	**Great**
Oroxylum indicum	Pteropodidae	100	**Essential**
Protea nana	Muridae	0	**No Increase**
Kniphofia caulescens	Fringillidae	33	**Modest**
Durio zibethinus	Pteropodidae	100	**Essential**
Roussea simplex	Gekkonidae	100	**Essential**
Liparia parva	Muridae	94	**Essential**
Madhuca longifolia	Pteropodidae	60	**Great**

Plant Species	Pollinator Family	% of increase in production	Impact by animal pollination
Metrosideros excelsa	Meliphigidae, Nestoridae, Callaeidae	16	**Modest**
Metrosideros excelsa	Meliphigidae, Nestoridae, Callaeidae	34	**Modest**
Aloe greatheadii var. davyana	Nectarinidae, Fringillidae, Collidae	16	**Modest**
Aloe marlothii (mountain aloe)	Nectarinidae, Fringillidae, Collidae	61	**Great**
Salvia sellowiana	Trochilidae	99	**Essential**
Kniphofia laxiflora	Nectarinidae	58	**Great**
Eriobotrya japonica	Pycnonotidae	50	**Great**
Parkia biglobosa	Pteropodidae	67	**Great**
Protea caffra	Nectariidae	0	**No Increase**
Protea caffra	Nectariidae	1	**Little**
Protea caffra	Nectariidae	9	**Little**
Protea dracomontana	Nectariidae	43	**Great**
Protea simplex	Nectariidae	0	**No Increase**
Protea welwitschii	Nectariidae	27	**Modest**
Aloe peglerae	Turdidae, Pycnonotidae, Fringillidae	87	**Great**
Encholirium vogelii	Phyllostomidae	16	**Modest**
Encholirium vogelii	Trochilidae	26	**Modest**
Aloe plicatilis	Nectarinidae	15	**Modest**
Alseuosmia macrophylla	Zosteropidae	82	**Great**
Alseuosmia macrophylla	Meliphagidae, Notiomystidae	92	**Essential**
C.hawaiiensis	Zosteropidae	57	**Great**
C.montis-loa	Zosteropidae	68	**Great**
Clermontia parviflora	Zosteropidae	62	**Great**
Leucospermum arenarium	Muridae	91	**Essential**
Echinocereus arizonicus	Trochilidae	36	**Modest**
Satyrium rhodanthum	Nectarinidae	82	**Great**
Satyrium rhodanthum	Nectarinidae	87	**Great**
Banksia prionotes	Meliphagidae	100	**Essential**
Protea roupelliae ssp. Roupelliae	Nectarinidae	85	**Great**
Ipomopsis aggregata	Trochilidae	23	**Modest**
Delphinium nelsoni	Trochilidae	38	**Modest**
Fouquieria splendens	Trochilidae	14	**Modest**
Fouquieria splendens	Trochilidae	24	**Modest**
Billbergia horrida	Phyllostomidae	0	**No Increase**
Billbergia horrida	Trochilidae	95	**Essential**
Protea foliosa	Muridae	99	**Essential**
Protea compacta	Nectariniidae	55	**Great**
Protea eximia	Nectariniidae	90	**Great**
Protea laurifolia	Nectariniidae	95	**Essential**
Protea longifolia	Nectariniidae	0	**No Increase**

Plant Species	Pollinator Family	% of increase in production	Impact by animal pollination
Protea magnifica	Nectariniidae	79	**Great**
Protea punctata	Nectariniidae	0	**No Increase**
Protea repens	Nectariniidae	35	**Modest**
Stenocereus queretaroensis var. Blanco	Trochilidae, Icteridae	66	**Great**
Stenocereus queretaroensis var. Blanco	Phyllostomidae	100	**Essential**
Stenocereus queretaroensis var. Tenamaste	Trochilidae, Icteridae	44	**Great**
Stenocereus queretaroensis var. Tenamaste	Phyllostomidae	100	**Essential**

Appendix C Supporting Information to Chapter 4

Appendix C.1 Invitation letter to pollination experts to join the online forum

Subject: Method for assessing pollination services at a site level: an online discussion group

Dear Dr. NAME

We invite you to join an online discussion group of pollination experts, working together to develop a simple method for assessing pollination services provided by protected sites. The discussion group is part of a collaborative project involving Southampton University, Cambridge University, RSPB, BirdLife International, Anglia Ruskin University and UNEP-WCMC.

The objective is to develop a tool for rapidly assessing the pollination services provided by sites of international importance for biodiversity conservation. This will help inform our understanding of the net benefits of conserving such sites. The aim is to provide a relatively straightforward set of guidelines which the site managers could use and which, in due course, would not require outside expertise for implementation.

The final output will form part of TESSA, the Toolkit for Ecosystem Services Site-Based Assessment (http://tessa.tools/). Currently, TESSA includes five classes of services only: global climate regulating services, water-related services, harvested wild goods cultivated goods and nature-based recreation. The toolkit is a product of a collaborative project that involved many ecosystem services experts, with an aim to design methods which enables stakeholders with limited capacity, time and resources to gather accessible, robust and locally relevant ecosystem services information. TESSA is already used by conservation professionals, project or site managers and technical field officers to inform site protection and management.

We will bring together researchers and conservation practitioners, with the single objective of designing some methods for rapid pollination service assessment. Already lined up to join the discussion group are Lynn Dicks (University ofCambridge; Coordinating Lead Author, IPBES Pollinators Assessment Report) and Dr. Simon Willcock (University of Southampton), who will provide us with valuable insights from their respective pollination research. Authorship on any outputs would, of course, be offered to participants.

We believe that you would bring valuable insight to the discussions and hope that you are able to join us for this exciting opportunity to develop these techniques, as well as to understand their potential limitations.

We very much hope you will be able to accept our invitation. Please reply to Fabrizia Ratto (fr2g13@soton.ac.uk) by 28 February. We will send you the joining instructions at the earliest opportunity. If you, however, cannot take part, we would appreciate that you recommend us other suitable potential participants for this online discussion.

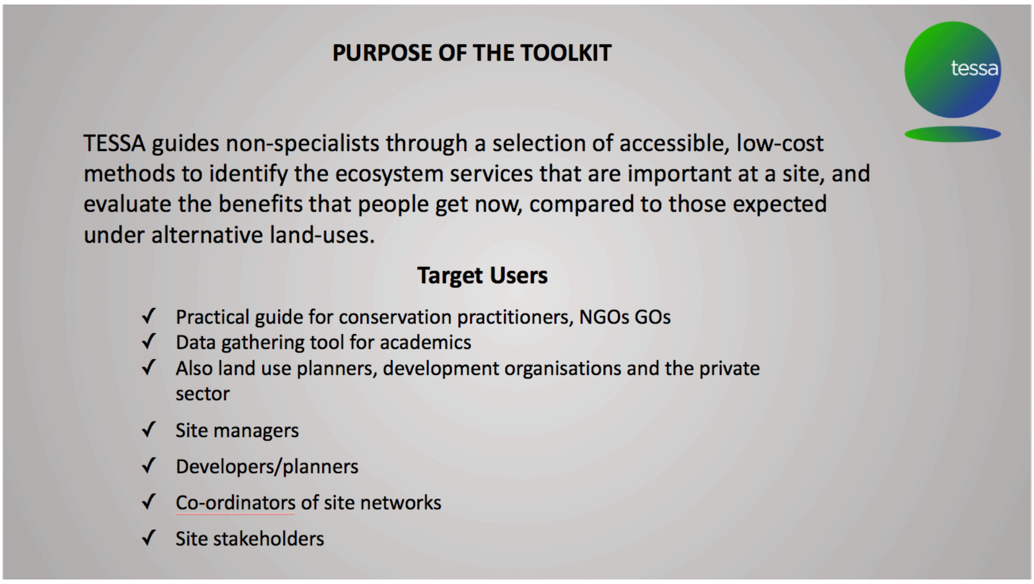
Yours Sincerely,

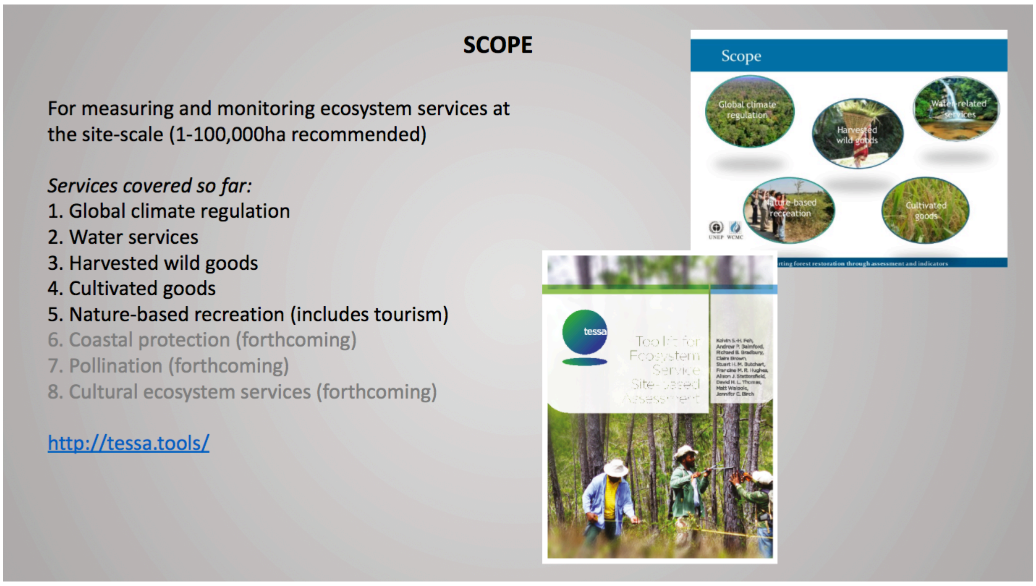
Fabrizia Ratto

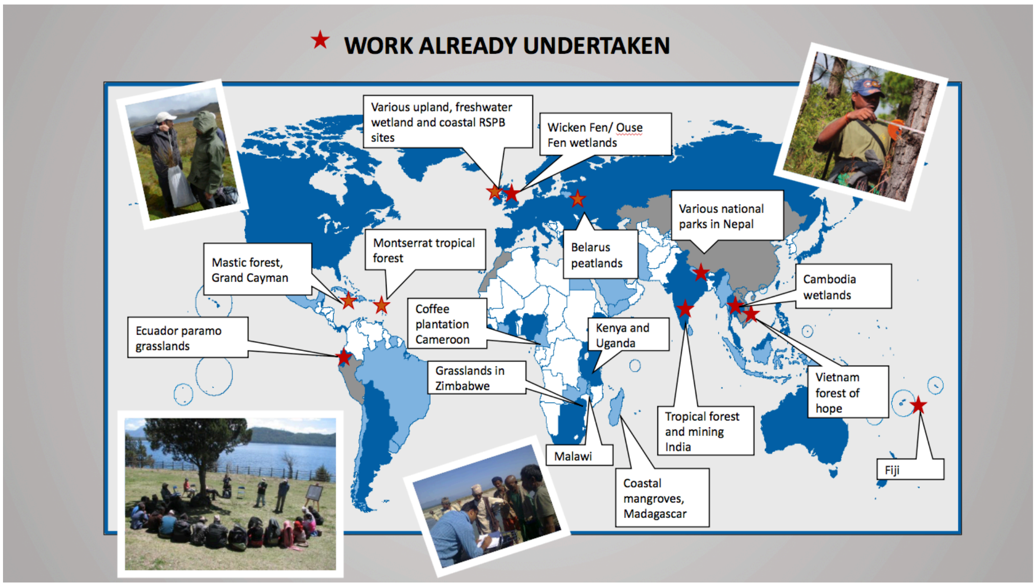
Appendix C.2 List of final participants to the online forum

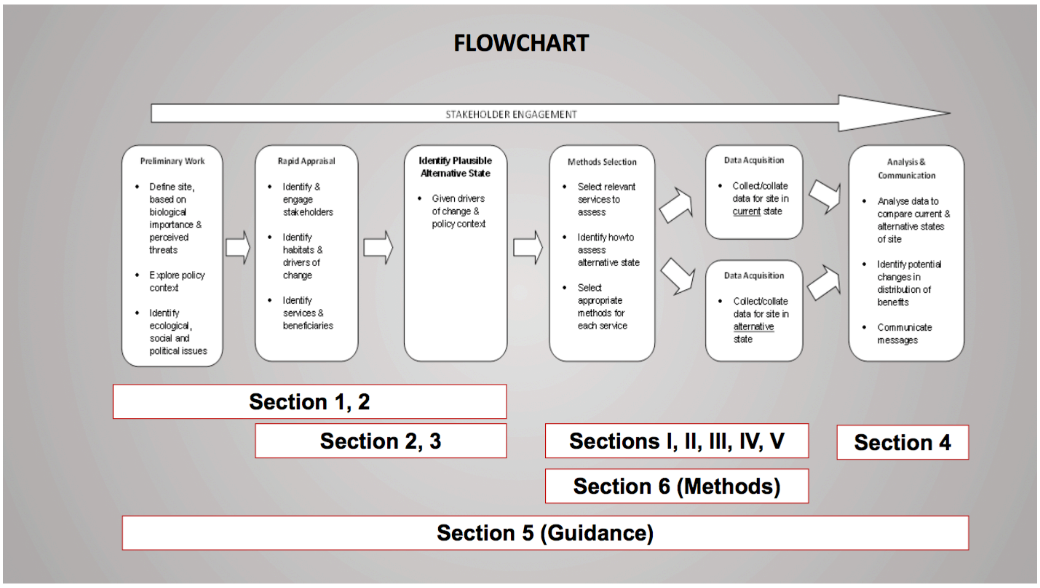
Title	First Name	Last Name	Country	Affiliation
Dr.	Erik	Andersson	Sweden	Stockholm University
Dr.	Jan	Axmacher	Germany	University College London
Dr.	Parthiba	Basu	India	University of Calcutta
Dr.	Berry	Brosi	United States of America	Emory University
Dr.	Madeleine	Chagnon	Belgium	Université du Québec
aDr.	Saul	Cunningham	Australia	Australian National University
Assoc. Prof.	G. Christopher	Cutler	Canada	Dalhousie University
Dr.	Lynn	Dicks	United Kingdom	University of East Anglia
Dr.	Mario	Espirito Santo	Brazil	Univerisdade Estadual de Montes Claros
Dr.	Úna	FitzPatrick	Ireland	National Biodiversity data Centre
Dr.	Nicolas	Gallai	France	ENFA
Prof.	David	Goulson	United Kingdom	Unievrsity of Sussex
Dr.	David	Inouye	United States of America	University of Maryland
Ms	Emma	Joslin	United Kingdom	University of Southampton
Dr.	Anikó	Kovács-Hostyánszki	Hungary	Centre for Ecological Research
Dr.	Gretchen	Lebuhn	United States of America	University of California
Prof. Dr.	Robert	Paxton	Germany	Martin Luther Universität
Dr.	Colleen	Seymour	South Africa	South African National Biodiversity Institute
Dr.	Adam	Van Bergen	United Kingdom	CEH
Dr.	Simon	Willcock	United Kingdom	University of Southampton

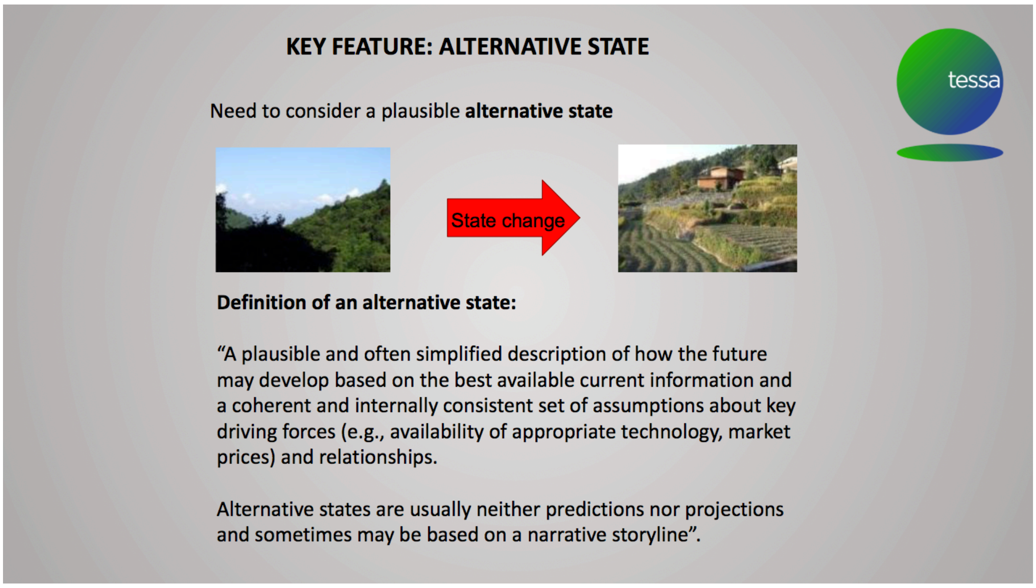
Appendix C.3 Overview of TESSA provided to forum participants in Step 1

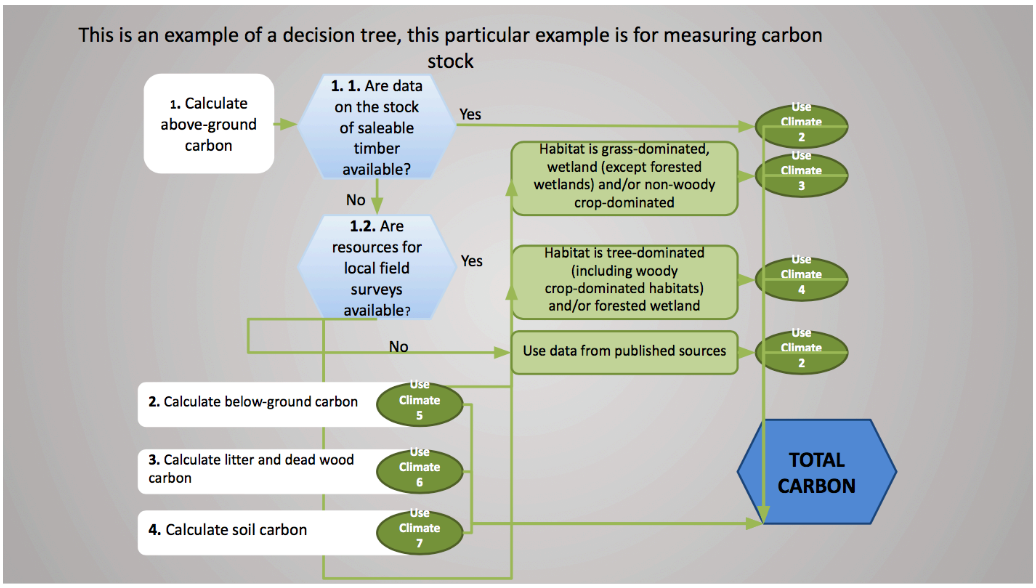


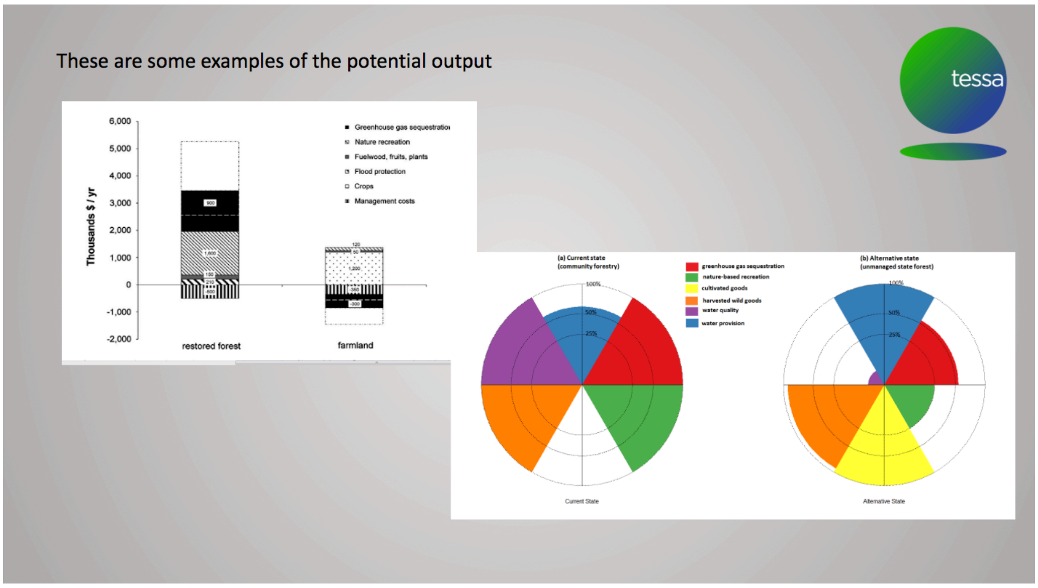



WORK ALREADY UNDERTAKEN
Various upland, freshwater wetland and coastal RSPB sites
Wicken Fen/ Ouse Fen wetlands
Various national parks in Nepal
Mastic forest, Grand Cayman
Montserrat tropical forest
Belarus peatlands
Cambodia wetlands
Ecuador paramo grasslands
Coffee plantation Cameroon
Kenya and Uganda
Grasslands in Zimbabwe
Vietnam forest of hope
Tropical forest and mining India
Malawi
Fiji
Coastal mangroves, Madagascar


FLOWCHART
STAKEHOLDER ENGAGEMENT
Preliminary Work
Define site, based on biological importance & perceived threats
Explore policy context
Identify ecological, social and political issues
Rapid Appraisal
Identify & engage stakeholders
Identify habitats & drivers of change
Identify services & beneficiaries
Identify Plausible Alternative State
Given drivers of change & policy context
Methods Selection
Select relevant services to assess
Identify how to assess alternative state
Select appropriate methods for each service
Data Acquisition
Collect/collate data for site in current state
Data Acquisition
Collect/collate data for site in alternative state
Analysis & Communication
Analyse data to compare current & alternative states of site
Identify potential changes in distribution of benefits
Communicate messages
Section 1, 2
Section 2, 3
Sections I, II, III, IV, V
Section 4
Section 6 (Methods)
Section 5 (Guidance)


KEY FEATURE: ALTERNATIVE STATE
tessa
Need to consider a plausible alternative state
State change
Definition of an alternative state:
“A plausible and often simplified description of how the future may develop based on the best available current information and a coherent and internally consistent set of assumptions about key driving forces (e.g., availability of appropriate technology, market prices) and relationships.
Alternative states are usually neither predictions nor projections and sometimes may be based on a narrative storyline”.





OUTPUT

Distribution of benefits

Ecosystem service	Local	National	Global
Change in annual flows if converted			
Greenhouse gas sequestration			– –
Water provision	=		
Water quality (water treatment cost)	–		
Harvested wild goods	– –		
Cultivated crops		+++	
Fodder for livestock		+++	
Nature-based recreation	– – –		
Change in stock if converted			
Carbon storage			– –
Wood products		+++	

	Location of beneficiaries		
Ecosystem service	Local	National	Global
Greenhouse gas sequestration			--
Water provision	=		
Water quality (water treatment cost)	-		
Harvested wild goods	--		
Cultivated crops		+++	
Fodder for livestock		+++	
Nature-based recreation	---		
Carbon storage			--
Wood products		+++	

LIMITATIONS

TESSA limitations to bear in mind

- Limited services included
- Does not include values relating to health
- Trade off between cost (time, resources), simplicity, utility vs. in-depth analysis and inclusion of complex factors
- May not provide the answers or the right kind of output you need to aid advocacy for conserving your site

SUMMARY OF PRINCIPLES

- Low cost
- Low expertise
- Site-based
- Measures actual values on the ground, not likely scenarios
- Participatory
- Comparison with alternative state
- Easy to use user manual

Appendix C.4 List of biometrics and economic metrics utilised for pollination measurement and valuation provided to forum participants

	A	B	C
1	**METRICS OF THE MEASUREMENT OF POLLINATION SERVICES**	**Suitable? YES/NO**	**Reason**
2			
3	**Biometrics**		
4	Measures of abundance/richness	NO	not easy, time consuming?
5	transect walk	maybe	
6	aerial nets	NO	require too much experise, time consuming?
7	Sweep netting	NO	require too much experise, time consuming?
8	beat trays	NO	require too much experise, time consuming?
9	pan trapping	NO	require too much experise, time consuming?
10	pitfall traps	NO	require too much experise, time consuming?
11	light traps	NO	require too much experise, time consuming?
12	emergence traps	NO	require too much experise, time consuming?
13	water and pan traps	NO	require too much experise, time consuming?
14	lres and baited traps	NO	require too much experise, time consuming?
15	quadrats	maybe	
16	mark-release-recapture	NO	require too much experise, time consuming?
17			
18	Flower visitation frequency	maybe	
19	Pollen deposition experiments	NO	too much expertise, equipment
20	Pollen load on animal (vertebrates)	NO	too much expertise, equipment
21	Distance from natural/semi-natural habitat	YES	
22			
23	exclusion experiments at increasing linear distance	maybe	
24			
25			
26			
27	**Economic metrics**		
28	Total annual production attribtuable to animal pollinaiton EVIP = D × Q × P,	YES	
29	Production function : Marginal increase in crop production (taking costs into account)	YES	
30	Replacement cost (managed bees/manual pollination)	YES	
31			
32	**Approaches**		
33	field techniques	YES	
34	lookup tables: main pollinators, foraging distances	YES	
35			
36	**habitat/landscape metrics**		
37	Foraging resources	YES	
38	nesting resources	maybe	
39	foraging distance	YES	
40			
41			
42			

Appendix C.5 Workshop Programme

Workshop in Cambridge on 19-20 September
This document contains information regarding the workshop programme.

18 Sep
Check in at Arundel hotel for those arriving on the Sunday

DAY 1 (19 Sep)
0930 Registration and Coffee
1000 Plenary – An introduction to the project
1030 Plenary – Setting the context
1055 Coffee
1110 Open forum
1200 Introduction to breakout session 1
1215 Lunch
1255 Breakout session 1
1400 Feedback
1445 Introduction to breakout session 2
1500 Coffee
1525 Breakout session session 2
1615 Feedback
1700 Close
1800 Hotel registration
1930 Dinner at Don Pasquale

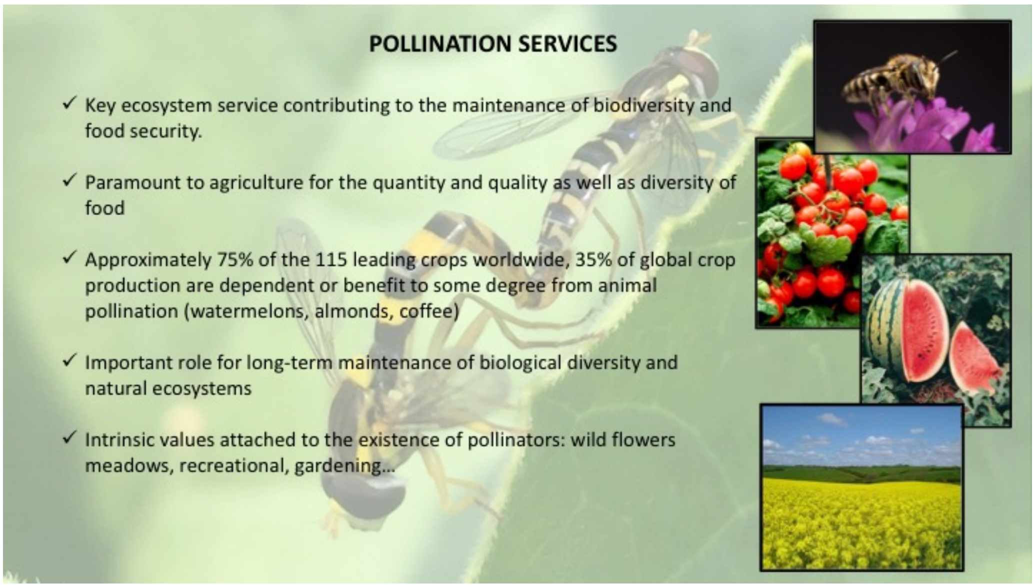
DAY 2 (20 Sep)

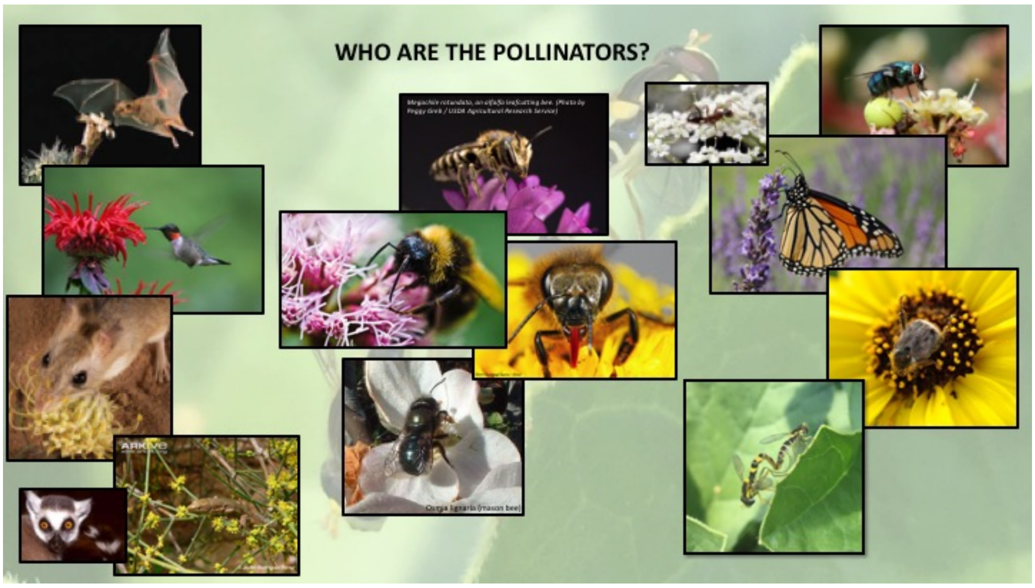
0915 Introduction to breakout session 3
0930 Breakout session 3 – Writing-up
1215 Lunch
1300 Feedback
1430 Coffee
1500 Introduction to Plenary session/group discussion?
1510 Group Discussion/Plenary session
1600 Workshop concludes

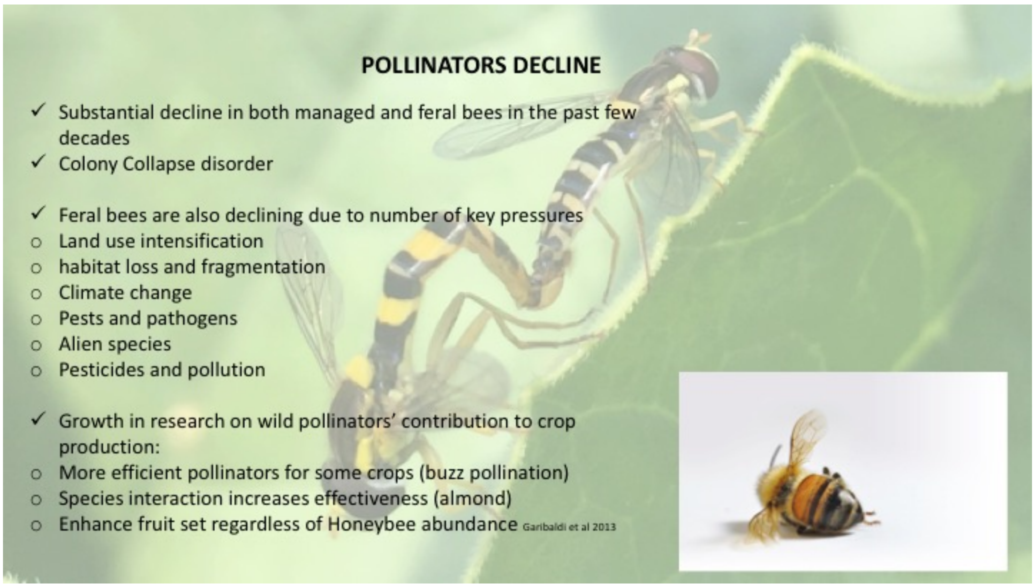
Appendix C.6 Structure of the pollination workshop

Workshop activities	Details
DAY 1	
Plenary session 1	Presentations by Kelvin Peh "An introduction to the project".
Plenary session 2	Presentation by Fabrizia Ratto - Setting the context-.
Open Forum	Open discussion to answers the following questions: ✓ What do we measure? ✓ Are the aims of the project clear? ✓ How feasible is the project? ✓ Any missing points?
Breakout session 1	✓ Catalogue all the possible metrics and approaches: • Biometrics • Habitat and landscape metrics • Economic ✓ The criteria for suitability: • Local relevance • Requirements for expertise • Prior data • Time and costs ✓ Potential Alternative state
Breakout session 2	✓ Structure the up-front decision tree • Note this has to be accessible, fit for purpose for valuing, monitoring etc. • More than one method? The decision tree may lead to different protocols ✓ Discuss approaches and key issues • Use existing toolkit as template ✓ Resources needed • Any lookup tables, existing databases
DAY 2	
Plenary Session 3	Structuring the initial decision trees
Breakout session 3	Structuring the three step-by-step methods
Plenary Session 4	Group discussion on the next steps: ✓ Potential sites for piloting the pollination protocol in 2017 ✓ Measurement of synergies across services in the toolkit (i.e. with cultivated goods) ✓ Potential double counting ✓ Uncertainties ✓ Next step: publications in which journal?

Appendix C.7 PowerPoint presentation to introduce the workshop participants to the broad context of pollination services, pollinator decline and the need for a rapid assessment







ECONOMIC VALUATIONS

- ✓ Various attempts to calculate value of pollination services in monetary terms
- ✓ Global, national and local scale
- ✓ Economic value of this benefit approximately €153 billion per annum globally, £400 million UK
- ✓ Most common methods:
- Production function W= $S^*\Delta q^*(p\text{-}c)$
- Replacement cost

Why economic valuation?

- ✓ Economic valuation helps quantifying the consequences of pollinators decline on human wellbeing
- ✓ Provides a rationale for pollinators management
- ✓ Raise interest amongst policy makers

POLLINATION SERVICES RAPID ASSESSMENT

Develop a rapid, inexpensive and accessible tool for the assessment of pollination services provided by sites of importance for biodiversity conservation

- ✓ Insect and non-insect pollinators
- ✓ Rapid, relatively simple whilst scientifically robust
- ✓ In line with the philosophy of TESSA

Currently available tools

Existing tools to measure pollination services (i.e. InVEST)

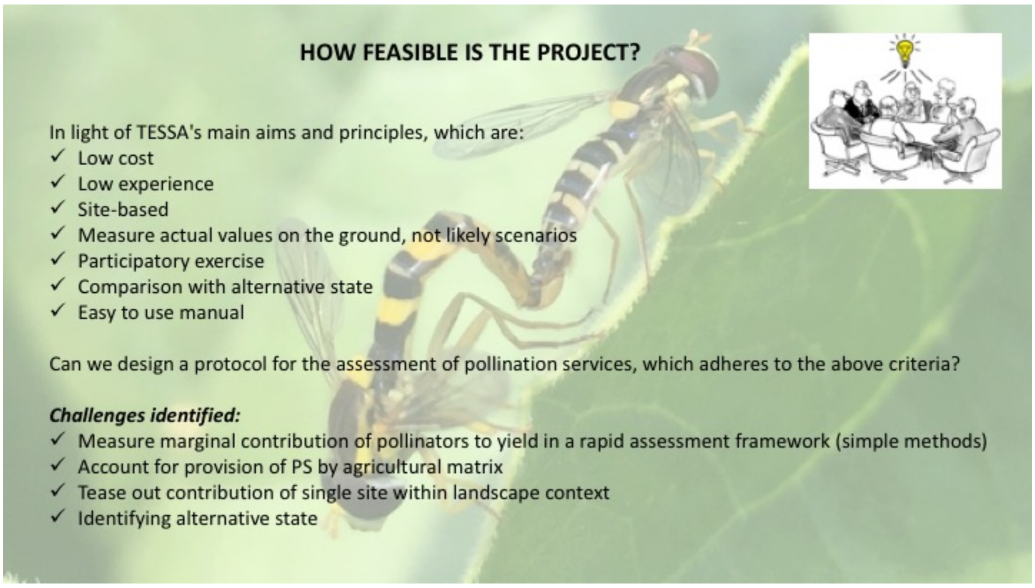
- landscape or global scale scope
- high data demand
- high technical and IT skills

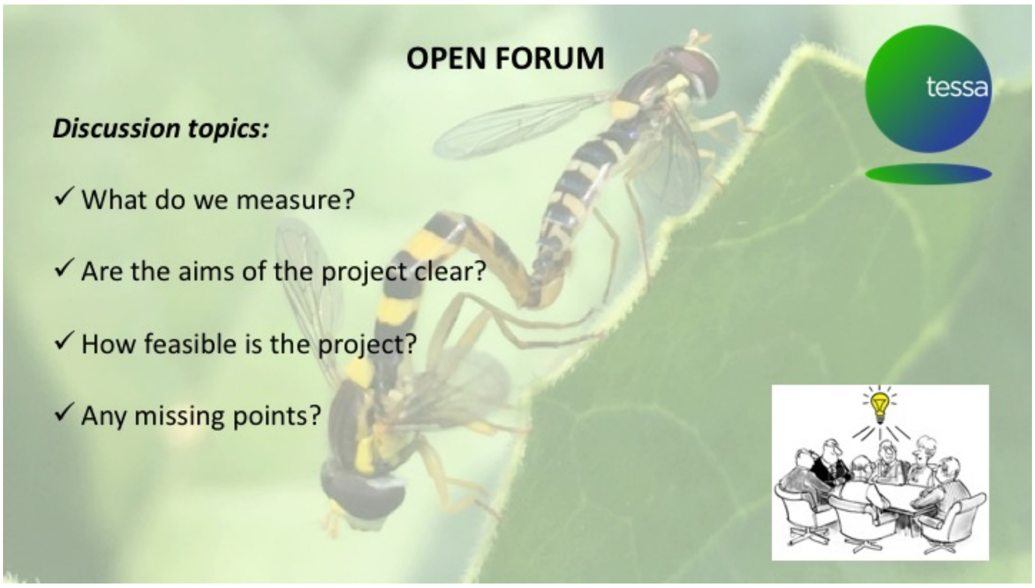
WHAT DO WE MEASURE?

Measure pollination services provided by sites of importance for biodiversity conservation

Contribution of pollination to human well-being:

- ✓ Contribution to crop yield quantity and quality
- ✓ Ensure variety of foods and provision of micronutrients and vitamins essential for human health
- ✓ Contribution to long-term maintenance of biological diversity and natural ecosystems
- ✓ Direct benefit attached to the existence, abundance and diversity of pollinators
- ✓ Indirect value benefit people derive from the functions carried out by pollinators: growing fruits and vegetables, enjoying wildflower meadows (enjoyment of effect pollinators have on the abundance of plants and flowers)


HOW FEASIBLE IS THE PROJECT?
In light of TESSA's main aims and principles, which are:
✓ Low cost
✓ Low experience
✓ Site-based
✓ Measure actual values on the ground, not likely scenarios
✓ Participatory exercise
✓ Comparison with alternative state
✓ Easy to use manual
Can we design a protocol for the assessment of pollination services, which adheres to the above criteria?
Challenges identified:
✓ Measure marginal contribution of pollinators to yield in a rapid assessment framework (simple methods)
✓ Account for provision of PS by agricultural matrix
✓ Tease out contribution of single site within landscape context
✓ Identifying alternative state


OPEN FORUM
tessa
Discussion topics:
✓ What do we measure?
✓ Are the aims of the project clear?
✓ How feasible is the project?
✓ Any missing points?

Appendix C.8 Guidance 5 "Uncertainty and error" extracted from TESSA V2.0

Guidance 5 uncertainty and error

Uncertainty and error

Estimates of ecosystem service values or quantities provided by a site (in its current or alternative state) derived from the methods presented in this toolkit will have varying degrees of uncertainty associated with them. It is important to understand, quantify if possible, and communicate this uncertainty and its implications, to assist decision makers in making the most informed decisions.

In general terms, such uncertainty derives from:

- **Measurement error:** observers may make errors when estimating and recording parameters such as tree diameter, river flow, counts of numbers of tourists, etc. For data derived from questionnaires, measurement errors may result from respondents' inaccurate estimates of parameters such as volumes or values of harvested goods.
- **Sampling error:** when data are taken from sample measurements, these may not be representative of the entire situation. For example, the trees measured at a sample station may be larger or smaller than the average across the site. Larger numbers of samples (or well-stratified samples) are likely to be less biased. A special case of sampling error relevant to the toolkit arises when data are derived from a look-up table or model. Such

Guidance 5 uncertainty and error

tessa

values may not be representative of the site if the table or model is based on too few data, or inadequately stratified data.

For estimates derived from models, errors may also arise if the model uses inappropriate parameters for the situation at an individual site, i.e., if it doesn't contain the most relevant factors.

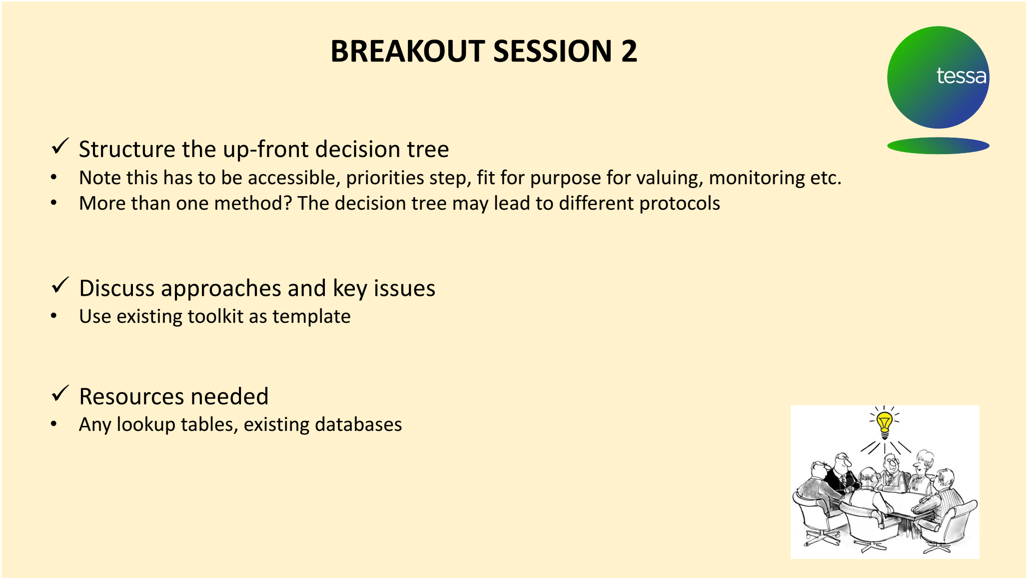
Ideally, the toolkit user should quantify the uncertainty associated with each parameter measured or calculated using the toolkit methods. Where feasible, value estimates can be presented as minimum to maximum ranges, for example reflecting uncertainty about the price of carbon. If more than one parameter contributes to a service (e.g. above and below-ground carbon, and soil carbon, all contribute to total carbon stock) then their uncertainties will be cumulative. Ideally, these uncertainties should be combined quantitatively to derive confidence intervals for the overall estimate of the ecosystem service. However, methods for doing this are computationally difficult.

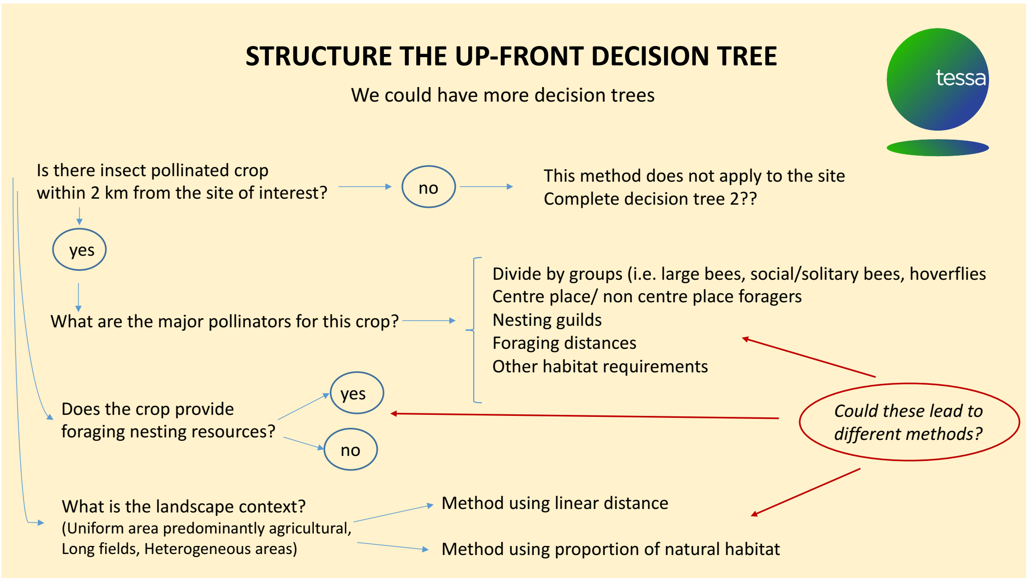
More simply, the toolkit user can categorise confidence as High, Medium or Low using the definitions in the table below. The categorisation needs to consider, for example, the representativeness of any sampled data (considering the number of samples taken relative to the size and heterogeneity of the site, and whether look-up tables were used or primary data were collected). Applying the High/Medium/Low ratings requires the user to consider the relative contribution of different parameter estimates to the overall service estimate, and the uncertainty associated with each one.

Guidance 5 uncertainty and error

Level of confidence	Description
High	Estimate is based on (a) existing data that are recently derived from the specific site; and/or (b) data from field measurements that use protocols provided in this toolkit (or more sophisticated approaches), with large and unbiased sample sizes; and/or (c) peer-reviewed published data derived recently from similar habitats near the site; and for all three data sources it is based on sound methods in terms of accuracy and precision level, judged in relation to site boundary definition, area stratification, type, number and distribution of measurement plots, and measurement frequency.
Medium	Estimate is based on (a) existing data that are recently derived from reasonable sampling effort and that are treated critically with their methodological limitations acknowledged; and/or (b) data from field measurements that use protocols provided in this toolkit but are derived from relatively low sample sizes and precision levels, or are subject to minor measurement and sampling errors; and/or (c) published data derived from similar habitats within your site's climate domain and region. Also applies to estimates based on data from look-up tables that use region-specific sources based on a compilation of data sources that is reasonably complete. Certain types of estimate based on modelling tools would also fall into this category.
Low	Estimate is based on (a) existing data that are derived from unknown methodology or poor sampling techniques (e.g. data are poorly representative, inadequately sampled, inappropriately stratified); and/or (b) data derived from an area that may not be a good surrogate for the site (e.g. moderately different habitat, very distant site, very old data) or data that are highly uncertain (e.g. substantial range between upper and lower confidence limits); and/or the estimate is based on look-up tables that use habitat-related sources not specific to the region and/or on a sparse compilation of data sources.

Appendix C.9 Slides with summarised information and initial ideas on decision trees and resources requirements provided for Breakout session 2 of the expert workshop





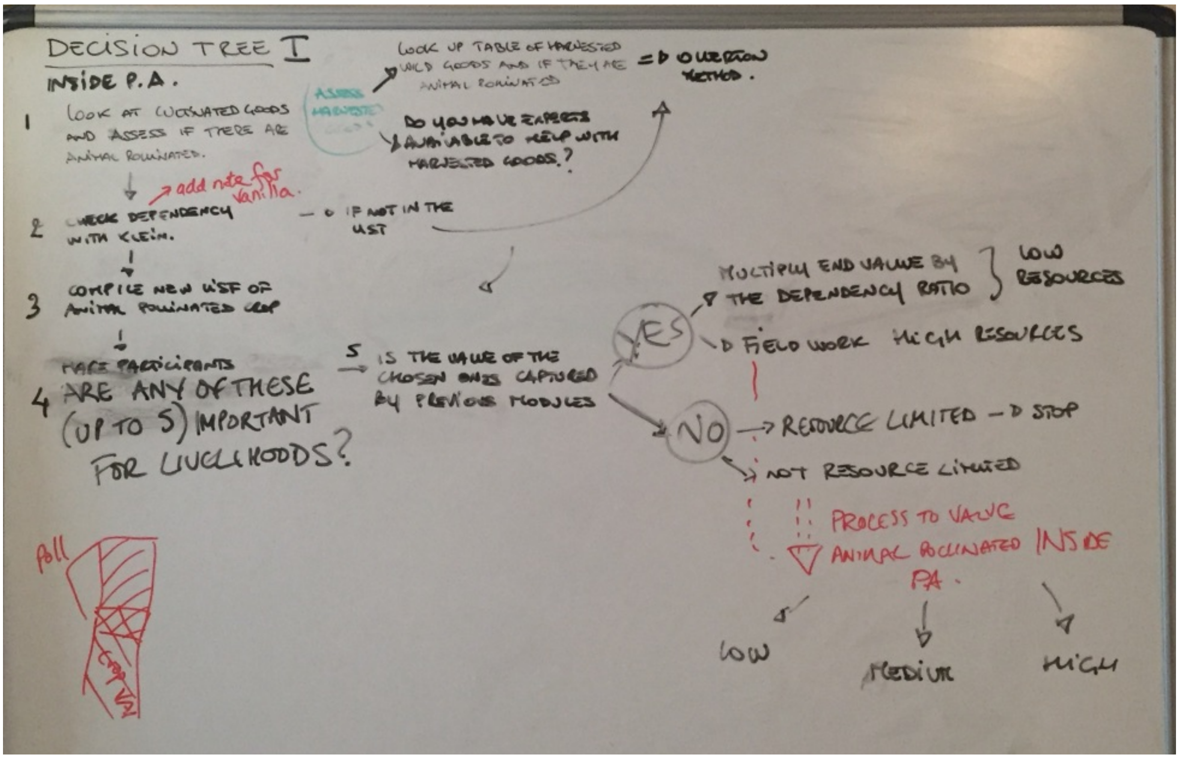
DISCUSS APPROACHES AND KEY ISSUES

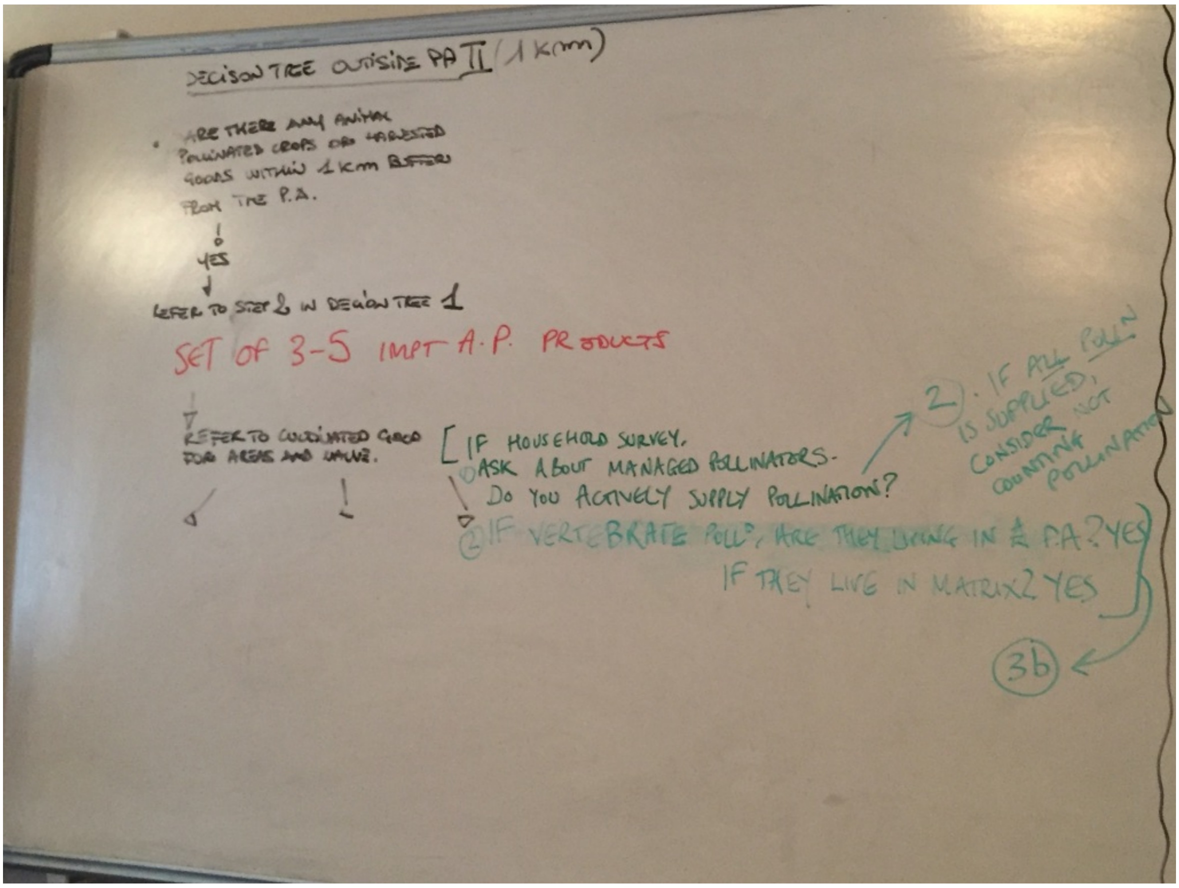
- ✓ More appropriate approach : linear distance or proportion of natural habitat?
- ✓ Measure marginal contribution of pollinators to yield in a rapid assessment framework (simple methods)
- ✓ Account for provision of PS by agricultural matrix
- ✓ Tease out contribution of single site within landscape context
- ✓ Identifying alternative state
- ✓ Identify use and dependence of different pollinators on the natural habitat within the site
- ✓ Partitioning managed from wild pollinators

RESOURCES NEEDED

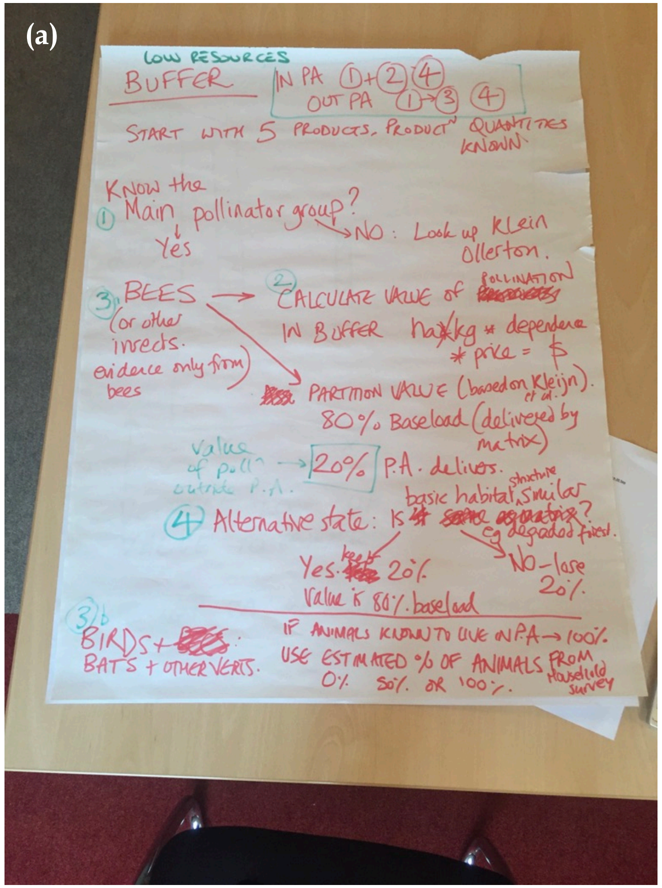
- ✓ Pollinators ID resources (protocol to be used everywhere..)
- ✓ Major pollinators for each crop
- ✓ Crop dependency tables (Klein et al 2007 + update from literature)
- ✓ Foraging distances
- ✓ Nesting requirements
- ✓ Field techniques:
  - Defra National Pollinator and Pollination Monitoring Framework (NPPMF)
  - FAO Pollination deficit protocol
  - Potts et al 2007 for nesting resources

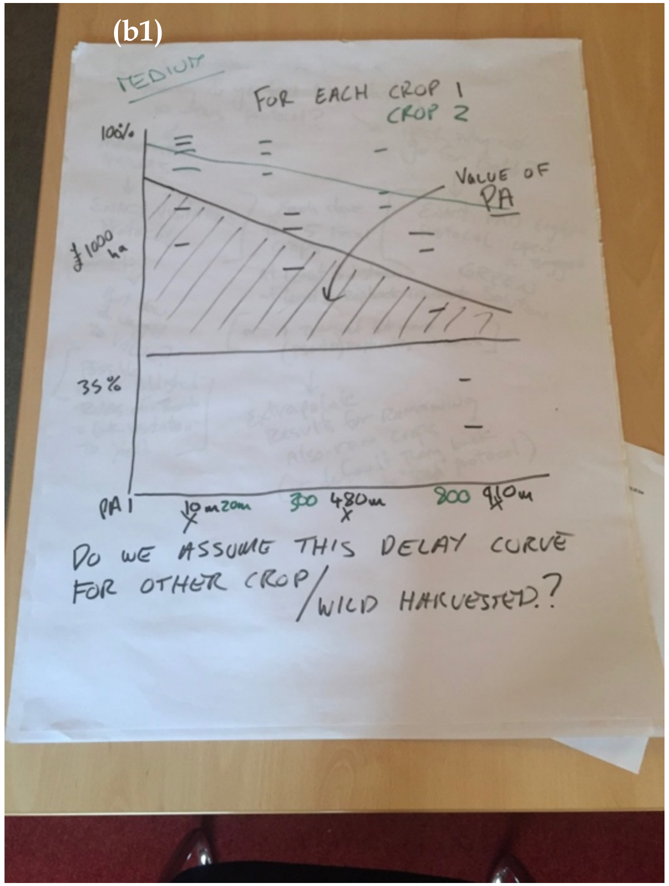
Appendix C.10 Outline of decision trees prepared for Plenary session 3 of the expert workshop

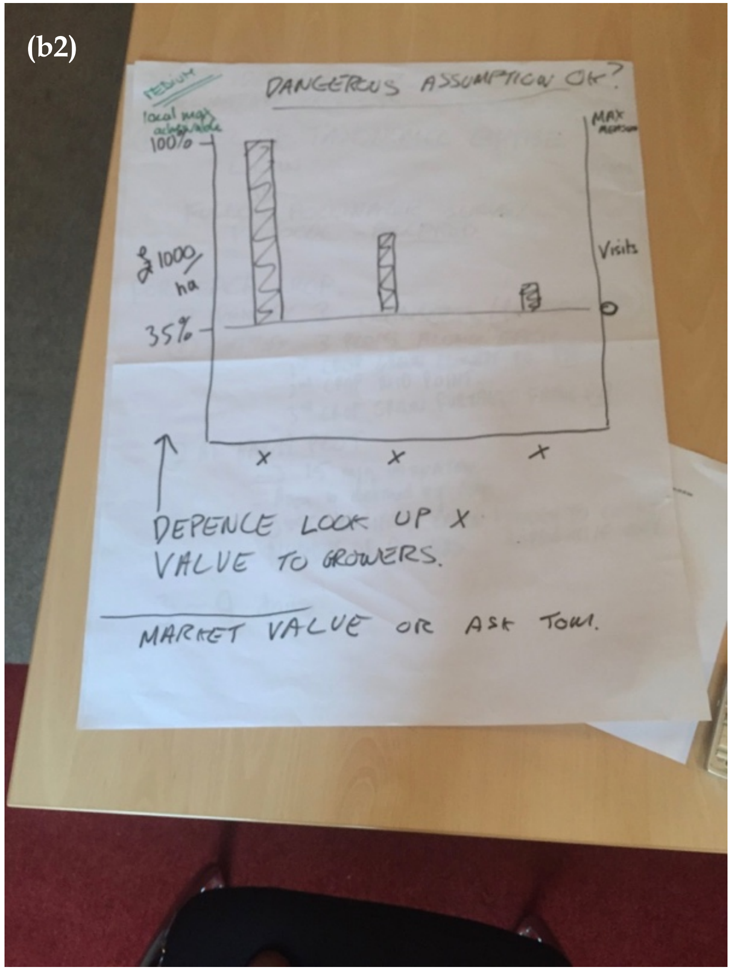


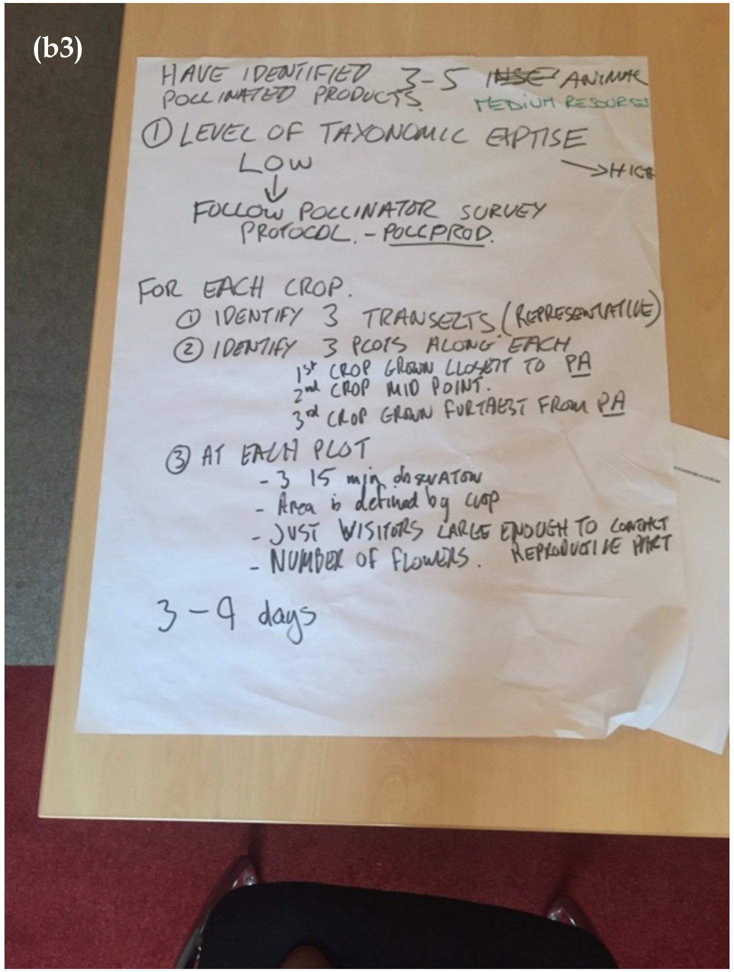


Appendix C.11 Drafts of methods produced during the expert workshop. (a) Group 1: Red standard methods ; (b1/b2/b3) Group 2: Amber standard methods






(b2)
MEDIUM
DANGEROUS ASSUMPTION OK?
local max achievable
100%
MAX
£1000/ha
Visits
35%
0
x
x
x
DEPENCE LOOK UP X
VALUE TO GROWERS.
MARKET VALUE OR ASK TOM.


(b3)
HAVE IDENTIFIED 3-5 ANIMAL POLLINATED PRODUCTS.
MEDIUM RESOURCES
① LEVEL OF TAXONOMIC EXPTISE
LOW
HIGH
FOLLOW POLLINATOR SURVEY PROTOCOL. - POLLPROD.
FOR EACH CROP.
① IDENTIFY 3 TRANSECTS (REPRESENTATIVE)
② IDENTIFY 3 PLOTS ALONG EACH
1st CROP GROWN CLOSEST TO PA
2nd CROP MID POINT.
3rd CROP GROWN FURTHEST FROM PA
③ AT EACH PLOT
- 3 15 min observaton
- Area is defined by crop
- JUST VISITORS LARGE ENOUGH TO CONTACT REPRODUCTIVE PART
- NUMBER OF FLOWERS.
3-4 days

Appendix C.12 Drafts of methods produced during the expert workshop

Group 3: Green standard methods

Direct value of ES – so not inclusive of tree harvesting for wood.

Green standard methodology: measure of pollination dependency inside the protected area.

Equipment: 1mm mesh bags (mosquito netting is ideal, size of mesh bags will be dependent on predicted size of resultant fruit), two colours of thread.

For each of the key animal pollinator plants identified by the stakeholder group select 15 distinct plants prior to flowering. From each plant select two floral units at a similar pre-flowering stage. These floral units will form your two treatment groups (i.e. Group 1: Bagged, Group 2: Unbagged). For plants with only single floral units two adjacent plants should be selected which are similar in form (e.g. height, number of leaves) Randomly select one of these floral units and carefully bag the floral unit to exclude pollinators with the other unit remaining unbagged. Ensure that the bagged and unbagged floral units are approximately consistent with respect to the number of flowers. Both units should be clearly marked with coloured thread indicating treatment. Bags should remain in place until harvest. At or before harvest quantify the yield for bagged and unbagged treatment groups. For each tree, determine the yield of bagged divided by the yield of unbagged. This resultant value (which should lie between zero and one) estimates the proportion of yield that is due to insect pollination (i.e. pollination dependence). The final value is calculated as the average of these proportions. Prior to calculating this average all plants where treatments have been interfered with (e.g. pests or diseases have impacted severely on yield) should be excluded.

- Need to create an example datasheet and include a worked example.
- Monitor tree: To facilitate identification of key sampling times (e.g. prior to flowering and to harvest).

Estimating pollination services delivered by the reserve

Order the key animal pollinated plant species identified to be growing in the 2km buffers surrounding the protected area. The number of key plants selected to investigate further should be based on the resources available.

Divide the buffer surrounding the reserve into three distinct zones based on distance from the reserve. OR USE THE SAME DIVISION OF POLLINATOR COUNT PROTOCOL – (i.e. rather than create these zones based on actual distance they are divide based on where the crop is as closest, furthest away and mid-point).

- Close (i.e. within a distance of 50 m)
- Medium (i.e. at a distance of 20 to 500 m)
- Distance (i.e. at a distance of over 1 km)

Where possible for each key plant species selected for more detailed examination three distinct transects should be established in each of these three distinct buffer zones where feasible. Transects should be established at a minimum distance of 200m? from When selecting each transect locations care should be taken to ensure that large area of similar semi-natural habitat to the protected area within the vicinity of the transect. At each transect five plants should be select. On these five plants the protocol on determining pollination dependence identified above should be implemented.

Assumption is that variation between plants is greater than influence of difference in resource allocation that could happen within a plant.

Appendix C.13 Lookup table 1 in TESSA V2.0 providing a list of dependence ratios collated from existing published literature

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Vegetable crops								
Abelmoschus esculentus	Okra, Gumbo	**modest**	**0.25**	honey bees (Apiscerana), solitary bees (Halictus spp.)	passive self-pollination	hermaphrodite, self-compatible	in Crane 1991; Hamon 1991; in Free 1993	In Klein et al 2007
Cajanus cajan	Pigeon pea, Cajan pea, Congo bean	**little**	**0.05**	honey bees, solitary bees (Megachile sp., Xylocopa sp., Chalicodoma sp.)	passive self-pollination	hermaphrodite, self-compatible	James et al. 1989; Grewal et al. 1990; in Free 1993; in Heard 1999	In Klein et al 2007
Canavalia ensiformis, C. gladiata, C. marittima, C. microcarpa, C. virosa		**modest**	**0.25**	solitary bees (Xylocopa confusa)	passive self-pollination, wind pollination	hermaphrodite, self-compatible	in Free 1993; Gross 1993 for C. rosea	In Klein et al 2007
Capsicum annuum, C. frutescens	Chile pepper, Red pepper, Bell pepper, Green pepper	**little**	**0.05**	honey bees, stinglee bees (Melipona favosa, M. subnitida), bumble bees (Bombus impatiens, B. terrestris), solitary bees (Osmia cornifrons, Megachile rotundata), hover flies (Eristalis tenax)	wind- or insect-mediated shaking necessary for self-pollination, passive self-pollination	hermaphrodite, self-compatible	Jarlan et al. 1997a,b; Meisels & Chiasson 1997; Raw 2000; Dag & Kammer 2001; Ercan & Onus 2003; De Oliveira Cruz et al. 2005; in Slaa et al. 2006 pollinators important in greenhouses to increase fruit weight, but less in open fields	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Chenopodium quinoa	Quinoa	**no increase**	**0**	flies	passive self-pollination, wind pollination	hermaphrodite, andro-monoecious	Simmonds 1965; Simmonds 1971	In Klein et al 2007
Cicer arietinum	Chickpea, Gram, Garbanzo bean	**no increase**	**0**	honey bees, solitary bees	passive self-pollination	hermaphrodite, self-compatible	in Free 1993; Abbo et al. 2003	In Klein et al 2007
Citrullus lanatus	watermelon	**essential**	**0.95**	honey bees (Apis cerana), bumble bees (Bombus californicus, B. impatiens, B. vosnesenskii) solitary bees (Halictus tripartitus, Peponapis pruinosa), species effective in pollen deposition are listed in Kremen et al. 2002		mostly monoecious, self-compatible	in Free 1993; Stanghellini et al. 1997; Stanghellini et al. 1998; in Delaplane & Mayer 2000; Kremen et al. 2002; Stanghellini et al. 2002; Kremen et al. 2004; Njoroge et al. 2004	In Klein et al 2007
Cucumis melo	Cantaloupe, Melon	**essential**	**0.95**	honey bees (Apis mellifera), bumble bees Bombus sp., solitary bees (Ceratina sp.)	passive self-pollination possible only in andro-monoecious varieties	monoecious or andro-monoecious, self-compatible	in Free 1993; Norden 1985; Kato & Nogueira-Couto 2002; Valantin-Morison et al. 2006	In Klein et al 2007
Cucumis sativus	Cucumber, Gherkin	**great**	**0.65**	honey bees (Apis mellifera), bumble bees (Bombus impatiens), solitary bees (Melissodes sp.)	passive self-pollination possible only in andro-	monoecious or andro-monoecious, self-compatible	in Free 1993; Stanghellini et al. 1997; Gingras et al. 1999; Stanghellini et al. 2002; in Slaa et al. 2006	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
					monoecious varieties		parthenocarpic gynoecious varieties of slicing cucumber grown in greenhouses for which insect pollinators can be detrimental to fruit quality	
Cucurbita maxima, C. mixta, C. moschata, C. pepo	Pumpkin, Squash, Gourd, Marrow, Zucchini	**essential**	**0.95**	honey bees (Apis cerana, A. mellifera), stingless bees (Scaptotrigona depilis), solitary bees, (Pithitis smaragdula, Peponapis limitaris, P. pruinosa, Xenoglossa sp., Ceratina sp.)		monoecious, self-compatible	Norden 1985; in Free 1993; Nepi & Paccini 1993; in Delaplane & Mayer 2000; Canto-Aguilar & Parra-Tabla 2000; Ashworth & Galetto 2001; Cardoso 2003 (higher germination rate and vigor with natural pollination compared to hand pollination); Fuchs & Müller 2004	In Klein et al 2007
Cyamopsis tetragonoloba	Guar bean, Goa bean	**little**	**0.05**	honey bee	passive self-pollination	hermaphrodite	in Free 1993	In Klein et al 2007
Dolichos biflorus, D. lablab	Hyacinth bean, Horse- gram, Lablab	**modest**	**0.25**	honey bee	passive self-pollination	hermaphrodite	Garcia Neto et al. 1988; in Free 1993	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Fagopyrum esculentum	Buckwheat	**great**	**0.65**	honey bee		hermaphrodite, self-incompatible (distylous)	no in Free 1993; Björkman 1995a,b; Campbell 1997; Goodman et al. 2001	In Klein et al 2007
Lens esculenta	Lentils	**no increase**	**0**	bees	passive self-pollination	hermaphrodite, self-compatible	Ladizinsky et al. 1984; Erskine & Muehlbauer 1991; in Free 1993; Richards 2001	In Klein et al 2007
Lycopersicon esculentum	Tomato	**little**	**0.05**	honey bees (Apis mellifera), stingless bees (Melipona quadrifasciata, Nannotrigona perliampoides), bumble bees (Bombus hypnorum, B. (Thoraco- bombus) pascuorum, B. sonorus, B. terrestris, B. vosnesenskii), solitary bees (Amegilla chlorocyanea, A. (Zonamegilla) holmesi, Xylocopa ssp.)	wind- or insect-mediated shaking necessary for self-pollination, parthenocarpy	hermaphrodite, self-compatible, buzz-pollination	in Free 1993; du Toit 1994; Asada & Ono 1996; in Delaplane & Mayer 2000; Hogendoorn et al. 2000; in Westerkamp & Gottsberger 2000; Morandin et al. 2001; Cauich et al. 2004; Higo et al. 2004; Greenleaf 2005; Bell et al. 2006; Hagendoorn et al. 2006; Greenleaf & Kremen 2006a; in Slaa et al. 2006	In Klein et al 2007
Mucuna pruriens (syn. Stizolobium spp.)	Velvet bean	**little**	**0.05**	honey bees (Apis dorsata, Apis florea), bumble bees, thrips	passive self-pollination	hermaphrodite, self-compatible	Du Toit 1990; in Crane 1991; in Roubik 1995; in Carrek & Williams 1998; Ibarra-Perez et al. 1999	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Phaseolus spp. (P. vulgaris, P. lunatus, P. angularis, P. aureus, P. mungo, P. coccineus, P. calcaratus, P. aconitifolius, P. acutifolius	Kidney bean, Haricot bean, Lima bean, Adzuki bean, Mungo bean, String bean	**little**	**0.05**	honey bees (Apis dorsata, Apis florea), bumble bees, thrips	passive self-pollination	hermaphrodite, self-compatible	Du Toit 1990; in Crane 1991; in Roubik 1995; in Carrek & Williams 1998; Ibarra-Perez et al. 1999	In Klein et al 2007
Pisum sativum, P. arvense	Garden pea, Field pea	**no increase**	**0**	bumble bees, solitary bees (Eucera dalmatica, Xylocopa ssp.)	passive self-pollination	hermaphrodite, self-compatible	Gritton 1980; in Free 1993, Franklin et al. 2000; Mcphee 2003	In Klein et al 2007
Psophocarpus tetragonolobus	Winged bean, Goa bean	**unknown**		solitary bees (Xylocopa confusa)	passive self-pollination	hermaphrodite, dichogamous, self-incompatible	in Free 1993	In Klein et al 2007
Solanum melongena	Eggplant, Aubergine	**modest**	**0.25**	wind- or insect- mediated shaking necessary for self-pollination,passive self-pollination	buzz-pollination	hermaphrodite, self-compatible,	in Free 1993	In Klein et al 2007
Vigna unguiculata	Cowpea, Blackeye pea, Blackeye bean	**little**	**0.05**	honey bees, bumble bees	passive self-pollination	hermaphrodite, self-compatible	Vaz et al. 1998	In Klein et al 2007
Vigna subterranea (syn.Voandzeia subterranea)	Bambara beans, Bambara	**little(indirect)**		ants (indirect effect on fruit set), bees mentioned in	passive self-pollination	hermaphrodite, self-compatible	in Free 1993,	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
	groundnuts, Earth pea			Roubik (1995, no source given)				
Fruit crops								In Klein et al 2007
Actinidia deliciosa	Kiwifruit	**essential**	**0.95**	honey bees (Apis mellifera),bumble bees (Bombus terrestris), solitary bees	wind pollinated but few, small fruits of low quality	dioecious	Costa et al. 1993; in Free 1993; Vaissière et al. 1996; Awasthi & Kumar 1997; Gonzalez et al. 1998; in Delaplane & Mayer 2000; Howpage et al. 2001	In Klein et al 2007
Annona squamosa	Atemoya,Cherimoya,Custard apple	**essential**	**0.95**	nitidulid beetles (Carpophilus hemipterus, Carpophilus mutilatus)	passive selfpollination, hand pollination	hermaphrodite	Galon et al. 1982; Gazit et al. 1982; George et al. 1989; George et al. 1992; Free 1993; Nadel & Pena 1994; Peña et al. 1999; Kill & da Costa 2003; Blanche & Cunningham 2005	In Klein et al 2007
Arbutus unedo	Tree-strawberry	**modest(indirect)**	**0.25**	honey bees (Apis mellifera), bumble bees (Bombus terrestris)	wind-mediated shaking can lead to self-pollination	hermaphrodite, self-compatible	Sealy 1949; Hagerup 1957; Herrera et al. 1984; Rasmont et al. 2005	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Artocarpus altilis (syns. A. incisus, A.incircus, A.incisa, A.communis)	Breadfruit	**unknown**		stingless bees	parthenocarpy in seedless varieties, wind pollination	monoecious, dichogamous	Morton 1987; Hasan & Razak 1992; in Free 1993; Ragone 1997; in Heard 1999	In Klein et al 2007
Artocarpus heterophyllus (syns. A. integrifolius, A. integrifolia)	jackfruit	**unknown**		stingless bees, flies and moths as flower visitors	parthenocarpy, wind pollination	monoecious, dichogamous	Moncur 1985; Morton 1987; in Heard 1999; Sakai & Kato 2000; Devy & Davidar 2003 insect-assisted wind pollination hypothesized by Brantjes 1981	In Klein et al 2007
Asimina triloba	Pawpaw, Indiana banana	**essential**	**0.95**	carrion flies and dung flies		hermaphrodite, self-incompatible	Willson & Schemske 1980; Gottsberger 1999; Pomper et al. 2003	In Klein et al 2007
Averrhoa carambola	Carambola, Starfruit	**great**	**0.65**	honey bees (Apis cerana), stingless bees (Trigona thoracica)	passive self-pollination	hermaphrodite, distylous, selfincompatible	in Free 1993; in Heard 1999; in Richards 2001	In Klein et al 2007
Carica papaya	Papaya	**little**	**0.05**	honey bees, thrips, large sphinx, hummingbirds, moths, butterflies	passive selfpollination, wind pollination, parthenocarpy	dioecious, monoecious, hermaphrodite, self-compatible	in Free 1993; Jindal & Sharma 1997; in Westerkamp & Gottsberger 2000	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Citrus aurantifolia, C. aurantium, C. bergamia, C. grandis, C. limetta, C. limon, C. maxima, C. medica (var. cedrata), C. myrtifolia, C. paradisi, C. reticulata, C. sinensis, C. unshiu, Fortunella japonica,	Bergamot,Chinotto,Citron, Clementine, Grapefruit, Kumquat, Lemmon, Lime, Manderine,Orange, Pomelo, Tangerine	**little**	**0.05**	honey bees (Apis cerana, A.mellifera), bumble bees (Bombus sp.)	variable passive self-pollination and parthenocarpy differs greatle among species and varieties	hermaphrodite (most species); variable level of selfcompatibility depending on species and varieties	in Crane 1991; in Free 1993; Bhatia et al. 1995; in Sharma & Jindal 1997; Wallace & Lee 1999; Sanford 2003; Chacoff 2007; Chacoff & Aizen 2006	In Klein et al 2007
Chrysophyllum cainito (syn. Achras caimito)	Star apple, Cainito	**little(indirect)**	**0.05**	bats, insects		hermaphrodite	Morton 1987; Degen et al.2001	In Klein et al 2007
Crataegus azarolus (syn.C. ruscionensis)	Azarole, Azzeruolo	**little(indirect)**	**0.05**	honey bees, midges	apomixis, but initiation requires pollination	hermaphrodite, self-compatible	Phipps 2003; Dönmez 2004	In Klein et al 2007
Dimocarpus longan (syn. Euphoria longan, Euphoria longana,Nephelium longana)	Longan, Lungan	**little**	**0.05**	honey bees (Apis mellifera), stingless bees (Trigona spp.)	passive selfpollination, windpollination	polygamous	in Heard 1999; Liu & Ma 2001; Blanche et al. 2006b	In Klein et al 2007
Diospyros kaki; D. virginiana	Persimmon	**little**	**0.05**	honey bees (Apis cerana, A. mellifera),bumble bees, solitary bees	variable level of parthenocarpy	monoecious, dioecious,rarely polygamous	Miura 1982; in Crane 1991; Mehta & Kashyap 1997	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
					among varieties			
Durio zibethinus	Durian	**great**	**0.65**	honey bees (Apis dorsata), bats (Eoncyteris spelaea), birds		hermaphrodite, monoecious,mai nly selfincompatible	Morton 1987; Salakpetch et al.1992; George et al. 1994; Yaacob & Subhadrabandhu 1995; Husin & Abidin 1998; Lim & Luders 1998; in Weterkamp & Gottsberger 2000	In Klein et al 2007
Eriobotrya japonica (syn. Mespilus japonicus)	Loquat, Japanese plum, Japanese medlar	**great**	**0.65**	honey bees (Apis cerana), bumble bees	passive self-pollination	hermaphrodite, self-incompatible	in Khan et al. 1986, Morton1987; in Crane 1991; in Free1993; in Sharma & Jindal1997	In Klein et al 2007
Feijoa sellowiana	Feijoa	**great**	**0.65**	birds (Turdus merula, Acridotheres tristis), honey bees, honey bees	passive self-pollination, wind pollination	hermaphrodite, varying level of self-incompatibility among varieties	Schroeder 1953; Stewart1984, 1989; Patterson 1990;in Free 1993 (vary among varieties); Ducroquet & Hickel1997; Degenhard et al. 2001	In Klein et al 2007
Ficus carica	Ficus	**modest**	**0.25**	wasp (Blastophaga psenes)	variable level of parthenocarpy among varieties	gyno-dioecious, monoecious	no in Free 1993; in Westerkamp & Gottsberger 2000	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Fragaria ssp	Strawberry	**modest**	**0.25**	honey bees (Apis mellifera), stingless bees (Trigona angusula, T. (Tetragonula) minangkabau, Nannotrigona testaceicornis), bumble bees, solitary bees (Osmia cornuta), hover flies	passive self-pollination, little wind pollination	hermaphrodite (most varieties), self-compatible	no Maeta et al. 1992; Chagnon et al. 1993; in Free 1993;Kakutani et al. 1993;Zebrowska 1998; inDelaplane& Mayer 2000; Malagodi-Braga & Kleinert	In Klein et al 2007
Litchi chinensis		**little**	**0.05**	honey bees (Apis sp.), flies	little self-pollination, widn pollinaiton	andro-monoecious, self compatible	in Free 1993; Bhatia et al.	In Klein et al 2007
Malus domestica	Apple	**great**	**0.65**	honey bees (Apis cerana, A. mellifera), bumble bees (Bombus sp., solitary bees (Andrena sp., Anthophora) sp., (Osmia cornifrons, O. lignaria propinqua, O. rufa), hover flies (Eristalis cerealis, E. tenax)	passive self-pollination, parthenocarpy in some varieties	hermaphrodite, mainly self-incompatible	in Crane 1991; in Free 1993; Sekita & Amada 1993; Fourez 1995; Batra 1998; inDelaplane & Mayer 2000; inWesterkamp & Gottsberger2000; Vicens & Bosch 2000; Kron et al. 2001; Sekita 2001; Stern et al. 2001; Thomson & Goodell 2001; Wei et al. 2002; in Soltész 2003; Ladurner etal. 2004; Sharma et al. 2004, Garratt et al 2013	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Mammea americana (syn. Mamea americana)	Mamee	**modest(indirect)**	**0.25**	bees		andro-dioecious passive self-pollination	Morton 1987; Roubik 1995; Dunthorn 2004	In Klein et al 2007
Mangifera indica	Mango	**great**	**0.65**	honey bees (Apis sp.), stingless bees (Trigona sp.), flies, ants, wasps	passive self-pollination, wind pollination	andro-monoecious, variable self-compatibility among varieties	in Free 1993; du Toit 1994; Bhatia et al. 1995; Dag et al.2001	In Klein et al 2007
Manikara zapotilla (syn. Manikara zapota, Achras sapota)	Sapodilla	**essential**	**0.95**			hermaphrodite, largely self-incompatibleThrips (Thrips hawaiiensis, Haplothrips (Haplothrips) tenuipennis)	Piatos & Knight 1975; Reddi 1989; Mickelbart 1996	In Klein et al 2007
Mespilus germanica	Medlar	**unknown**		honey bees (Apis mellifera)	passive self-pollination, parthenocarpy	hermaphrodite, self-compatible	Reiter 1947; Phipps 2003	In Klein et al 2007
Nephelium lappaceum	Rambutan	**little**	**0.05**	honey bees (Apis cerana), stingless bees, flies	apomixis in some varieties	hermaphrodite (functional gynoecious), androecious	in Roubik 1995; in Heard 1999; in Slaa et al. 2006	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Opuntia ficus- indica	Prickly pear	**modest(indirect)**	**0.25**	bumble bees	parthenocarpy	hermaphrodite, mostly self-incompatible	Grant & Hurt 1979; Weiss et al. 1993; in DeFelice 2004	In Klein et al 2007
Passiflora edulis	Passion fruit, Maracuja	**essential**	**0.95**	carpenter bees (=solitary bees) (Xylocopa frontalis, X. suspecta) bumble bees, hummingbirds	passive self-pollination in some varieties (Bruckner et al.1995), hand pollination	hermaphrodite, most varieties largely self-incompatible	Corbert & Willmer 1980; in Free 1993; Brancher 1999; Camillo 1996; Da Silva 1999; in Delaplane & Mayer 2000; in Westerkamp & Gottsberger 2000; Almeida Lima 2002; Freitas & De Oliveira Filho 2003	In Klein et al 2007
Persea americana	Avocado	**great**	**0.65**	honey bees, stingless bees, solitary bees	passive self-pollination	hermaphrodite, dichogamous, self-incompatible	Vithanage 1990; in Free 1993; Ish-Am & Eisikowitch 1993, du Toit 1994; Ish-Am 1998a,b; Ish-Am 1999 in Heard 1999; in Delaplane & Mayer 2000; Gazit & Degani 2002; Can- Alonso et al. 2005	In Klein et al 2007
Pouteria sapota (syns. Calocarpum sapota, Calocarpum	Sapote, Mamey colorado	**unknown**		honeynbees	unknown	hermaphrodite, night anthesis	Morton 1987; Davenport & O'Neal 2000	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
mammosum, Pouteria mammosa)								
Prunus domestica, P. spinosa	Plum, Greengage, Mirabelle, Sloe	**great**	**0.65**	honey bees (Apis mellifera),bumble bees, solitary bees (Osmia lignaria propinqua), flies	passive self-pollination	hermaphrodite varieties self-incompatible or self-compatible	in Free 1993; Calzoni & Speranza 1998; in Delaplane & Mayer 2000; in Westerkamp & Gottsberger 2000; Frève et al. 2001; in Szábo 2003	In Klein et al 2007
Prunus persica,Persica laevis	Peach, Nectarine	**great**	**0.65**	honey bees (Apis mellifera), bumble bees, solitary bees (Osmia cornifrons, O. lignaria propinqua), flies	passive self-pollination	hermaphrodite, self-compatible	in Free 1993; in Delaplane & Mayer 2000; in Westerkamp & Gottsberger 2000; da Mota & Nogueira-Couto 2002; in Szábo et al. 2003b	In Klein et al 2007
Prunus avium	Sweet cherry	**great**	**0.65**	honey bees (Apis mellifera),bumble bees, solitary bees (Osmia lignaria),flies	passive self-pollination	hermaphrodite, mostly self-incompatible	Bosch & Kemp 1999; in Delaplane & Mayer 2000; in Nyéki et al. 2003a; Bosch et al. 2006	In Klein et al 2007
Prunus armeniaca	Apricot	**great**	**0.65**	honey bees (Apis mellifera), bumble bees,solitary bees (Osmia cornifrons, O. lignaria propinqua), flies	passive self-pollination	hermaphrodite (old-world varieties self-compatible, new-world varieties self-incompatible)	no in Free 1993; McLaren et al. 1995; Austin et al. 1996; in Delaplane & Mayer 2000; in Westerkamp & Gottsberger 2000; in Szábo et al. 2003a;	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
							Benedek et al. 2006; Vaissière et al. 2006	
Prunus cerasus	Sour cherry	**great**	**0.65**	honey bees (Apis mellifera),bumble bees, solitary bees, flies	passive self-pollination	hermaphrodite, varying level of self-compatibility	no in Free 1993; in Delaplane & Mayer 2000; in Nyéki et al.2003b	In Klein et al 2007
Psidium guajava	Guava, Guayaba	**modest**	**0.25**	honey bees (Apis mellifera), stingless bees (Trigona cupira), bumble bees (Bombus mexicanus), solitary bees (Lasioglossum spp.)	passive self-pollination	hermaphrodite, self-compatible	Hedström 1988; in Sharma & Jindal 1997; Lakshmi & Mohana Rao 1998; in Heard 1999	In Klein et al 2007
Punica granatum	Pomegranate	**modest**	**0.25**	honey bees, beetles (Cetonia, Trichodes)	passive self-pollination	hermaphrodite, andro-monoecious, partly self-incompatible	in Free 1993; in Knuth 1908; Rana & Dwivedi 1997; Melgarejo et al. 2000; Derin & Eti 2001; Mars & Marrakchi 2004	In Klein et al 2007
Pyrus communis	Pear	**great**	**0.65**	honey bees (Apis mellifera), bumble bees, solitary bees (Osmia sp.), flies (Eristalis sp.)	passive self-pollination	hermaphrodite, lself-incompatible	in Free 1993; in Delaplane & Mayer 2000; in Westerkamp & Gottsberger 2000;Maccagnani et al. 2003; in Nyéki & Soltész 2003; Monzón et al. 2004; Stern et al. 2004	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Ribes nigrum, R. rubrum	Black currant, Red currant	**modest**	**0.25**	honey bees (Apis mellifera), bumble bees (Bombus sp.), solitary bees	passive self-pollination	hermaphrodite, varying degree of self-incompatibility depending on species and variety	no in Free 1993; Koltowski et al.1997; Koltowski et al. 1999; in Soltész et al. 2003b	In Klein et al 2007
Rosa spp. (R. canina and all other spp. in section Caninae)	Rose hips, Dogroses	**great**	**0.65**	honey bees, bumble bees (Bombus spp.), carpenter bees (Xylocopa spp.), solitary bees, hover flies (Eristalis spp.)	self-pollination, parthenocarpy	hermaphrodite, varying degree of self-compatibility depending on species and hybrids	Jicinska 1976; Stougaard 1983; Yeboah Gyan & Woodell 1987; Kevan et al. 1990; Ueda & Akimoto 2001; in Kevan 2003	In Klein et al 2007
Rubus idaeus,R. fruiticosus,R.chamaem orus,R. flagellaris, R.trivalis	Raspberry, Blackberry, Clouderry, Northern Dewberry	**great**	**0.65**	honey bees (Apis mellifera),bumble bees (Bombus spp.),solitary bees (Osmia aglaia, O.cornuta),hover flies (Eristalis spp.)	passive self-pollination yielding inferior fruits	hermaphrodite, self-compatible	Yeboah Gyan & Woodell 1987; Chagnon et al. 1991; in Free 1993; Willmer et al.1994; Pinzauti et al. 1997;Pelletier et al. 2001; Cane 2005	In Klein et al 2007
Sambucus nigra	Elderberry	**modest**	**0.25**	honey bees, flies, longhorn beeltes	passive self-pollination	hermaphrodite, self-compatible	Bolli 1994	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Solanum quitoense	Naranjillo	**great**	**0.65**	bumble bees		hermaphrodite, self-compatible, buzz-pollination	Heiser et al. 1972; Roubik, 1995; Almanza et al. 2006	In Klein et al 2007
Sorbus aucuparia	Rowanberry	**essential**	**0.95**	honey bees, bumble bees, syrphid flies	passive selfpollination	hermaphrodite, self-incompatible	Campbell et al. 1991; Bixby & Levin 1996; Sperens 1996; Raspé 1998; Pías & Guitián 2006	In Klein et al 2007
Sorbus domestica	Service-apple	**modest(indirect)**	**0.25**	bees, flies		hermaphrodite, self incompatible	Campbell et al. 1991; Kausch-Blecken von Schmeling 1992	In Klein et al 2007
Spondias ssp.,mainly S.mombin, S.tuberosa	Hog plum,Mombin	**little**	**0.05**	honey bees (Apis mellifera), stingless bess (Melipona sp.)	wind pollinated	hermaphrodite,varying degree of selfincompatibility depending on species and varieties	Dominguez Sanchez et al. 2002	In Klein et al 2007
Tamarindus indica	Tamarind	**little**	**0.05**	honey bees (Apis dorsata)	passive self-pollination	hermaphrodite	in Free 1993	In Klein et al 2007
Vaccinium corymbosum, V.angustifolium, V. ashei, V.myrtillus	Highbush, blueberry,Lowbush blueberry, Rabbiteye, blueberry, Bilberry	**great**	**0.65**	honey bees (Apis mellifera),bumble bees (Bombus impatiens), solitary bees (Anthophora pilipes, Colletes sp.,	passive self-pollination	hermaphrodite, self-compatible, with varying, degree of selfincompatibili	Payne et al. 1989; Cane & Payne 1990; in Free 1993; Dogterom 1999; Stubbs & Drummon 1999, 2001;Dogterom et al. 2000; Sampson & Cane	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
				Habropoda laboriosa, Osmia ribifloris, O. lignaria)		ty, buzz-pollination	2000; in Delaplane & Mayer 2000; Hokanson & Hancock 2000; Aras et al. 1996; Cane 1997;Javorek et al. 2002; Dedej & Oliveira 2006al. 2004; Desjardins & DeDelaplane 2003; Sampson et	
Vaccinium macrocarpon, V. oxycoccus	American cranberry, European cranberry	**great**	**0.65**	honey bees (Apis mellifera), bumble bees (Bombus affinis), solitary bees (Megachile (Delomegachile) addenda, M. rotundata)	passive self-pollination	hermaphrodite, self-compatible	in Free 1993; Cane et al. 1996; in Delaplane & Mayer 2000; Cane & Schiffhauer 2003; Brown & McNeil 2006; Evans & Spivak 2006	In Klein et al 2007
Vitis vinifera	Table grape, Vine grapre	**no increase**	**0**	honey bees, solitary bees	passive self-pollination, wild pollination	hermaphrodite, self-compatible	in Free 1993; Rhodes 2002; but production increase in V.rotundifolia Sampson et al.2001	In Klein et al 2007
Zizyphus jujuba	Jujube	**modest**	**0.25**	honey bees (Apis mellifera) flies, beetles, wasps	passive self-pollination	hermaphrodite, self-compatible	in Free 1993; Sharma & Jindal 1997	In Klein et al 2007
								In Klein et al 2007
Nut crops								In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Amygdalus communis	Almond	**great**	**0.65**	honey bees (Apis mellifera), bumble bees, solitary bees (Osmia cornuta), flies	passive self-pollination	hermaphrodite, self-incompatible, but some new varieties self-compatible	in Free 1993; Bosch 1994; Bosch & Blas 1994; Torre Grossa et al. 1994; in Delaplane & Mayer 2000; in Westerkamp & Gottsberger 2000; De Grandi-Hoffman 2001; Thomson & Goodell 2001; Soltész et al. 2003a; Lumkin 2005	In Klein et al 2007
Anacardium occidentale	Cashew nut, Cashewapple	**great**	**0.65**	honey bees (Apis dorsata, Apis mellifera), stingless bees, bumble bees, solitary bees (Centris tarsata), butterflies, flies, hummingbirds	passive self-pollination	andro-monoecious	Heard et al. 1990; in Crane 1991; in Free 1993; Freitas & Paxton 1998; De Holanda- Neto et al. 2002; Freitas et al. 2002; Bhattacharya 2004	In Klein et al 2007
Arachis hypogea	Peanut, Groundnut	**little**	**0.05**	honey bees (Apis dorsata, Apis florae, **Apis mellifera**), bumble bees, solitary bees, hover flies, butterflies	self-pollination (many varieties cleistogamous)	hermaphrodite, self-compatible	in Crane 1991; in Free 1993, vary among varieties and no benefit found by Blanche et al.2006 because of infrequent flower visitation	In Klein et al 2007
Bertholletia excelsa	Brazil nut, Para nut, Cream nut	**essential**	**0.95**	bumble bees, solitary bees (Euglossini, Xylocopa sp.)		hermaphrodite, self-incompatible	no O'Malley et al. 1988; Mori & Prance 1990; in Free 1993; Mauès 2002	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Castanea sativa	Chestnut	**modest**	**0.25**	honey bees, solitary bees	wind pollination	monoecious, largely self-incompatible	Manino et al. 1991; De Oliveira et al. 2001	In Klein et al 2007
Macadamia ternifolia	Macadamia	**essential**	**0.95**	honey bees (Apis mellifera), stingless bees (Trigona carbonaria), solitary bees (Homalictus sp.), wasps, butterflies		hermaphrodite, largely self-incompatible	in Free 1993; Heard 1993; Heard 1994; Wallace et al. 1996; Blanche et al. 2006b	In Klein et al 2007
								In Klein et al 2007
Edible oil and proteinaceous crops								In Klein et al 2007
Brassica alba, B. hirta, Sinapis alba, B. nigra, Sinapis nigra	Mustard seeds	**modest**	**0.25**	honey bees (Apis mellifera), solitary bees (Osmia cornifrons, O. lignaria lignaria)	passive selfpollination, wind pollination	hermaphrodite, self-compatible	in Free 1993; Abel & Wilson 1999; Abel et al. 2003	In Klein et al 2007
Brassica napus oleifera	Rapeseed, Oilseed rape	**modest**	**0.25**	honey bees (Apis mellifera), bumble bees, solitary bees (Andrena sp., Osmia cornifrons, Osmia lignaria lignari, Halictus sp., Bombus sp.), hoverflies	passive selfpollination, wind pollination	hermaphrodite, self-compatible	in Free 1993; Adegas & Noqueira Couto 1992; Abel & Wilson 1999; Bürger 2004; Manning & Boland 2000; Abel et al. 2003; Morandin & Winston 2005	In Klein et al 2007
Brassica rapa (formerly B. campestris)	Turnip rape, Canola	**great**	**0.65**	honey bees (Apis cerana, A. florea, A. mellifera), solitary bees (Andrena	passive self-pollination,	hermaphrodite, largely self-incompatible	in Crane 1991; in Free 1993; Schittenhelm et al. 1997; Abel & Wilson	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
				ilerda, O. cornifrons, O.lignaria lignari, Halictus spp.), flies (Eristalis spp., Trichometallea pollinosa)	wind pollination		1999; in Delaplane & Mayer 2000; Westcott & Nelson 2001; Abel et al. 2003	
Carthamus tinctorius	safflower	**little**	**0.05**	honey bees (Apis cerana, A. mellifera), solitary bees	variable passive self-pollination	hermaphrodite, self-compatible	in Crane 1991; in Free 1993; Dajue & Mündel 1996	In Klein et al 2007
Cocos nucifera	Coconut monoecious,	**modest**	**0.25**	honey bees, stingless bees	passive self-pollination, little wind pollination	partially self-compatible	in Free 1993; Da Conceicao et al. 2004; Meléndez-Ramírez et al. 2004	In Klein et al 2007
Elaeis guineensis	Oil palm	**little**	**0.05**	weevils (Elaeidobius sp.), thrips (Thrips hawaiiensis)	wind pollination	monoecious	in Free 1993; Dhileepan 1994; in Westerkamp & Gottsberger 2000; Tandon et al. 2001; Krantz & Poinar 2004; Mayfield 2005 (but no effects of forest distance on pollination)	In Klein et al 2007
Glycine max, G. soja	Soybean	**modest**	**0.25**	honey bees (Apis mellifera), bumble bees, solitary bees, (Megachile rotundata)	passive self-pollination (most varieties cleistogamous)	hermaphrodite, self-compatible	Koelling et al. 1981; in Free 1993; Moreti et al. 1998; Nogueira-Couto et al. 1998 for G. wightii; Chiari et al. 2005a,b (vary greatly among varieties, no benefit found by Ray	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
							et al. 2003 and some studies in Free 1993)	
Gossypium hirsutum, G. barbadense, G. arboreum, G. herbaceum	Seedcotton	**modest**	**0.25**	honey bees (Apis sp.), bumble bees (Bombus sp.), solitary bees (mainly Xylocopa sp.), wasps	passive self-pollination	hermaphrodite, self-compatible	in Free 1993; Rhodes 2002	In Klein et al 2007
Helianthus annuus	Sunflower seeds	**modest**	**0.25**	honey bees (Apis cerana, A. mellifera), bumble bees, solitary bees, stingless bees (Trigona iridipennis)	passive self-pollination, but very low	dichogamous, variable level of self-compatibility among varieties	Bichee & Sharma 1988; in Crane 1991; in Free 1993; DeGrandi-Hoffman & Martin 1993; Moreti et al. 1996; in Heard 1999; DeGrandi-Hoffman & Watkins 2000; Dag et al. 2002; Greenleaf 2005,Greenleaf & Kremen 2006b	In Klein et al 2007
Linum usitatissimum	Flaxseed	**little**	**0.05**	honey bees (Apis sp.), bumble bees	passive self-pollination, wind pollination	hermaphrodite, self-compatible	in Free 1993	In Klein et al 2007
Olea europaea	Olive	**no increase**	**0**	honey bees visit flowers occasionally	passive self-pollination, wind pollination	andro-monoecious, variable level of self-incompatibility among varieties	in Free 1993; Singh 1997 (differ greatly among varieties) some authors classify olives to have little benefit according to Griggs et al. 1975	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Sesamum indicum	Sesame	**modest**	**0.25**	honey bees (Apis cerana, A. mellifera), solitary bees, wasps, flies	passive self-pollination	hermaphrodite, self-compatible	in Free 1993; in Crane 1991	In Klein et al 2007
Vicia faba	Broad bean, Faba bean, Field bean, Horse bean	**modest**	**0.25**	honey bees (Apis mellifera), bumble bees (Bombus lapidarius, B. pascuorum, B. hortorum), solitary bees (Anthophora plumipes, Eucera spp., Megachile rotundata)	variable level of passive self-pollination among varieties	hermaphrodite, self-compatible	in Free 1993; Le Guen et al. 1993; Suso et al. 1996; Bond & Kirby 1999; Pierre et al.1999; Somerville 1999	In Klein et al 2007
Vitellaria paradoxa (syn. Butyrospermum paradoxum)	karite nuts, Sheanuts	**modest**	**0.25**	honey bees (Apis mellifera adansonii)		hermaphrodite	Millogo-Rasolodimby 1989; Kelly et al. 2004; Sanou et al. 2005; Tchuenguem Fohouo et al. 2005	In Klein et al 2007
Stimulant crops	**Stimulant crops**							
Coffea arabica,C. canephora	Coffee	**modest** C. canephora classified in **great**	**0.25**	honey bees (Apis dorsata A. mellifera,), stingless bees (Trigona (Lepidotrigona) terminata), solitary bees (Creightonella frontalis, Xylocopa (Zonohirsuta dejeanii)	passive self-pollination (mainly C. arabica), windpollinatio n (mainly C. canephora)	hermaphrodite, variable level of self-compatibility	in Free 1993; Malerbo-Souza **& Nogueira-Couto 1997;** Manrique & Thimann 2002; Roubik 2002a,b; Klein et al. 2003a,b,c; De Marco & Coelho 2004; Ricketts et al 2004; Ricketts 2004	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Cola nitida, C. vera, C. acuminata	Cola nut, Kola nut	**great (indirect)**	**0.65**	flies		hermaphrodite, andromonoeciou s, self-incompatible	in McGregor 1976; Jacob 1980; Osei 1995-1996	In Klein et al 2007
Theobroma cacao	Cocoa	**essential**	**0.95**	bees, cecidomyiid, midges, ceratopogonid midges		hermaphrodite, variable level of self-incompatibility (self-compatible in the amelonado varieties)	in Free 1993; Falque et al. 1995, 1996; Lachenaud 1994	In Klein et al 2007
Spices and condiments								
Afromomum melegueta	Grains of paradise	**unknown**		unknown	unknown	unknown	unknown	In Klein et al 2007
Carum carvi	Caraway	**modest**	**0.25**	solitary bees, flies (Ricciardelli D'Albore 1986)	wind pollination, little passive selfpollination	andromonoeciou s, dichogamous, self-compatible	Bouwmeester et al. 1995; Bouwmeester & Smid 1995; Németh et al. 1999, Németh & Székely 2000; Langenberger & Davis 2002	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Coriandrum sativum	Coriander	**great**	**0.65**	honey bees (Apis cerana, A. dorsata, A. florea, A. mellifera), stingless bees, solitary bees	passive self-pollination	hermaphrodite, self-compatible	in Crane 1991; in Free 1993; Koul et al. 1993; Diederichsen 1996	In Klein et al 2007
Cuminum cyminum	Cumin	**great**	**0.65**	unknown	wind pollination, little passive self- pollination	hermaphrodite, self-compatible	in Free 1993	In Klein et al 2007
Elettaria cardamomum	Cardamom	**great**	**0.65**	honey bees (Apis cerana, Apis dorsata, Apis florea), solitary bees	passive self-pollination	hermaphrodite	in Crane 1991; in Free 1993; Sasikumar et al. 1999	In Klein et al 2007
Illicium verum	Star anise	**unknown**		unknown	unknown	hermaphrodite, self-incompatible	unknown	In Klein et al 2007
Foeniculum vulgare	Fennel seed	**great**	**0.65**	honey bees (**Apis florea**, A. mellifera	wind pollination, little passive self- pollination	hermaphrodite, few andro-monoecious, dichogamous, self-incompatible	in McGregor 1976; in Free 1993; Koul et al. 1993; Németh et al. 1999; Falzari et al. 2005	In Klein et al 2007
Myristica fragrans	Nutmeg	**great (indirect)**	**0.65**	beetles (Formicomus braminus)	wind pollination	dioecious	Armstrong & Drummond 1986	In Klein et al 2007

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Pimenta dioica (syn. P. officinalis, P. dioica)	Allspice, Pimento	**great (indirect)**	**0.65**	honey bees, Halictus, Exomalopsis, Ceratina	unknown	dioecious	Free 1993; Lughadha & Proenca 1996	In Klein et al 2007
Piper nigrum, P.longum	Pepper	**no increase**	**0**	bees, hover flies as flower vistors	passive self-pollination, wind pollination	hermaphrodite, self-compatible, dichogamous	in Free 1993, but insect pollination mentioned in Roubik 1995; Sargent & Otto 2004	
Pimpinella anisum	Anise	**unknown**		honey bees (Apis mellifera), solitary bees, flies	passive self-pollination, wind pollination	hermaphrodite	in McGregor 1976; Ricciardelli D'Albore 1986	In Klein et al 2007
Vanilla planifolia, V. pompona	Vanilla	**essential**	**0.95**	stingless bees, solitary bees, hummingbirds	hand pollination	hermaphrodite, self-incompatible	little natural pollination (<1%) in Free 1993	In Klein et al 2007
Klein's Levels of dependency					***Mean ratios to use for economic valuation (Gallai et al 2009)***			

Essential: pollinators essential for most varieties (production reduction by 90% more, comparing experiments with and without animal pollinators);	**95%**
High: animal pollinators are extreme (40 to less than 90% reduction);	**65%**
Modest: animal pollinators are clearly beneficial (10 to less than 40% reduction);	**25%**

CROP SPECIES	VERNACULAR NAME	IMPACT BY ANIMAL POLLINATION	(DR)	POLLINATORS AND VISITORS	POLLINATION WITHOUT VISITORS	BREEDING	REFERENCE	SOURCE
Little: some evidence suggests that animal pollinators are beneficial (greater than 0 to less than 10% reduction);					**5%**			
No increase: no production increase with animal-mediated pollination;					**0%**			

Appendix C.14 Household surveys for: (a) the "Cultivated goods" methods, and (b) the "Harvested wild goods" assessment methods extracted from TESSA V2.0

(a)

Template questionnaire - cultivated goods

General information			
Name/number of respondent	MG1		
If appropriate include one or more questions which allow you to differentiate respondents according to the key factors affecting receipt of benefits. You may want to ask this at the end of the questionnaire, once they feel more comfortable about the content of the questionnaire. E.g. Household size / Education / Ethnicity / Age / Marital status / Wealth status			
Date	27 April 2012		
Location/name of village	Pina		
Are the questions being answered per individual, or household, or business?	Individual	Household X	Business

Crops	
It is important here that you only focus on **up to five** cultivated goods identified as most important in the stakeholder workshop. If any livestock are among the top five cultivated goods then complete section 3.	
What is your **total** size of the land you farm in the area (use local units of area if appropriate):	10 hal

Template questionnaire - cultivated goods

Which of the top five cultivated goods do you grow? O Please answer the column of questions for each one in turn, giving answers for the past year and all the land you farm in the area*.	1. Wheat	2. Barley	3. Potatoes	4. Dhal	5. -
Unit of measurement for that crop O	muri	muri	muri	muri	
Last year, how much of that crop did you produce? O	2	4	2.5	2	
Last year, what was the average price obtained per unit**? O	0 Substitute would cost 25NR per kg	30NR	20NR	0 Substitute would cost 10NR per kg	
Percentage for own use	100%	0%	20%	100%	
Percentage sold/bartered	0%	100%	80%	0%	
Did you, or family members, spend (unpaid) time cultivating/ harvesting/processing this crop? (Yes/No)	Yes	Yes	Yes	Yes	

Template questionnaire - cultivated goods

If yes, how many person-days did you or your family spend cultivating/harvesting/ processing this crop last year*? O	150	70	35	100	
Did you hire people to cultivate/ harvest/process this crop? (Yes/ No)	No	No	No	No	
If yes, how many person-days did you hired people spend cultivating/ harvesting/ processing this crop last year*? O	0	0	0	0	
What is the average daily wage rate you paid these hired people (outside of any reciprocal arrangements)?	-	-	-	-	
What is the cost of other inputs for this crop (seed, fertiliser, pesticide, water, fuel for machinery)*? O	minimal	minimal	minimal	minimal	
What capital items (tools, materials or equipment) do you need for cultivating/ harvesting/ processing this crop? (e.g. tools, machinery)? O	Cutting tools	Use same as for wheat	Spade	Harvesting tools	

Template questionnaire - cultivated goods

How long do you expect each of these tools / machines to last (years)***? **O**	20yrs	-	15yrs	10yrs	
How much did each tool / machine cost to buy? **O**	500NR		10000NR	300NR	
Last year, what was spent on transporting and marketing this crop*? **O**	-	500NR	250NR	-	
If the crop is a perennial crop (e.g. fruit trees, vines, nut bushes, perennial herbs) ask the following:					
How much did it cost to establish the crop (e.g. plants, stakes, labour)? **O**					
For how many years will the crop remain productive? **O**					

Livestock******					
It is important to find out the value of livestock as a contribution to cultivated goods. The value of the service that the land provides to livestock is determined from the value of all the feed it provides them.					
Do you have any livestock? **O**	Yes				
If yes, what? **O**	Cattle				
How many of each type did you have on average last year*? **O**	2				

Template questionnaire - cultivated goods

What percentage of the total food that these animals needed last year* came from the area*****? Think about all the food they ate (including pasture, fodder crops, hay, food waste, etc.) **O**	75%				
What is the value of that feed? (i.e. how much would it cost you to replace that feed with purchased alternatives?) **O**	550NR per month				

* If respondents find it difficult to recall cultivation details accurately for the past 12 months or for all the land they farm in the area, then break these questions down. For example, ask about the harvest on a monthly basis, and ask how many months the harvest lasts (and then add these figures up yourself, to get an annual total). If necessary you could do the same for each field the cultivator uses, and then add the answers up to get a total for their entire farm.
** If the individual respondent does not sell what they cultivate but others do, then apply the mean price recorded from other respondents.
*** If any tools or equipment have a lifetime of more than one year, divide the initial purchase cost by their expected lifetime and add typical repair/maintenance costs. If tools are not specifically used/purchased for producing this particular good but are for general use, apply a sensible percentage to their purchase and maintenance cost.
**** Only complete this section for livestock whose feed is identified as among the top 5 most important cultivated goods. Complete a separate column for each form of livestock which is among these top 5.
***** Here you are asking the respondent about all the animal feed they obtain from the current area or the alternative state that you are studying, i.e. not just from their farm. This may include cultivated feed crops, crop residues, pasture, browse cut from hedgerows and field margins.

It is important that you get answers to all of the questions marked with O as without these you will not be able to calculate economic values

(b)

Template questionnaire - harvested wild goods

Name/number of respondent	Mr Basnyat
Date	23 November 2012
Location/name of village	Phulchoki
Are the questions being answered per individual, or household, or business?	Individual

Name of product (if more than 3 products, use additional forms)	Fuel wood	Fodder	Compost
Quantity and value of product			
a. Total quantity collected from the site in last 12 months* O	4	27	16
b. Local Unit O	Bundle	Bundle	Bundle
c. Conversion to metric unit (local units per kg) O	45	40	40
d. Percentage for own use	80%	100%	
e. Percentage sold/ bartered	20%	0%	
f. Average price obtained per unit** O	$5 Bundle	$3 Bundle	$0.70 Bundle

Family labour			
g. Annual time taken by respondent and family members (unpaid) to harvest and process the product (person days)* O	2	25	10
Hired labour			
h. Annual input of hired labour for harvesting and processing (person days)* O	1	0	0
i. Typical daily wage rate paid for hired labour	$2	$2	$2
Equipment costs* **			
j. What capital items (tools, materials, equipment) do you need for harvesting and processing this product? O	Axe	none	none
k. How long do you expect each of these tools etc. to last? O	5 years		
l. How much did each item cost to buy? O	$10		
Transport and marketing costs			
m. What are the annual costs of transporting and marketing this product?* O	Zero-sold from home	Zero	Zero

* If respondents find it difficult to recall accurately the harvest for the past 12 months, then break these questions down. For example, ask for the harvest on a monthly basis (and then add these figures up yourself, to get an annual total). Do the same for each of these questions (price, inputs of labour, costs of equipment and other inputs, etc.).

** If the individual respondent does not sell the product they gather, but others do, then apply the mean price recorded from other respondents.

Template questionnaire - harvested wild goods

*** If any tools or equipment have a lifetime of more than one year, divide the initial purchase cost by their expected lifetime and add typical repair/maintenance costs. If tools are not specifically used/purchased for this product but are for general use, apply a sensible percentage of their cost/maintenance.
It is important that you get answers to all of the questions marked with O as without these you will not be able to calculate economic values

Feed for respondent's own livestock

If wild harvested feed for harvesters' own livestock was identified as one of the most important harvested wild goods then ask each respondent the following questions.

The value of the service that the land provides to livestock is determined from the value of the feed it provides for them. Here we are focus only on wild harvested feed (not cultivated feed).			
In the last 12 months, did you feed any livestock with wild harvested feed obtained from the site? O			Yes
If yes, what and how many animals do you own (sheep, goats, cows, chickens, etc.)? O	1. 8 cows	2. 4 goats	3. -
For each animal type, approximately what percentage of their feed did you obtain from wild harvest at the site? O	50%	80%	
What is the estimated value of that feed? (i.e. how much would it cost you to replace that feed if you had to buy it from someone else, or if you had to replace it with another kind of animal feed?) O	$25 per day per animal	$10 per day per animal	

Appendix C.15 Methods for estimating the value of pollination services to cultivated and harvested wild goods using a desk-based method: (a) within the site boundaries with very limited resources (M0); (b) within the site boundaries (M1); and (c) within the 1km buffer from the site (M2) extracted from the "Pollination services" protocol in TESSA V2.0

(a)

Pollination M0

Pollination Method 0

Estimating the value of pollination services to cultivated and harvested wild goods within the site boundaries with very limited resources

This section will provide you with information on how to gain an approximate value of the pollination services provided to cultivated and harvested wild goods **within the assessment site only**, and which have already been evaluated in previous modules (**Cultivated goods** and **Harvested wild goods** modules).

1. Use the end commercial economic values for each of the key animal pollinated plants calculated in the Cultivated or Harvested wild goods modules
2. Multiply this value by the dependency ratio (DR) of that key plant (Use **Pollination lookup table 1** for dependency ratio)

NOTE: if the dependency ratio is not known, this method is not suitable and you will need to collect field data. You must take into account that due to the simplicity of this method, it is not possible

Pollination M0

to estimate the baseline pollination service that is the pollination provided by those pollinators, which persist in the agricultural matrix. Therefore, the value of pollination services provided by the site might be overestimated in this method. This method cannot be used for the 1km buffer as it uses existing values calculated in the **Cultivated goods** and **Harvested wild goods** modules. If there is data available for crops or harvested goods that falls outside the boundaries of the site, within a 1km buffer, then this method can be used for the buffer too.

Pollination M0

Worked example

The site is a 200ha area in South-East England consisting of rich calcareous grassland, mixed and yew woodland and cropland. Oilseed rape (*Brassica napus*) is grown on 10ha inside the assessment site. In the immediate surrounding area, the agricultural landscape consists of a mixture of oilseed rape (covering 51ha), field beans (*Vicia faba*, covering 45ha) and cereal fields. There are no harvested wild goods for this site. All pollinators in this region are invertebrates.

The animal pollinated goods for this site are oilseed rape and field beans; cereal is wind pollinated. The only good grown inside the assessment site is oilseed rape.

The alternative state is the result of a total conversion of the site to agricultural use.

The estimated annual return for oilseed rape grown inside the assessment site, obtained using the "Cultivated Goods" module is **£13,431**

The estimated dependency ratio (DR, obtained from Lookup table 1) for oilseed rape is **0.25**.

Therefore, the estimated value for pollination services provided by the site within the site boundaries is 13,431 x 0.25 = **£3,358** per year.

(b)

Pollination M1

Pollination Method 1

Estimating the value of pollination services to cultivated and harvested wild goods within the site boundaries using a desk based method **(Red Standard)**

This section will provide you with information on how to estimate the value of pollination services provided by the assessment site using a desk based method.

This approach can be used to estimate the value of pollination services provided to a 1km buffer from the site (refer to **Pollination M2**)

Apply this method to each identified key animal pollinated plant.

You will need:

Pollination lookup table 1
Polination Appendix 1

Before you start you need to know:

- Total area (ha) of key animal pollinated crops and harvested wild goods, which grow inside the assessment site (from rapid appraisal)
- Maximum yield (in kg ha^{-1} $year^{-1}$ or tonnes ha^{-1} $year^{-1}$)

Pollination M1

achievable in the region for each of the key animal pollinated species (from rapid appraisal)

- Dependency ratio (DR) of the 5 key animal pollinated plants (Lookup table 1)
- Farmgate price (net value of the product when it leaves the farm, after marketing costs have been subtracted) of crops of interest and commercial price of wild goods
- Spreadsheet for yield and value calculation (**Pollination calculations** - Red Standard)

For each identified animal pollinated plant follow instructions below

Use the excel file provided (**Pollination calculations** - Red Standard)

Formulae are already embedded in the spreadsheet; you only need to enter the data specific to your assessment site. Instructions are available in the spreadsheet by hovering over title cells.

This method merges with **Pollination M2** in order to provide an overall value of pollination services provided within the site and in the 1km buffer. Use the same spreadsheet for both methods.

Visitation frequency inside the assessment site is assumed to be the highest rate achievable, which is = 1.

1. Calculate the maximum achievable yield for the area due to pollination by multiplying (maximum yield (in tonnes/ ha^{-1} $year^{-1}$) achievable in the region) X (the known dependency ratio)
2. Multiply the value obtained from step 1 by the farmgate price of the crop of interest for the region. This will give

Pollination M1

you the value of pollination for inside the assessment site in £/ha

3. Put the value in the spreadsheet (in the "inside the site" row)

4. Does the crop occur in a 1km buffer area from the site boundaries?

YES Go to **Pollination M2**

NO In the **Pollination calculations** - Red Standard spreadsheet, delete the rows "**Close**", "**Medium**" and "**Far**" to obtain the value of pollination services inside the assessment site only.

Pollination M1

Worked example

The site is a 200ha area in South-East England consisting of rich calcareous grassland, mixed and yew woodland and cropland. Oilseed rape (*Brassica napus*) is grown on 10ha inside the assessment site. In the immediate surrounding area, the agriculture landscape consists of a mixture of oilseed rape (covering 51ha), field beans (*Vicia faba*, covering 45ha) and cereal fields. There are no harvested wild goods for this site. All pollinators in this region are invertebrates.

The animal pollinated goods for this site are oilseed rape and field beans; cereal is wind pollinated. The only good grown inside the assessment site is oilseed rape.

The alternative state is the result of a total conversion of the site to agricultural use

The maximum yield (in tonnes per hectare) achievable in the region for oilseed rape is **4.2**t/ha

Total area (ha) of oilseed rape grown inside the assessment site is **10**ha

Pollination M1

The known dependency ratio (DR, obtained from Lookup table 1) for oilseed rape is **0.25**

The farmgate price of oilseed rape for the region is **319.80**£/t

Assuming maximum yield corresponds to highest visitation frequency, convert the visitation frequency value in £/m^2 (or £/ha) by multiplying the values from step 1 by the price of the crop per kg or tonne.

The maximum yield due to pollination is 4.2*0.25 = **1.05** t/ha

The value of pollination inside the assessment site is 1.05 * 319.8 = **335.79** £/ha

(c)

Pollination Method 2

Estimating the value of pollination services to cultivated and harvested wild goods within a 1km buffer from the site boundaries using a desk based method (**Red standard**)

This section will provide you with information on how to estimate the value of pollination services delivered to the 1km buffer from the site boundaries using a desk based method.

You need to know your key pollinator groups as this section provides different methods of calculating the value depending on the main pollinators groups (bees and other invertebrates, vertebrates).

Apply this method to each identified key animal pollinated plant.

Before you start you need to know:

- Total area (ha) of key animal pollinated crops and harvested wild goods, which grow within a 1km buffer of the assessment site (from rapid appraisal)
- Maximum yield (in kg ha^{-1} $year^{-1}$ or tonnes ha^{-1} $year^{-1}$) achievable in the region for each of the key animal pollinated species (from rapid appraisal)
- Dependency ratio (DR) of the 5 key animal pollinated plants (**Pollination lookup table 1**)

- Farmgate price (net value of the product when it leaves the farm, after marketing costs have been subtracted) of crops of interest and commercial price of wild goods
- Spreadsheet for yield and value calculation (**Pollination Calculations** Red Standard)

For each identified animal pollinated plant:

Do you know the main pollinator group?

No Use **Pollination lookup table 1** and **Pollination Appendix 1** to identify main pollinators of your plant.

Once the main pollinators have been identified, follow the guidance below appropriate to your pollinator group

Yes: Follow instructions below

From this point use the excel file provided (**Pollination Calculations** Red Standard)

Formulae are already embedded in the spreadsheet; you only need to enter the collected data specific to your assessment site. Instructions are available in the spreadsheet by hovering over title cells.

Bees or other invertebrates:

1. Divide the buffer surrounding the reserve into three distinct zones, each of which should include:

   -1st closest patch to the assessment site (C)

   -2nd patch at a middle point (M)

   -3rd patch furthest from the site (F)

Pollination M2

1. Calculate the visitation frequency in each zone at the distance at which the crop occurs, using the formula below and the decay rate, which has already been obtained from published results (Ricketts et al., 2008)

   a) $y(d) = a^*e^{kd}$

   Pollination Calculations Red Standard

Where:

$y(d)$ = is the value of visitation frequency at distance d

a = is the value of visitation frequency at the start (inside the assessment site)

e= the inverse function of the natural logarithm (ln)

K = rate of decay (see table 2 in Ricketts et al., 2008)

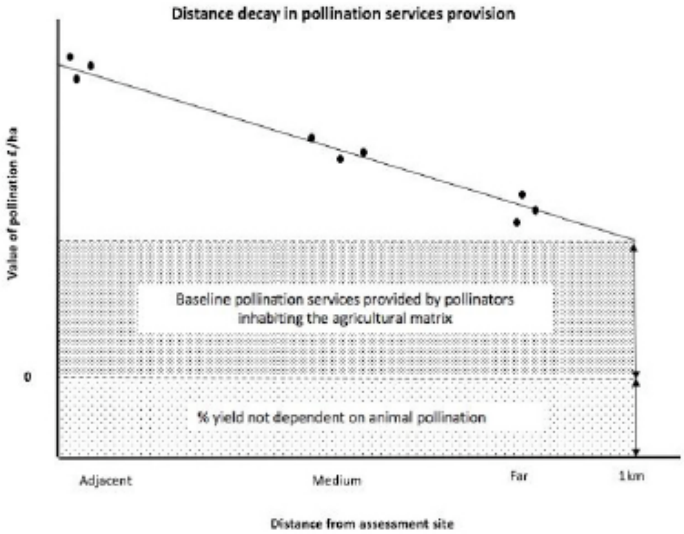
d = is a given distance

NOTE: The formula is already embedded in the cells in the "Mean Visitation Frequency" column. You only have to change the distance in metres in the formula according to the real distances for your site.

2. Assuming maximum yield corresponds to highest visitation frequency, convert the visitation frequency value in £/m^2 (or £/ha) by multiplying the values from point 1 by the price of the crop per kg or tonne. Do this for the value of each visitation frequency to obtain 3 values. This is done automatically in the spreadsheet; the values are in the "£/m^2 or £/ha" column.

Pollination M2

3. Deduct the estimated pollination value at 1km from the values at the other distances and from the value obtained from **Pollination M1** (if the crop only occurs in the buffer area and not inside the site, delete the row "**Inside the site**" in the **Pollination Calculations** Red Standard). This is done to exclude the baseline pollination service that is the pollination provided by those pollinators, which persist in the agricultural matrix. This is done automatically in the spreadsheet, the resulting values are in the "Adjusted values" column.



4. Following deduction of the baseline measure of pollination services, calculate the average of the above values (Resulting value under "average£/m^2").

5. Multiply this by the total area of that crop grown in the buffer strip and this gives you the value of pollination in the buffer area. Add the total area in the "Total area of

Pollination M2

crop A (ha/m²)" column. The final value will appear in the "Value of pollination for crop A" column.

The above method assumes that the area of crop within your buffer is evenly distributed.

If you have data for maximum achievable yield at close/medium/far distances and the proportion of crop area for each portion of the buffer (close/medium/far distances), you will obtain a more accurate estimate by calculating the specific amount of crops per distance with differential yield in kg ha^{-1} $year^{-1}$.

For instance, instead of averaging the value of pollination across the buffer, you could calculate the actual value at each portion of the buffer (by multiplying the maximum yield due to pollination by the proportion of crop area in each distance buffer area). The sum of these values would give you a much more accurate estimate as in reality the crop area is likely not to be distributed evenly within the buffer.

Vertebrates (bats, birds):

1. Calculate the economic value of pollination with the following formula

    b) $\$ = A*(kg\ ha^{-1}\ y^{-1})\ *DR*P$

Where:

\$ = value of pollination services in dollars (or local currency)

A = area under production (ha),

kg ha^{-1} $year^{-1}$ = quantity of the good produced in kilograms per hectare (or tonnes per hectare)

Pollination M2

DR= dependency ratio for the good of interest (obtained from **Pollination Lookup table 1**)

P=farmgate price for the crop, or price of wild goods if bought on the market

2. Partition the final value as shown below.

Are those animals known to live in the site and/or in the 1km buffer area?

	Action
Only in the site	allocate 100% value to the site
Only in the buffer area	allocate 100% value to the buffer area
In both	partition the final value: 50% between site and buffer area

Alternative state

Is the basic habitat structure similar to the assessment site? (i.e. degrading forest but still providing service as the intact assessment site)

Yes Keep 100% as the value of pollination provided by the site

No Lose a % of the provision by the site according to the proportion of natural habitat that is lost with the conversion. We assume that a 50% loss will reduce pollination services by 50%. If there is a total loss of the assessment site, the value of pollination services provided by the alternative state would be £0, as the only pollination service would be the baseline provided by pollinators that inhabit the agricultural matrix, value that is not attributable to the assessment site.

Pollination M2

Worked example

The site is a 200ha area in South-East England consisting of rich calcareous grassland, mixed and yew woodland and cropland. Oilseed rape is grown in 10ha inside the assessment site. In the immediate surrounding area, the agriculture landscape consists of a mixture of oilseed rape (*Brassica napus*, covering 51ha), field beans (*Vicia faba*, covering 45ha) and cereal fields. There are no harvested wild goods for this site. All pollinators in this region are invertebrate.

The animal pollinated goods for this site are oilseed rape and field beans; cereal is wind pollinated. The only good grown inside the assessment site is oilseed rape.

The alternative state is the result of a total conversion of the site to agricultural use.

The maximum yield (in Pollination Lookup table 1) achievable in the region for oilseed rape is **4.2** t/ha

The maximum yield (in tonnes per hectare) achievable in the region for field beans is **5.89** t/ha

Pollination M2

Total area (ha) of oilseed rape grown within a 1km buffer from the assessment site is **51**ha

Total area (ha) of field beans grown within a 1km buffer from the assessment site is **45**ha

The known dependency ratio (DR, obtained from Lookup table 1) for oilseed rape is **0.25**

The known dependency ratio (DR, obtained from Lookup table 1) for field beans is **0.25**

The farmgate price of oilseed rape for the region is **319.8** £/t

The farmgate price of field beans for the region is **156.27** £/t

The published decay rate is-0.00104

Therefore, the visitation frequency on oilseed rape at each distance, calculated using published distance decay rate, is:

Distance	Formula	Visitation frequency
0m	Maximum visitation frequency	**1**
50m	$1*e^{-0.00104*50}$	**0.95**
670m	$1*e^{-0.00104*670}$	**0.50**
800m	$1*e^{-0.00104*800}$	**0.44**
1km	$1*e^{-0.00104*1000}$	**0.35**

Note: The distances in metres in the "Distance" column represent the distances at which the oilseed rape crop occurs in each buffer zone

The maximum yield due to pollination for oilseed rape is 4.2*0.25 = **1.05** t/ha

The value of pollination at the 0m is 1.05 * 319.8 = **335.79** £/ha (obtained from **Pollination M1**)

The value of pollination at the 50m is (335.79 *0.95)/1= **318.78** £/ha

Pollination M2

The value of pollination at the 670m is (335.79 *0.50)/1 = **167.89** £/ha

The value of pollination at the 800m is (335.79 *0.50)/1 = **167.89** £/ha

The value of pollination at the 1km is (335.79 *0.35)/1= **118.69** £/ha

The above values are adjusted to exclude this baseline pollination service (i.e. the value of pollination at the 1km).

335.79-118.69 = **217.10** £/ha

319-118.69 = **200.31** £/ha

167.28-118.69 = **48.70** £/ha

118.69-118.69 = **0** £/ha

The average of the above value is (217.10 + 200.31 + 48.70 + 0)/4 = **116.45** £/ha

Finally, the total estimated value of pollination services provided to oilseed rape crop within 1km buffer from this worked example is 116.45 (i.e. average estimated value of pollination services) * 61 (i.e. total hectares of oilseed rape) = **£7,103**

Pollination M2

The same calculations are repeated for field beans

Distance	Formula	Visitation frequency
0m	Maximum visitation frequency	**1**
70m	$1*e^{-0.00104*70}$	**0.93**
750m	$1*e^{-0.00104*750}$	**0.46**
1km	$1*e^{-0.00104*1000}$	**0.35**

Note: The distances in metres in the "Distance" column represent the distances at which the oilseed rape crop occurs in each buffer zone

The maximum yield due to pollination is 5.89*0.25 = **1.47** t/ha

The value of pollination at the 0m is 1.47 * 156.27= **230.11** £/ha

The value of pollination at the 70m is (230.11 *0.93)/1= **213.95** £/ha

The value of pollination at the 750m is (230.11 *0.46)/1 = **105.48** £/ha

The value of pollination at the 1km is (230.11 *0.35)/1= **81.33** £/ha

The above values are adjusted to exclude the baseline pollination service that is the pollination provided by those pollinators which persist in the agricultural matrix.

230.11 – 81.33 = **148.77** £/ha

213.95 – 81.33 = **132.62** £/ha

105.48 - 81.33 = **24.15** £/ha

81.33 - 81.33 = **0** £/ha

The average of the above values is (148.77 + 132.62 + 24.15 +

Pollination M2

0)/4 = **76.39** £/ha

The total estimated value of pollination provided to the 1km buffer is 76.39 * 45 = **£3,437**. This is the value of pollination services provided to the field beans crop within a 1km buffer from the assessment site.

Finally, the total estimated value of pollination services provided to the crops within a 1km buffer from the assessment site is:

7,103 (i.e. for oilseed rape) + 3,437 (i.e. for field beans) = **£10,540**

Turning to the alternative state:

If the alternative state is complete conversion to agricultural land, the only value of pollination is the baseline value at 1km, which is deducted by the total value as it would persist even without the presence of the site.

Therefore, the additional value of pollination services provided by the alternative state is £**0**.

Appendix C.16 Guidance on size of sampling plots and observation techniques, extracted from the "Pollination services" protocol in TESSA V2.0

Pollination Appendix 3

Size of the sampling plot and on observation techniques

- The number of floral units to observe should be set at the start of your observation period. The number should be adjusted according to the density of the flowers so that you can manage to observe all of them at all time during the 15 minutes; for small abundant flowers, such as oilseed rape, you can count the average number of flowers in a $1m^2$ and use that as you sampling plot.
- Take into account the size and the attractiveness of the floral units so as to avoid too many null values;
- Choose flowers that are in the sun at the beginning of the observation period;
- Stand in a way that does not cast a shadow on the plant/ flowers;
- Stand far enough not to affect pollinator behaviour; for vertebrate pollinators, you might have to hide so make sure that all the flowers in the observation plot are visible at all times;
- Record all visit to flowers in your observation plot. Every time a pollinator lands on a new flower, it counts as a new visit, even if it is a pollinator you have already recorded on another flower;
- You can either record all pollinators in one single group,

Pollination Appendix 3

or divide them in morphospecies (i.e. honeybees, bumblebees, small bee, other) depending on your level of ID skills (you may want to take photos of visitors prior to collecting data to create a morphospecies ID guide);

- Observations should only be carried out during dry, sunny weather with temperatures ≥ 13°C and only between 10:00hrs and 16:00hrs;
- Between 13 and 17°C, observations may be carried out with less than 40% cloud cover. Over 17°C, observations may be carried out during any dry weather
- Wind speed should be below 5 on the Beaufort scale (Pollard 1977)

Beaufort Scale

Beaufort number	Wind Speed km/h		On land	Field ecologists' impressions
0	Under 1	Calm	Calm, smoke rises vertically	You're having a good time
1	1-3	Light air	Direction of wind shown by smoke, vanes do not move	You're still having a good time
2	4-7	Light breeze	Wind felt on face, leaves rustle, vanes begin to move	It's a bit tricky to photograph insects on plants
3	8-12	Gentle breeze	Leaves, small twigs in constant motion, light flags extended	At least there are no biting insects to contend with
4	13-18	Moderate breeze	Dust, leaves and loose paper raised up; small branches move	It's hard to keep your notes from flapping
5	19-24	Fresh breeze	Small trees begin to sway	You prefer to work in sheltered places

Pollination Appendix 3

6	25-31	Strong breeze	Large branches of trees in motion, whistling heard in wires	Your tripod is blowing over
7	32-38	Moderate gale	Whole tree in motion, resistance felt in walking against the wind	You're doing this for the good of science
8	39-46	Fresh gale	Twigs and small branches broken off trees	You're not being paid enough
9	47-54	Strong gale	Slight structural damage occurs; slate blown from roof	You're thinking about where you've parked your vehicle
10	55-63	Whole gale	Seldom experienced on land, trees broken; structural damage occurs	You're wondering how you'll get home
11	64-72	Storm	Very rarely experienced on land; usually with widespread damage	You're wondering what shape your home is in
12	73 or higher	Hurricane force	Violence and destruction	Time to find a new study site

References

Pollard E. 1977. A method for assessing changes in the abundance of butterflies. Biol Conserv 12: 115–34.

Jones J.C. and Reynolds J.D. (2000) Environmental variables, In: Ecological Census Techniques: A Handbook (ed. W.J. Sutherland) Cambridge University Press, Cambridge, 281 – 316.

Appendix C.17 Methods for estimating the value of pollination services to cultivated and harvested wild goods using visitation rate as a proxy for pollination services: (a) within the site boundaries (M3), and (b) within a 1km buffer from the site (M4), extracted from the "Pollination services" protocol in TESSA V2.0

(a)

Pollination Method 3

Estimating the value of pollination services to cultivated and harvested wild goods within the site boundaries using visitation rate as a proxy for pollination services (**Amber standard**)

This section will provide you with information on how to estimate the value of pollination services provided by the assessment site using measures of flower visitation as a proxy for pollination services.

This method measures flower visitation frequency to estimate the economic value of the pollination services being provided by the assessment site.

This approach can be used to estimate the value of pollination services provided to a 1km buffer from the site (refer to Method **Pollination M4**)

Apply this method to each identified key animal pollinated plant.

You will need:

A map of the site

A stop watch or a watch or a mobile phone

A data recording sheet (see **Pollination Appendix 2** for templates)

Pollination M3

A tape measure (to measure the observation plot, optional)

Tally counter (optional)

Spreadsheet for yield and value calculation (**Pollination Calculations** Amber Standard)

Before you start you need to know:

- Total area (ha) of key animal pollinated crops and harvested wild goods, which grow inside the assessment site (from rapid appraisal)
- Maximum yield (in kg ha^{-1} $year^{-1}$ or tonnes ha^{-1} $year^{-1}$) achievable in the region for each of the key animal pollinated species (from rapid appraisal)
- Dependency ratio (DR) of the 5 key animal pollinated plants (**Pollination lookup table 1**)
- Farmgate price of crops of interest and commercial price of wild goods

For each identified key animal pollinated plant:

1. Identify nine sampling locations within the site as far apart as possible from one another so that they are independent and representative of the site.

2. At each sampling location randomly identify 3 plots (See **Pollination Appendix 3** for help in choosing the size of plots)

Pollination M3

NOTE: Carry out the sampling at least 50m away from any field edge for large fields or use the field's centre point for smaller fields, to minimise edge effects. Keep this sampling structure consistent throughout, both for the current and for the alternative state.

3. Observe the flowers inside each plot for 15 minutes and count all visits to flowers within this time. Every time a pollinator lands on a new flower it counts as a visit, even if it is the same animal visiting more flowers. Write down your data on a data recording sheet (see **Pollination Appendix 3** for invertebrate and vertebrate observation techniques and **Pollination Appendix 2** for data sheet template)

NOTE: Only count visitors that are big enough to contact the reproductive parts of the plant (See **Pollination Appendix 3** for full guidance on observation techniques)

4. When the 15 minutes are over, count all the flower heads inside the plot (visit/flower/minute will be your unit of measure)

Pollination M3

NOTE: Ideally, the observations should be done at the same time of the day. If you have more people available, carry out the observations simultaneously. If there is only one person, carry out the observations on three separate days at the same time.

From this point, use the excel file provided
(**Pollination Calculations** Amber Standard)
Formulae are already embedded in the spreadsheet; you only need to enter the collected data specific to your assessment site. Instructions are available in the spreadsheet by hovering over title cells.

This method merges with **Pollination M4** in order to provide an overall value of pollination services provided within the site and in the 1km buffer.

Use the same spreadsheet for both methods.

5. Calculate the mean of the visitation frequencies.
6. Calculate the maximum yield due to pollination by multiplying the maximum yield value by the dependency ratio.
7. Assuming maximum yield corresponds to highest visitation frequency, convert the visitation frequency value in £/m^2 (or £/ha) by multiplying the value from point 6 by the price of crop per kg or per tonne. This will give you the value of pollination for inside the assessment site in £/ha

   Use **Pollination Calculations** Amber Standard.

Pollination M3

8. Does the crop occur in a 1km buffer area from the site boundaries?

   YES Go to **Pollination M4**

   NO Follow the instructions below

9. In the **Pollination Calculations** Amber Standard spreadsheet, delete the rows "**Close**", "**Medium**" and "**Far**". In this case you will not be able to construct a distance decay curve with real data. Therefore, use the published decay curve rate (used in **Pollination M2**) to calculate the baseline value of pollination services (at 1km distance from the site).

10. Deduct the estimated pollination value at 1km from the value for inside the site. This is done to exclude the baseline pollination service that is the pollination provided by those pollinators, which persist in the agricultural matrix. This is done automatically in the spreadsheet and the result appears in the "Adjusted values" column.

11. Multiply this by the total area of that crop grown in the buffer strip and this gives you the value of pollination in the buffer area. (This is done automatically in the spreadsheet). The final value of pollination services for the crop will appear in the "Value of pollination for crop A" column.

    Use **Pollination Calculations** Amber Standard.

Pollination M3

Worked Example

The site is a 200ha area in South-East England consisting of rich calcareous grassland, mixed and yew woodland and cropland. Oilseed rape is grown in 10ha inside the assessment site. In the immediate surrounding area, the agriculture landscape consists of a mixture of oilseed rape (*Brassica napus*, covering 51ha), field beans (*Vicia faba*, covering 45ha) and cereal fields. There are no harvested wild goods for this site. All pollinators in this region are invertebrates.

The animal pollinated goods for this site are oilseed rape and field beans; cereal is wind pollinated. The only good grown inside the assessment site is oilseed rape.

The alternative site is the result of a total conversion of the site to agricultural use.

The maximum yield (in tonnes per hectare) achievable in the region for oilseed rape is **4.2** t/ha

Total area (ha) of oilseed rape grown inside the assessment site is **10** ha

Pollination M3

The known dependency ratio (DR, obtained from Lookup table 1) for oilseed rape is **0.25**

The farmgate price of oilseed rape for the region is **319.8** £/t

We average the 9 sampling plots and obtain a mean visitation frequency of **0.006**

(This value is used subsequently to calculate the value of the crop in £/m^2 at given distances from the assessment site)

The maximum yield due to pollination is 4.2 * 0.25 = **1.05**

The value of pollination for oilseed rape, expressed in £ per hectare, for inside the assessment site is

1.05 * 319.8 = **£336** per ha

This value will be incorporated with the results from **Pollination M4** to construct a decay curve and gain an overall value for the assessment site and the 1km buffer (See **Pollination M4** and **Pollination Calculations** Amber Standard for more details).

(b)

Pollination M4

Pollination Method 4

Estimating the value of pollination services to cultivated and harvested wild goods within a 1km buffer from the site boundaries using visitation rate as a proxy for pollination services (**Amber standard**)

This section will provide you with information on how to estimate the value of pollination services delivered by the assessment site to the buffer area using measures of flower visitation as a proxy for pollination services.

Apply this method to each identified key animal pollinated plant.

You will need:

A map of the site

A stop watch or a watch or a mobile phone

A data recording sheet (see **Pollination Appendix 2** for templates)

A tape measure (to measure the observation plot, optional)

Tally counter (optional)

Spreadsheet for yield and value calculation (**Pollination Calculations** Amber Standard)

Pollination M4

Before you start you need to know:

- Total area (ha) of key animal pollinated crops and harvested wild goods, which grow within a 1km buffer of the assessment site (from preliminary scoping appraisal)
- Maximum yield (in kg ha^{-1} $year^{-1}$ or tonnes ha^{-1} $year^{-1}$) achievable in the region for each of the key animal pollinated species (from rapid appraisal)
- Dependency ratio (DR) of the 5 key animal pollinated plants (**Pollination lookup table 1**)
- Farmgate price (net value of the product when it leaves the farm, after marketing costs have been subtracted) of crops of interest and commercial price of wild goods

For each identified animal pollinated plant:

1. Divide the buffer surrounding the reserve into three distinct zones, each of which should include:

   -1st closest patch to the assessment site (C)

   -2nd patch at a middle point (M)

   -3rd patch furthest from the site (F)

2. Identify 3 sampling locations within each buffer zone at the distance at which the crop occurs

NOTE: Carry out the sampling at least 50m away from any field edge for large fields or use the field's centre point for smaller fields, to minimise edge effect. Keep this sampling structure consistent throughout, both for the current and for the alternative state.

Pollination M4

It is important to identify any other patch of semi-natural habitat occurring within the buffer area, and its proximity. Wherever possible, you should lay transects as far as possible from other patches of semi-natural habitat to minimise influx of pollination services delivered by those patches.

3. At each sampling location, randomly identify 3 plots (See **Pollination Appendix 3** for help in choosing the size of plots)

4. Observe the flowers inside each plot for 15 minutes and count all visits to flowers within this time. Every time a pollinator lands on a flower, count it as a new visit, even if it is the same animal visiting multiple flowers. Write down your data on a data recording sheet (see **Pollination Appendix 3** for invertebrate and vertebrate observation techniques and **Pollination Appendix 2** for data sheet template)

NOTE: Only count insects that are big enough to contact the reproductive parts of the plant (see **Pollination Appendix 3** for guidance)

5. When the 15 minutes are over, count all the flower heads inside the plot (visit/flower/minute will be your unit of measure)

Pollination M4

NOTE: Ideally, the observations should be done at the same time of the day. If you have more people available, have one person at each distance to carry out the observations simultaneously. If there is only one person, carry out the observations at the three distances on three separate days at the same time.

From this point, use the excel file provided
(**Pollination Calculations** Amber Standard)
Formulae are already embedded in the spreadsheet; you only need to enter the collected data specific to your assessment site. Instructions are available in the spreadsheet by hovering over title cells.

This method merges with **Pollination M3** in order to provide an overall value of pollination services provided within the site and in the 1km buffer. Use the same spreadsheet for both methods. (if the crop only occurs in the buffer area and not inside the site, delete the row "**Inside the site**" in the **Pollination Calculations** Amber Standard spreadsheet)

1. For each distinct zone, calculate the mean of the visitation frequencies and of the distances from the site. Input your data in the "No of visitors" and "No of flower heads" columns, the means will appear in the "Visit/ flower/min" column.

2. After averaging them, you will have 3 values for visitation frequency at three increasing distances from the site. The values will appear in the "Mean Visitation Frequency" column, including the value for the 0m obtained from **Pollination M3**.

Pollination M4

3. Assuming maximum yield corresponds to highest visitation frequency, convert the visitation frequency value in £/m² (or £/ha) by multiplying the values from point 7 by the price of the crop per kg or tonne. Do this for each visitation frequency's value to obtain 4 values. Input the price of crop in the "Price of crop £/kg or £/tonne" column, the values in £/m² (or £/ha) will be calculated automatically.

4. Look at the graph representing the distance decay curve in pollination services provision. The graph shows £/m² (or £/ha) on the y-axis and distance from the site in metres on the x-axis. Extract the value at the 1km point from the graph in £/m² (or £/ha) by either:

   -Manually draw a horizontal line from the point where the decay curve intersects the 1km to estimate the value in £/m² (or £/ha) for that distance;

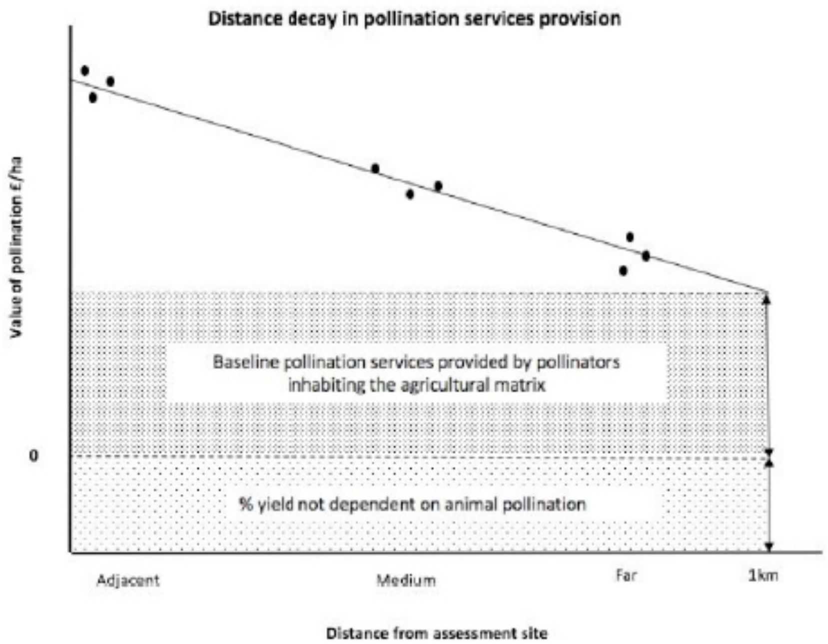
OR

   -Use the exponential decay curve equation obtained from the graph to calculate the value at 1km (see spreadsheet for further instructions).

NOTE The graph is already available in the spreadsheet. The decay curve and exponential decay equation are also already displayed. If they do not appear go to "Add chart Element" and choose the option "Trendline" then select "exponential". Then double click on the trendline, this will open a formatting panel where you can tick the option "Display equation on chart".

Pollination M4

5. Deduct the estimated pollination value at 1km from the values at the other distances. This is done to exclude the baseline pollination service that is the pollination provided by those pollinators, which persist in the agricultural matrix. This is done automatically in the spreadsheet and the results appear in the "Adjusted values" column.



6. Following deduction of the baseline measure of pollination services, calculate the average of the above values (This is done automatically in the spreadsheet).

7. Multiply this by the total area of that crop grown in the buffer strip and this gives you the value of pollination

in the buffer area. (This is done automatically in the spreadsheet). The final value of pollination services for the crop will appear in the "Value of pollination for crop A" column.

The above method assumes that the area of crop within your buffer is evenly distributed.

If you have data for maximum achievable yield at close/ medium/far distances and the proportion of crop area for each portion of the buffer (close/medium/far distances), you will obtain a more accurate estimate by calculating the specific amount of crops per distance with differential yield in kg ha^{-1} $year^{-1}$.

For instance, instead of averaging the value of pollination across the buffer, you could calculate the actual value at each portion of the buffer (by multiplying the maximum yield due to pollination by the proportion of crop area in each distance buffer). The sum of these values would give you a much more accurate estimate as, in reality, the crop area is likely not to be distributed evenly within the buffer.

Pollination M4

Worked example

The site is a 200ha area in South-East England consisting of rich calcareous grassland, mixed and yew woodland and cropland. Oilseed rape is grown in 10ha inside the assessment site. In the immediate surrounding area, the agriculture landscape consists of a mixture of oilseed rape (*Brassica napus*, covering 51ha), field beans (*Vicia faba*, covering 45ha) and cereal fields. There are no harvested wild good for this site. All pollinators in this region are invertebrate.

The animal pollinated goods for this site are oilseed rape and field beans; cereal is wind pollinated. The only good grown inside the assessment site is oilseed rape.

The alternative state is the result of a total conversion of the site to agricultural use.

The maximum yield (in tonnes per hectare) achievable in the region for oilseed rape is **4.2** t/ha

The maximum yield (in tonnes per hectare) achievable in the region for field beans is **5.89** t/ha

Pollination M4

Total area (ha) of oilseed rape grown within a 1km buffer from the assessment site is **51**ha

Total area (ha) of field beans grown within a 1km buffer from the assessment site is **45**ha

The known dependency ratio (DR, obtained from Lookup table 1) for oilseed rape is **0.25**

The known dependency ratio (DR, obtained from Lookup table 1) for field beans is **0.25**

The farm gate price of oilseed rape for the region is **319.80** £/t

The farm gate price of field beans for the region is **156.27** £/t

Therefore, the visitation frequency on oilseed rape at each distance, calculated as the mean of the values from each sampling plot is:

Mean Distance	Visitation frequency
0m	**0.0062**
52m	**0.0058**
461m	**0.0017**
826m	**0.0013**

Note: The distances in metres in the "Mean Distance" column represent the mean distances at which the oilseed rape crop occurs in the each buffer zone

The maximum yield of oilseed rape due to pollination is 4.2*0.25 = **1.05** t/ha

The value of pollination at 0m is 1.05 * 319.8 = **335.79** £/ha (Obtained from **M2**)

The value of pollination at 52m is (335.79 *0.0058)/0.0061= **312.96** £/ha

Pollination M4

The value of pollination at 461m is (335.79 *0.0017)/0.0061 = **92.68** £/ha

The value of pollination at 826m is (335.79 *0.0016)/0.0061= **71.19** £/ha

The value of pollination at 1km is **27.47** £/ha (estimated from the graph in Calculations.xlsx-Amber Standard.)

The above values from the buffer area are adjusted to exclude the baseline pollination service that is the pollination provided by those pollinators which persist in the agricultural matrix.

335.79 - 27.47 = **308.32** £/ha

318.26-27.47 = **285.49** £/ha

153.93-27.47 = **65.21** £/ha

84.96-27.47 = **43.72** £/ha

27.47 -27.47 = **0** £/ha

The average of the above values is (308.32 + 285.49 + 65.21 +43.72 + 0)/5 = **140.55** £/ha

Finally, the total value of pollination provided to oilseed rape in the site and the 1km buffer is: 140.55 * (10 + 51) = **£8,573**

The same calculations are repeated for field beans:

Mean Distance	Visitation frequency
0m	**N/A**
52m	**0.0058**
461m	**0.0013**
826m	**0.0017**

Pollination M4

Note: The distances in metres in the "Mean Distance" column represent the mean distances at which the oilseed rape crop occurs in the each buffer zone

The maximum yield due to pollination is 5.89*0.25 = **1.47** t/ha

The value of pollination at 0m is 1.47 * 156.27= **230.11** £/ha

The value of pollination at 52m is (230.11 *0.0058)/0.0062= **215.38** £/ha

The value of pollination at 461m is (230.11 *0.0013)/0.0062 = **48.78** £/ha

The value of pollination at 826m is (230.11 *0.0017)/ 0.0062 = **63.51** £/ha

The value of pollination at 1km is **25** £/ha (estimated from the graph)

The above values from the buffer area are adjusted to exclude the baseline pollination service that is the pollination provided by those pollinators which persist in the agricultural matrix.

230.11 – 25 = **205.11** £/ha

215.38 – 25 = **190.38** £/ha

48.78 - 25 = **23.78** £/ha

63.51- 25 = **38.51** £/ha

25 – 25 = **0** £/ha

The average of the above value is (205.11 + 190.38 + 23.78 + 38.51 + 0)/5 = **91.56** £/ha

Pollination M4

The total value of pollination provided to field beans to the 1km buffer is 91.56 * 45 = **£4,120**.

Finally, the total estimated value of pollination services provided to the crops in the site and within a 1km buffer around the site is 8,573 (i.e. for oilseed rape) + 4,120 (i.e. for field beans) = **£ 12,693**

Turning to the alternative state:

If the alternative state is complete conversion to agricultural land, the only value of pollination is the baseline value at 1km, which is deducted by the total value as it would persist even without the presence of the site.

Therefore, the additional value of pollination services provided by the alternative state is **£0**.

Appendix C.18 Video with guidance on plant bagging techniques, extracted from the "Pollination services" protocol in TESSA V2.0

https://www.youtube.com/watch?v=m4csyNwDe8s

Appendix C.19 Methods for estimating the value of pollination services to cultivated and harvested wild goods using exclusion experiments: (a) within the site boundaries (M5), and (b) within a 1km buffer from the site (M6), extracted from the "Pollination services" protocol in TESSA V2.0

(a)

Pollination M5

Pollination Method 5

Estimating the value of pollination services to cultivated and harvested wild goods within the site boundaries using exclusion experiments (**Green standard**)

This section will provide you with information on how to estimate the value of pollination services delivered by the assessment site using pollinator exclusion experiments.

It focusses on short term production, not on long term viability and sustainability, e.g. on seed production for the next season's cultivation/harvesting etc., due to limited time-frame of the assessment.

This approach can be used to estimate the value of pollination services provided to a 1km buffer from the site (refer to **Pollination M6**)

Apply this method to each identified key animal pollinated plant.

You will need:

A map of the site

1mm mesh bags (mosquito netting is ideal; size of mesh bags will be dependent on predicted size of the flower heads and of the pollinators. See **Pollination Appendix 4** for guidance on how to make bags)

Pollination M5

Two colours of thread and garden tags

Spreadsheet for yield and value calculation (**Pollination Calculations** Green Standard)

Before you start you need to know:

- Total area (ha) of key animal pollinated crops and harvested wild goods, which grow inside the assessment site (from **preliminary scoping appraisal**)
- Maximum yield (in kg ha^{-1} $year^{-1}$ or tonnes ha^{-1} $year^{-1}$) achievable in the region for each of the key animal pollinated species (from rapid appraisal)
- Farmgate price (net value of the product when it leaves the farm, after marketing costs have been subtracted) of crops of interest and commercial price of wild goods

For each identified animal pollinated plant

1. Randomly select 15 distinct plants prior to flowering. From each plant, select two floral units at a similar pre-flowering stage (flower not yet opened). These floral units will form your two treatment groups (i.e. Group 1: Bagged, Group 2: Unbagged) **OR** Randomly select 15 pairs of plants prior to flowering, these pairs will form your two treatment groups (i.e. Group 1: Bagged, Group 2: Unbagged). In the latter case, a whole plant is bagged and the other one is the unbagged treatment.

NOTE: For plants with only single floral units or when bagging a whole plant, two adjacent plants should be selected which are similar in form (e.g. height, number of leaves). In this case, you would have 30 plants in total.

Pollination M5

Bag plants at least 50m away from any field edge for large fields or use the field's centre point for smaller fields, to minimise edge effect. Keep this sampling structure consistent throughout, both for the current and for the alternative state.

2. Randomly select one of these floral units and carefully bag the floral unit to exclude pollinators, with the other unit remaining unbagged. (See **Pollination Appendix 4** for a video on bagging techniques). Ensure that the bagged and unbagged floral units are approximately consistent with respect to the number of flowers. Both units should be clearly marked with coloured thread or tags indicating treatment. Bags should remain in place until the end of the flowering period.

NOTE: When bagging the flowers, ensure that there are no pollinators or any other invertebrate (e.g. spiders) trapped in the bags!

Bagging may have an impact on yield and exposure to pest/diseases and may constrain fruit formation. You should therefore aim to remove bags as soon as fruit is set.

Monitor the plants on a regular basis to facilitate the identification of key sampling times (e.g. prior to flowering and prior to harvest). Identify survey locations and plots on a map first and make sure you have resources to locate the plots easily on a second visit (e.g. using GPS or marking plants with coloured tape).

Pollination M5

3. At or before harvest, quantify the yield for bagged and unbagged treatment groups.

   Choose a measure of yield that is meaningful to the people on the ground, it is appropriate to the crop of interest and will allow economic valuations(e.g. seed number, fruit number, number of seed per pod, seed weight).

From this point, use the excel file provided
(**Pollination Calculations** Green Standard)
Formulae are already embedded in the spreadsheet; you only need to enter the collected data specific to your assessment site. Instructions are available in the spreadsheet by hovering over title cells.

4. For each plant, divide the yield of bagged flowers by the yield of unbagged flowers.

   This resultant value (which should lie between zero and one) estimates the proportion of yield that is due to self-pollination.

5. Calculate the proportion of yield that is due to animal pollination (i.e. pollination dependence DR) by using the following formula: 1 – (value from point **4**).

6. Calculate an average of these proportions to obtain a final value (DR)

7. Put the value in the spreadsheet (in the “inside the site” row)

Pollination M5

8. Does the crop occur in a 1km buffer area from the site boundaries?

   YES Go to **Pollination M6**

   NO Follow the instructions below

9. In the **Pollination Calculations** Green Standard spreadsheet, delete the rows "**Close**", "**Medium**" and "**Far**".

10. Calculate the economic value of pollination for inside the assessment site with the following formula:

    a) $\$= A*(kg\ ha^{-1}\ year^{-1})*DR*P$

    Where:

    \$ = value of pollination services in dollars (or local currency)

    A = area under production (ha),

    kg ha^{-1} $year^{-1}$ = quantity of the good produces in kilograms per hectare (or tonnes per hectare)

    DR= mean dependency ratio for the good of interest (obtained from point **6**)

    P=farmgate price for the crop, or price of wild goods if bough on the market

    Again, this formula is already embedded in the spreadsheet and the final value will appear in the "Value of pollination for crop A" column.

Pollination M5

Worked example

The site is a 200ha area in South-East England consisting of rich calcareous grassland, mixed and yew woodland and cropland. Oilseed rape is grown in 10ha inside the assessment site. In the immediate surrounding area, the agriculture landscape consists of a mixture of oilseed rape (*Brassica napus*, covering 51ha), field beans (*Vicia faba*, covering 45ha) and cereal fields. There are no harvested wild good for this site. All pollinators in this region are invertebrates.

The animal pollinated goods for this site are oilseed rape and field beans; cereal is wind pollinated. The only good grown inside the assessment site is oilseed rape.

The alternative state is the result of a total conversion of the site to agricultural use.

The maximum yield (in tonnes per hectare) achievable in the region for oilseed rape is **4.2** t/ha

Total area (ha) of oilseed rape grown inside the assessment site is **10** ha

Pollination M5

The farm gate price of oilseed rape for the region is **£319.80** £/t

Once seed set is measured for each flower unit, the mean dependency ratio for each of the 15 plants is calculated and the average of those is **0.24**. This is the final value for dependency ratio of oilseed rape on insect pollination for this site.

(b)

Pollination M6

Pollination Method 6

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Estimating the value of pollination services to cultivated and harvested wild goods within a 1km buffer of the site boundaries using exclusion experiments (**Green standard**)

This section will provide you with information on how to estimate the value of pollination services delivered by the site using exclusion experiments.

This method enables you to calculate the marginal crop yield produced within a 1km buffer that is the direct result of pollination.

Apply this method to each identified key animal pollinated plant.

You will need:

A map of the site

1mm mesh bags (mosquito netting is ideal; size of mesh bags will be dependent on predicted size of resultant fruit. See **Pollination Appendix 4** for guidance on how to make bags)

Two colours of thread and garden tags

Spreadsheet for yield and value calculations (**Pollination Calculations** Green Standard)

Pollination M6

Before you start you need to know:

- Total area (ha) of key animal pollinated crops and harvested wild goods, which grow within a 1km buffer of the assessment site (from **preliminary scoping appraisal**)
- Maximum yield (in kg ha^{-1} $year^{-1}$ or tonnes ha^{-1} $year^{-1}$) achievable in the region for each of the key animal pollinated species (from **preliminary scoping appraisal**)
- Farmgate price (net value of the product when it leaves the farm, after marketing costs have been subtracted) of crops of interest and commercial price of wild goods

For each identified animal pollinated plant:

1. Divide the buffer surrounding the reserve into three distinct zones, each of which should include:

   -1st closest patch to the assessment site (C)

   -2nd patch at a middle (M)

   -3rd patch furthest from the site (F)

2. Select three distinct transects in each of these three distinct buffer zones at distances at which the crop occurs. Adjacent transects should be established at a minimum distance of 200m apart to ensure independence.

3. Along each transect, randomly select five plants and identify two floral units per plants that are at similar pre-flowering stage (flowers are not yet opened).

Pollination M6

These floral units or these two plants will form your two treatment groups (i.e. Group 1: Bagged, Group 2: Unbagged). OR at each transect, randomly select five pairs of plants that are at similar pre-flowering stage; these pairs will form your two treatment groups (i.e. Group 1: Bagged, Group 2: Unbagged). In the latter case, a whole plant is bagged and the other one is the unbagged treatment.

NOTE: For plants with only single floral units or when bagging a whole plant, two adjacent plants should be selected which are similar in form (e.g. height, number of leaves). In this case, you would have 30 plants in total. Identify your transects and plots on a map first and make sure you have resources to locate the plots easily on a second visit (e.g. using GPS or marking plants with coloured tape).

It is important to identify any other patch on semi-natural habitat occurring within and the proximity of the buffer area. Wherever possible, you should lay transects as further as possible from those patches to minimise influx of pollination services delivered by those patches. Bag plants at least 50m away from any field edge for large fields or use the field's centre point for smaller fields, to minimise edge effects. Keep this sampling structure consistent throughout, both for the current and for the alternative state.

4. Carefully bag the floral units selected to exclude pollinators with the other unit remaining unbagged. (See **Pollination Appendix 4** for a video on bagging techniques). Ensure that the bagged and unbagged floral units are approximately consistent with respect

Pollination M6

to the number of flowers. Both units should be clearly marked with coloured thread or tags indicating treatment. Bags should remain in place until the end of the flowering period.

NOTE: when bagging the flowers, ensure that there are no pollinators or any other invertebrate (e.g. spiders) trapped in the bags!

Bagging may have an impact on yield and exposure to pest/diseases, constraining fruit formation. You should aim to remove the bags as soon as fruit is set.

Monitor the plants on a regular basis to facilitate the identification of key sampling time (e.g. prior to flowering and to harvest).

At or before harvest, quantify the yield for bagged and unbagged treatment groups.

Choose a measure of yield that is meaningful to the people on the ground, it is appropriate to the crop of interest and will allow economic valuations(e.g. seed number, fruit number, number of seed per pod, seed weight).

From this point use the excel file provided (**Pollination Calculations** Green Standard)

Formulae are already embedded in the spreadsheet; you only need to enter the collected data specific to your assessment site. Instructions are available in the spreadsheet by hovering over title cells.

Pollination M6

5. For each plant, divide the yield of bagged flowers by the yield of unbagged flowers.

   This resultant value (which should lie between zero and one) estimates the proportion of yield that is due to self-pollination.

6. Calculate the proportion of yield that is due to animal pollination (i.e. pollination dependence DR) by using the following formula: 1 – (value from point **6**, the formula is already embedded in the "DR" column).

NOTE: Prior to calculating this average, all plants where treatments have been interfered with (e.g. pests or diseases have impacted severely on yield) should be excluded.

You may want to identify a "monitor plant" to facilitate identification of key sampling times (e.g. prior to flowering and prior to harvest).

7. Calculate an average of these proportions for inside the site (obtained from **Pollination M5**, if the crop only occurs in the buffer area and not inside the site, delete the row "**Inside the site**" in the **Pollination Calculations** Green Standard spreadsheet) and for each buffer zone to obtain a mean value (DR) at each distance. (this is done automatically in the spreadsheet; the resulting values will appear in the "Mean DR" column).

8. Look at the graph representing the dependency ratio at increasing distances from the site. The graph shows DR on the y-axis and distance from the site in metres on the x-axis. Extract the value of DR from the graph by either:

Pollination M6

-Using the linear trendline to estimate the value of DR at 1km

OR

-If your data follow a decay curve, use the decay curve equation obtained from the graph to calculate the value of DR at 1km (see spreadsheet for further instructions).

NOTE: The graph is already available in the spreadsheet. The linear trendline, the decay curve and exponential decay equation are also already displayed. If they do not appear go to "Add chart Element" and choose the option "Trendline", select either "linear" or "exponential". Then double click on the trendline, this will open a formatting panel where you can tick the option "Display equation on chart".

9. Deduct the estimated DR value at 1km from the values at the other distances. This is done to exclude the baseline pollination service that is the pollination provided by those pollinators, which persist in the agricultural matrix. This is done automatically in the spreadsheet and the results appear in the "Adjusted values of DR" column. Calculate the mean of the resulting DRs.

10. Calculate the economic value of pollination for the whole buffer area with the following formula:

    a) $\$= A^*(\text{kg ha}^{-1}\ \text{year}^{-1})\ ^*DR^*P$

Pollination M6

Where:

\$ = value of pollination services in dollars (or local currency)

A = area under production (ha),

kg ha^{-1} $year^{-1}$ = quantity of the good produces in kilograms per hectare (or tonnes per hectare)

DR= mean dependency ratio for the good of interest (obtained from point **10**)

P=farmgate price for the crop, or price of wild goods if bough on the market

Again, this formula is already embedded in the spreadsheet and the final value will appear in the "Value of pollination for crop A" column.

The above method assumes that the area of crop within your buffer is evenly distributed.

If you have data for maximum achievable yield at close/medium/far distances and the proportion of crop area for each portion of the buffer (close/medium/far distances), you will obtain a more accurate estimate by calculating the specific amount of crops per distance with differential yield in kg ha^{-1} $year^{-1}$.

For instance, instead of averaging the value of DR across the buffer, you could calculate the actual value at each portion of the buffer with formula (a) by using values of DR obtained at the three buffers. The sum of these values would give you a much more accurate estimate as in reality the crop area is likely not to be distributed evenly within the buffer.

Pollination M6

Worked Example

The site is a 200ha area in South-East England consisting of rich calcareous grassland, mixed and yew woodland and cropland. Oilseed rape is grown in 10ha inside the assessment site. In the immediate surrounding area, the agriculture landscape consists of a mixture of oilseed rape (*Brassica napus*, covering 51ha), field beans (*Vicia faba*, covering 45ha) and cereal fields. There are no harvested wild goods for this site. All pollinators in this region are invertebrates.

The animal pollinated goods for this site are oilseed rape and field beans; cereal is wind pollinated. The only good grown inside the assessment site is oilseed rape.

The alternative state is the result of a total conversion of the site to agricultural use.

The maximum yield (in tonnes per hectare) achievable in the region for oilseed rape is **4.2** t/ha

The maximum yield (in kg/t) achievable in the region for field beans is **5.89** t/ha

Pollination M6

Total area (ha) of oilseed rape grown within a 1km buffer from the assessment site is **51**ha

Total area (ha) of field beans grown within a 1km buffer from the assessment site is **45**ha

The known dependency ratio (DR, obtained from Lookup table 1) for oilseed rape is **0.25**

The known dependency ratio (DR, obtained from Lookup table 1) for field beans is **0.25**

The farmgate price of oilseed rape for the region is **319.80** £/t

The farmgate price of field beans for the region is **156.27** £/t

Once the seed set of oilseed rape is measured for each flower unit the mean dependency ratio at each buffer area is:

Location	Dependency Ratio (DR)
Inside the site	**0.24**
Close	**0.24**
Medium distance	**0.19**
Far	**0.16**
1km	**0.15**

The adjusted values after deducting the DR at 1km from the DRs at the other distances are:

Location	Dependency Ratio (DR)
Inside the site	**0.09**
Close	**0.09**
Medium distance	**0.04**
Far	**0.01**
1km	**0.00**

Pollination M6

The average of these proportion is (0.09+0.09+0.04+0.01+0.00)/5 = **0.05**. This is the final value of dependency ratio

Finally, the total value of pollination provided to oilseed rape in the site and the 1km buffer is : 61 *4.2*0.05*319.8 = **£3,738**

The same calculations are carried out for field beans.

The dependency ratio at each buffer area is:

Location	Dependency Ratio (DR)
Inside the site	**N/A**
Close	**0.19**
Medium distance	**0.15**
Far	**0.14**
1km	**0.13**

The adjusted values after deducting the DR at 1km from the DRs at the other distances are:

Location	Dependency Ratio (DR)
Inside the site	**N/A**
Close	**0.06**
Medium distance	**0.02**
Far	**0.01**
1km	**0.00**

The average of these proportion is (0.06+0.02+0.01+0.00)/4 = **0.022** This is the final value of dependency ratio

Pollination M6

The economic value for pollination services in the 1km buffer for field beans is:

45*5.89*0.022*156.27 = **£828**

The total value of pollination services provided by the site to the crops in the 1km buffer is:

3,768+828= £4,596

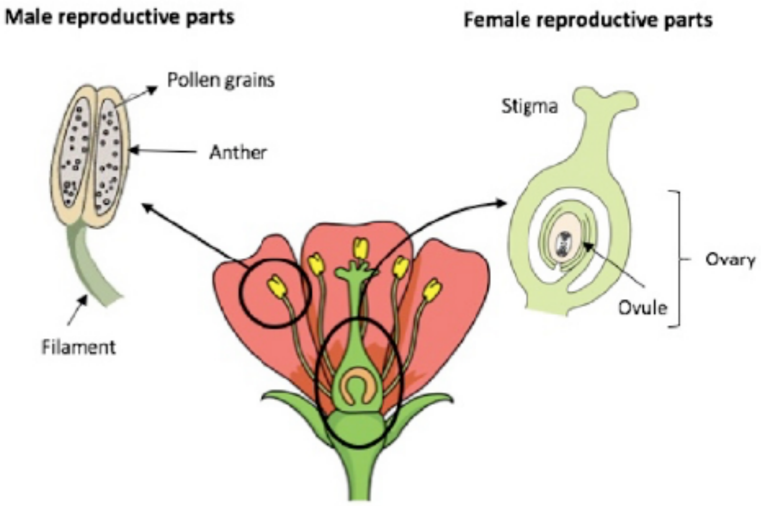
Turning to the alternative state:
If the alternative state is complete conversion to agricultural land, the only value of pollination is the baseline value at 1km, which is deducted by the total value as it would persist even without the presence of the site.

Therefore, the value of pollination services provided by the alternative state is **£0**.

Appendix C.20 Guidance on flower reproductive parts and pollen vector identification, extracted from the "Pollination services" protocol in TESSA V2.0

Pollination Appendix 1

Flower reproductive parts



Carpel modified from **http://cronodon.com/BioTech/Plant_Bodies_Flowers.html**
Stamen modified from **http://leavingbio.net/thestructureandfunctionsofflowers%5B1%5D.htm**

Flowers can be divided in three different types according to their reproductive parts:

1. Flowers with **both** female and male reproductive parts (hermaphrodite)
2. Flowers with **male** reproductive parts **only**
3. Flowers with **female** parts **only**

Pollination Appendix 1

It is important to identify uni-sexual flowers (about 10% of plant species) as you will only have to bag flowers with female reproductive parts (stigma, style and ovaries) in this case.

On the plant

Some plants have both male and female flowers on the same individual (**monoecious**).

Monoecious plant can be:

1. Monoecious hermaphrodite (with hermaphrodite flowers)
2. Monoecious with male and female flowers

Some plants have male and female flowers on different individual (**dioecious**).

Pollination Appendix 1

Identify the main pollen vector

Use the below table to determine if your plant of interest is wind or animal pollinated (this is a very rough guide, bear in mind that there are many exception)

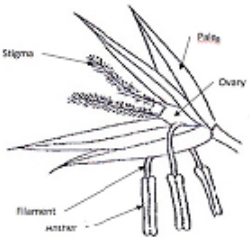
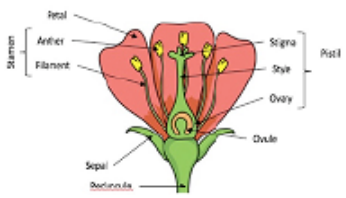
		
	Wind pollinated flowers	**Animal pollinated flowers**
Flowers	Small flowers, often without petals	Larger, coloured or vivid white flowers. If small they might form a dense inflorescence
Scent	Lack scent	Scented
Nectar	Have no nectar	Can have nectar as a reward for pollinators
Anthers and pollen	Have exposed anthers with dry, powdery pollen that is released in clouds when the flowers are shaken	Don't release masses of pollen when you shake them, pollen in much low quantity, often quite sticky
Stigma	Exposed, often feathery	Small and compact, not as exposed
Other features	Flowers sometimes appear before leaves	Most importantly, insects and/ or vertebrates visit the flowers and contact the sexual parts

Fig 1 Modified from **http://oldschool.com.sg/module/PublicAccess/action/Wrapper/sid/ea5f3768e0dae62aa6d01beee8123931/cmbn_id/4050/qba/1**

Pollination Appendix 1

What "qualifies" as a pollinator?

A pollinator can be defined as an animal that is a regular and non-destructive flower visitor, that transfers pollen between plants and that successful pollination occurs during visits, which culminates in the production of seeds (Carthew & Goldingay 1997)

Therefore, a flower visitor is a pollinator if it makes contact with the reproductive parts of the plant, if it collects pollen and drinks nectar from the flower. In order to do the above, flower visitors need to be over a certain size.

As effective pollination depends on many factors (pollen load, pollen deposited..) it would be hard to judge whether the visit was effective only through observations. Therefore, for the purpose of this protocol, any landing on the flower by an animal big enough to act as pollinators is counted as a visit.

Is it a bee?

Other invertebrate and vertebrates visit flowers and may act as pollinators:

- Butterflies have four feathery wings, the colour of which varies with the species;
- Beetles have a hard pair of wings that look like a case enclosing the second pair of wings;
- Birds also pollinate many species of plants;
- Some flowers, for instance cactus flowers, open at night (nocturnal anthesis) consequently nocturnal animals such as moths and bats can act as pollinators for some plants especially in tropical regions;

Pollination Appendix 1

The table below provides guidance on how to distinguish bees from other insect pollinators

You may want to consult some ID guides of local pollinators before starting the data collection.

					
	Honeybee	**Solitary bee**	**Bumblebee**	**Hoverfly**	**Wasp**
Wings	Four wings	Four wings	Four wings	Two wings	Four wings
	Folded into their body when at rest	Folded into their body when at rest	Folded into their body when at rest	Resting at an angle	Folded into their body when at rest
Eyes	Oval, more on the side of the head	Oval, more on the side of the head	Oval, more on the side of the head	Large, more to the front of the head	Oval, more on the side of the head
Pollen	Female carry pollen on pollen baskets (on back legs)	Female carry pollen on pollen baskets (on back legs)	Female carry pollen on pollen baskets (on back legs)	Carry pollen that sticks to their body, no pollen basket	Carry pollen that sticks to their body, no pollen basket
Antennae	Long	Long	Long	Short	Long
Hair	Smooth body, some hair on the thorax	Smooth body, some hair on the thorax	Furry all over the body	Usually hairless but flies which mimic bumblebees are furry	hairless
Colour	Orange bands on abdomen, brown and black body	Varies across species. From yellow bands, orange to entirely black	Black, white, orange/ yellow or red or large bands	Normally colours that mimic bees or wasps (black, yellow, orange)	Black or brown with yellow bands

Honeybee photo: **https://www.sciencenews.org/article/bees-may-neonicotinoids-some-may-be-harmed**

Pollination Appendix 1

Wasps photo: **http://www.greenleafpestcontrol.com/obvious-reasons-love-wasps-least-hate-much/**
Bumblebee and hoverfly photo: F. Ratto

References

Carthew S. & Goldingay, R. (1997). Non-flying mammals as pollinators. Trends Ecol. Evol., 12, 104-108.

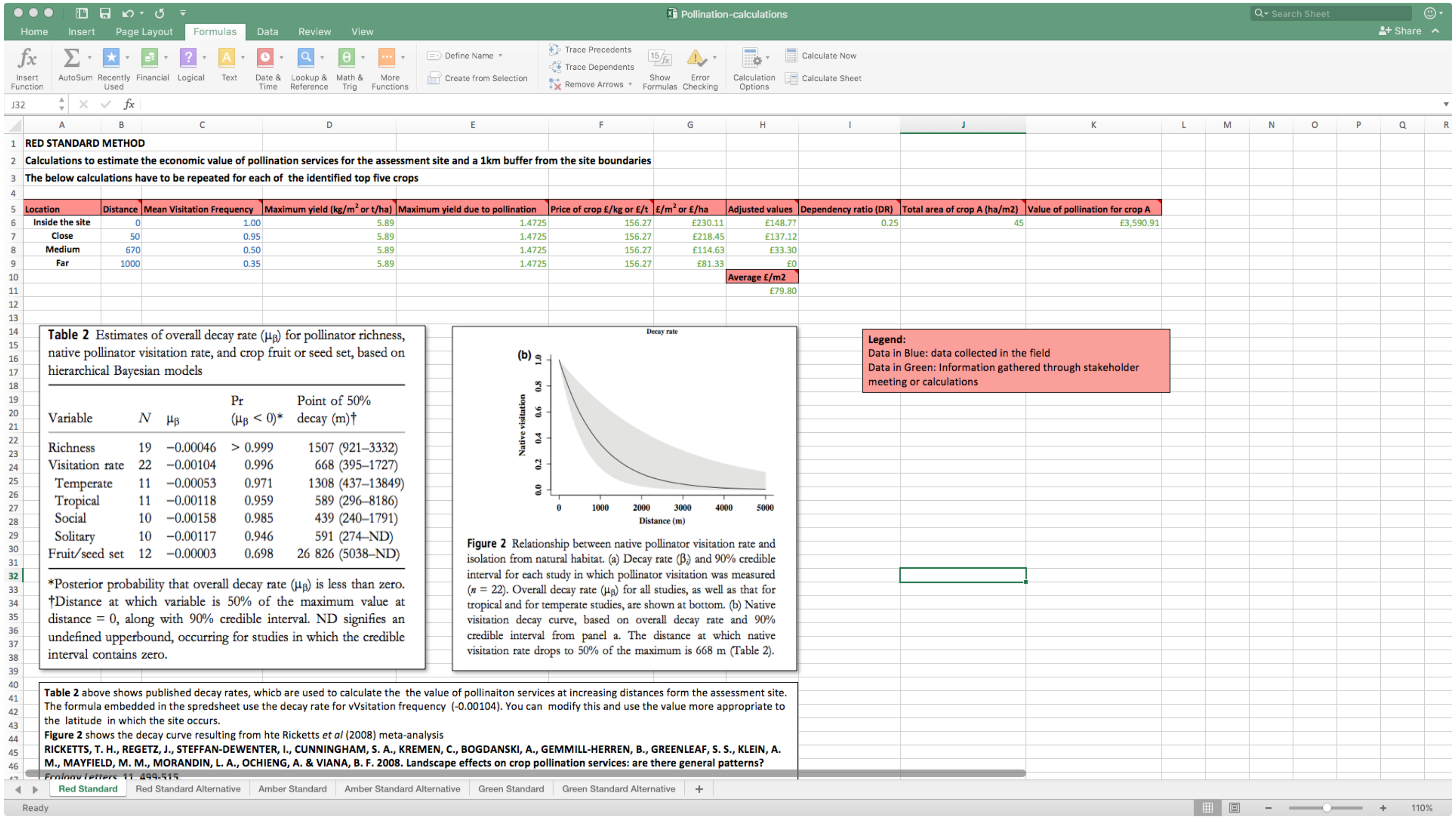
Appendix C.21 Template of data collection sheets for visitation frequency data (Amber standard method), extracted from the "Pollination services" protocol in TESSA V2.0

Amber Method

Pollinators vistation frequency													
Country:													
	Site:							**Year:**		**Crop:**			
							Numer of flower visitors						
Date	Time at start	Weather conditions	Distance from site	Plot N	N of flowers in plot	Honey bee	Bumble bee	Small bee	other				total N visits
				C1									
				C2									
				C3									
				C4									
				C5									
				C6									
				C7									
				C8									
				C9									

Appendix C.22 Spreadsheet with embedded calculations for the estimation of the economic value of pollination service for (a) Red standard methods, (b) Amber standard methods, (c) Green standard methods, extracted from the "Pollination services" protocol in TESSA V2.0

(a)



(b)

AMBER STANDARD METHOD

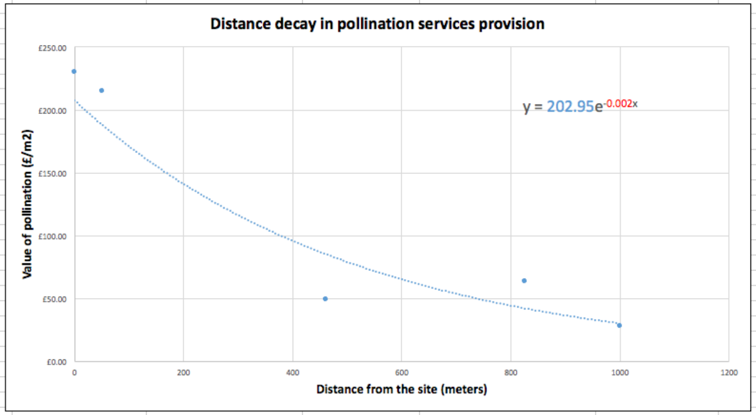
Calculations to estimate the economic value of pollination services for the assessment site and a 1km buffer from the site boundaries

The below calculations have to be repeated for each of the identified top five crops

Location	Sampling location	Plot	No of visitors	No flower heads	distance (m)	Visit/flower/min
Inside the Protected Area	1	PA1	13	300	0	0.00
	1	PA2	33	300	0	0.01
	1	PA3	45	300	0	0.01
	2	PA4	30	300	0	0.01
	2	PA5	30	300	0	0.01
	2	PA6	30	300	0	0.01
	3	PA7	30	300	0	0.01
	3	PA8	20	300	0	0.00
	3	PA9	19	300	0	0.00
close	1	C1	10	300	50	0.00
	1	C2	29	300	50	0.01
	1	C3	47	300	50	0.01
	2	C4	35	300	35	0.01
	2	C5	23	300	35	0.01
	2	C6	23	300	35	0.01
	3	C7	23	300	70	0.01
	3	C8	23	300	70	0.01
	3	C9	20	300	70	0.00
medium distance	1	M1	4	300	456	0.00
	1	M2	2	300	456	0.00
	1	M3	6	300	456	0.00
	2	M4	7	300	366	0.00
	2	M5	7	300	366	0.00
	2	M6	7	300	366	0.00
	3	M7	7	300	560	0.00
	3	M8	6	300	560	0.00
	3	M9	7	300	560	0.00
far	1	F1	7	300	845	0.00
	1	F2	11	300	845	0.00
	1	F3	11	300	845	0.00
	2	F4	11	300	900	0.00
	2	F5	4	300	900	0.00
	2	F6	8	300	900	0.00
	3	F7	5	300	734	0.00
	3	F8	8	300	734	0.00
	3	F9	4	300	734	0.00

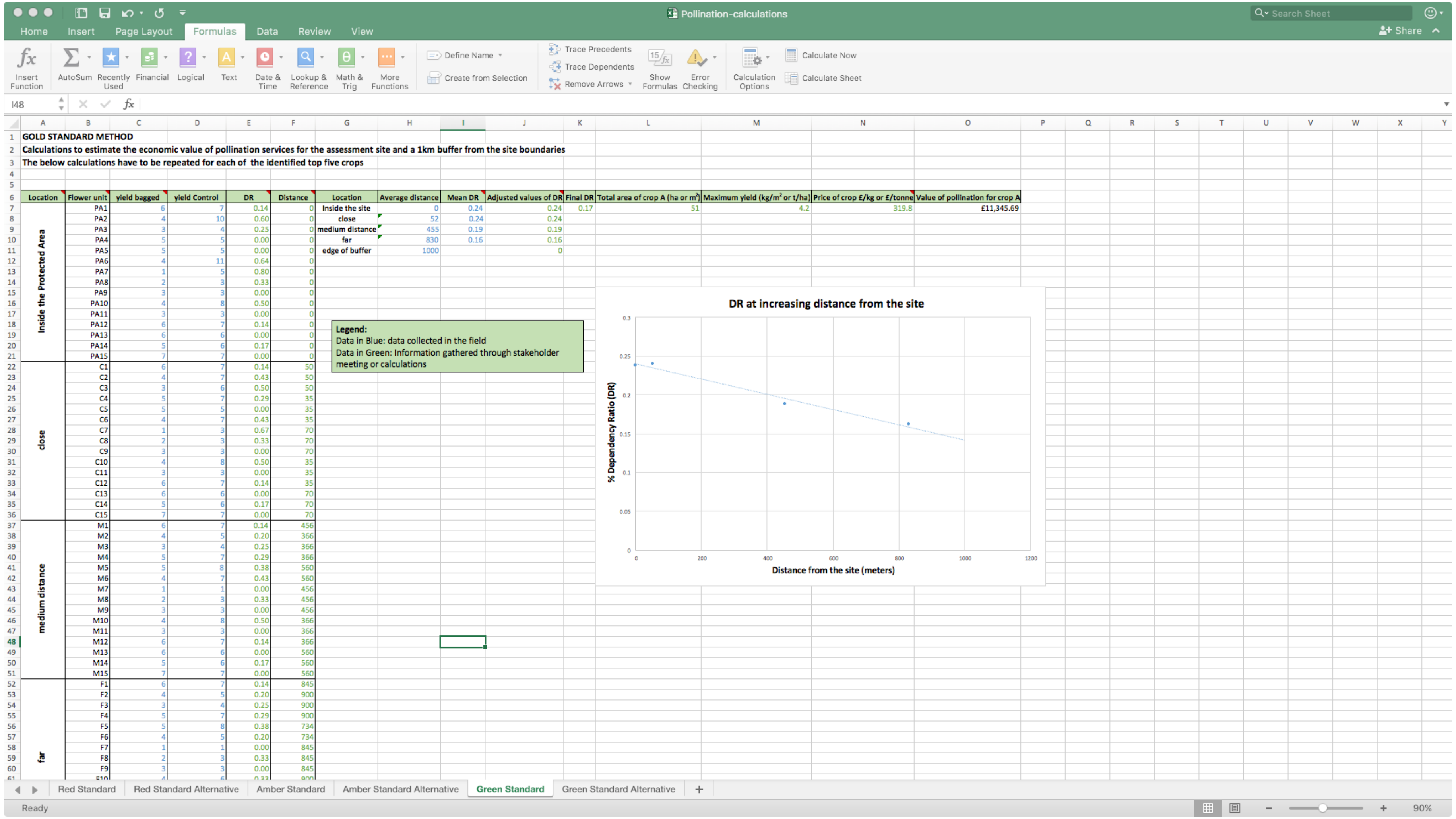
Location	Average Distance	Mean Visitation Frequency	Maximum yield (kg/m² or t/ha)	Dependency ratio (DR)	Maximum yield due to pollination	Price of crop £/kg or £/to	£/m²	Adjusted values	Total area of crop A (ha or m	Value of pollination for crop A
Inside the site	0	0.0062	5.89	0.25	1.4725	156.27	£230.11	£230.11	45	£4,270.15
Close	52	0.0058	5.89		1.4725	156.27	£214.46	£186.99		
Medium	461	0.0013	5.89		1.4725	156.27	£48.78	£21.32		
Far	826	0.0017	5.89		1.4725	156.27	£63.51	£36.04		
Edge of buffer	1000						£27.47	£0		
								Average £/m2		
								£94.89		

Legend:
Data in Blue: data collected in the field
Data in Green: Information gathered through stakeholder meeting or calculations



Red Standard | Red Standard Alternative | Amber Standard | Amber Standard Alternative | Green Standard | Green Standard Alternative

(c)



GOLD STANDARD METHOD

Calculations to estimate the economic value of pollination services for the assessment site and a 1km buffer from the site boundaries

The below calculations have to be repeated for each of the identified top five crops

Location	Flower unit	yield bagged	yield Control	DR	Distance
Inside the Protected Area	PA1	6	7	0.14	0
	PA2	4	10	0.60	0
	PA3	3	4	0.25	0
	PA4	5	5	0.00	0
	PA5	5	5	0.00	0
	PA6	4	11	0.64	0
	PA7	1	5	0.80	0
	PA8	2	3	0.33	0
	PA9	3	3	0.00	0
	PA10	4	8	0.50	0
	PA11	3	3	0.00	0
	PA12	6	7	0.14	0
	PA13	6	6	0.00	0
	PA14	5	6	0.17	0
	PA15	7	7	0.00	0
close	C1	6	7	0.14	50
	C2	4	7	0.43	50
	C3	3	6	0.50	50
	C4	5	7	0.29	35
	C5	5	5	0.00	35
	C6	4	7	0.43	35
	C7	1	3	0.67	70
	C8	2	3	0.33	70
	C9	3	3	0.00	70
	C10	4	8	0.50	35
	C11	3	3	0.00	35
	C12	6	7	0.14	35
	C13	6	6	0.00	70
	C14	5	6	0.17	70
	C15	7	7	0.00	70
medium distance	M1	6	7	0.14	456
	M2	4	5	0.20	366
	M3	3	4	0.25	366
	M4	5	7	0.29	366
	M5	5	8	0.38	560
	M6	4	7	0.43	560
	M7	1	1	0.00	456
	M8	2	3	0.33	456
	M9	3	3	0.00	456
	M10	4	8	0.50	366
	M11	3	3	0.00	366
	M12	6	7	0.14	366
	M13	6	6	0.00	560
	M14	5	6	0.17	560
	M15	7	7	0.00	560
far	F1	6	7	0.14	845
	F2	4	5	0.20	900
	F3	3	4	0.25	900
	F4	5	7	0.29	900
	F5	5	8	0.38	734
	F6	4	5	0.20	734
	F7	1	1	0.00	845
	F8	2	3	0.33	845
	F9	3	3	0.00	845
	F10	4	6	0.33	900

Location	Average distance	Mean DR	Adjusted values of DR	Final DR	Total area of crop A (ha or m²)	Maximum yield (kg/m² or t/ha)	Price of crop £/kg or £/tonne	Value of pollination for crop A
Inside the site	0	0.24	0.24	0.17	51	4.2	319.8	£11,345.69
close	52	0.24	0.24					
medium distance	455	0.19	0.19					
far	830	0.16	0.16					
edge of buffer	1000		0					

Legend:
Data in Blue: data collected in the field
Data in Green: Information gathered through stakeholder meeting or calculations

Appendix C.23 Guidance on how to identify a plausible alternative state, extracted from TESSA V2.0

The need to consider a plausible alternative state

Assessments of the difference resulting from changes in land use can be more useful to decision-makers than single state values. Comparative assessments can make the impacts on biodiversity and on ecosystem services explicit and can provide information on who is affected.

Defining the alternative state

Simple assessments of the value of a particular service or services at an **assessment site** are a useful first step in understanding the importance of the site for delivering benefits to people. However, **decision-makers** are likely to be concerned with the social, ecological and economic consequences of their decisions, and so also need to know the difference between the amount of the ecosystem service(s) provided by a site in its current state compared to a plausible alternative one, where the habitat is converted (e.g. to agriculture), restored (e.g. to a **wetland** following quarrying) or in which resources are used differently (e.g. increased intensity of fishing). This encourages them to consider the impacts of decisions and whether conservation delivers greater benefits than, for example, conversion to other land uses. If this is the case, then information on ecosystem services can be used to support the conservation of a site (e.g. when under threat from conversion or development) or the restoration of a site (e.g. rehabilitating logged forest or polluted or drained wetlands). Additionally, when aggregated at national or regional **scales**, data on ecosystem services at multiple sites could also support arguments for the expansion and enhanced management of protected area networks.

Economists refer to this alternative state as a '**counterfactual**', but here we simply label it as the '**alternative state**' of a site.

The choice of the alternative state will depend on the objective of your assessment. For example, there may be various threats to the **biodiversity** of a site as a result of human activities in the surrounding areas. In this case the alternative state can be 'better' or 'worse' in terms of biodiversity (e.g. natural forest vs cocoa plantations) or it could be two alternative management approaches (e.g. community conserved area and strict protected area).

In determining the alternative state, some of the key considerations will be:

- Policy and management context at a site;
- The most likely threats / drivers of change that occurred in the past or are likely to occur in future;
- Ecological, political and social attributes.

We provide full guidance on how to determine the alternative state in **Using the toolkit**.

Identifying the most plausible alternative state will often require consideration of the broader trends and issues in the locality of your site. For example, is there a development plan for the area, is the expansion of agriculture a policy objective for the government, are local people abandoning land and leaving it unmanaged? This wider context is important to consider when you are identifying which actions and decisions are likely to lead to a change in management, land cover, land use or habitat quality at a site. This may affect the delivery of ecosystem services as well as the conservation of species. For example, changes may occur to habitat types (e.g. forest conversion to agriculture) or to land use (e.g. rice crops being replaced by tea plantations) or in habitat quality (e.g. pollution of waterways).

Introducing ecosystem services and natural capital: key concepts

Land use surrounding Shivapuri National Park, Nepal demonstrating a possible alternative state for the forested protected area. *Credit: Alison Stattersfield*

A pasture in Anguilla representing an alternative land use to the adjacent wood and scrubland. *Credit: Richard Bradbury*

Introducing ecosystem services and natural capital: key concepts

Conversion of wetland to rice paddy in Myanmar
Credit: BANCA

Forest clearance resulting in soil erosion
Credit: Jenny Merriman

Appendix C.24 Questionnaire interviews template for local farmers at the Noar Hill reserve

Farm Code	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5
What is the total size of the land you farm in the area (use local units of area if appropriate):					
Which crops do you grow?					
Unit of measurement for that crop					
Maximum yield (in kg/ha or tonne/ha) achievable in the region for each of the crops you grow?					
What are the production costs for each crop?					
What is the total area (ha) of each crop, that you grow inside Noar Hill?					
What is the total area (ha) of each crop that you grow in a 1km buffer from Noar Hill?					
What is the farm gate price of the crops you grow in your farm					

Appendix C.25 Production costs for oilseed rape and field bean obtained by local farmers at the Noar Hill reserve

Crop Gross Margin Detailed

Main Business: Rotherfield Farms LLP
Year: 2017
Currency: GBP Area:ha

Rotherfield Farms LLP
Joes Laptop
Tel: E-Mail:
07464 543826

gatekeeper

Crop	Working Area	Heading	Value/ha	Value	Value / Unit Output
Rape Winter	43.100	Adjuvants	14.26	614.64	3.898
		Fungicides	86.77	3739.87	23.719
		Herbicides	120.07	5174.90	32.820
		Insecticides	13.37	576.20	3.654
		Molluscicides	4.82	207.64	1.317
		Pesticides	**239.29**	**10313.25**	**65.407**
		Fertiliser	219.25	9449.59	59.930
		Lime	16.77	722.70	4.583
		Organic Manure	0.00	0.00	0.000
		Trace Elements	18.72	806.92	5.118
		Rebates	(1.43)	(61.77)	(0.392)
		Seed / Plants	47.79	2059.90	13.064
		Variable Costs	**540.39**	**23290.60**	**147.711**
		Primary Output	0.00	0.00	0.000
		Outputs	**0.00**	**0.00**	**0.000**
		Establishment	304.65	13130.22	83.273
		Harvest	76.90	3314.31	21.020
		Fixed Costs	**381.54**	**16444.52**	**104.292**
		Gross Margin	(540.39)	(23290.60)	(147.711)
		Net Margin	(921.93)	(39735.12)	(252.003)
		Output quantity	3.66	157.68 t	
Total	43.100	**Gross Margin**	(540.39)	(23290.60)	
		Net Margin	(921.93)	(39735.12)	

Crop Gross Margin Detailed

Main Business: Rotherfield Farms LLP
Year: 2017
Currency: GBP Area:ha

Rotherfield Farms LLP
Joes Laptop
Tel: E-Mail:
07464 543826

gatekeeper

Crop	Working Area	Heading	Value/ha	Value	Value / Unit Output
Beans Spring	48.500	Adjuvants	11.81	572.67	3.920
		Fungicides	36.38	1764.31	12.078
		Herbicides	88.61	4297.65	29.421
		Insecticides	9.74	472.35	3.234
		Pesticides	**146.54**	**7106.98**	**48.653**
		Fertiliser	65.79	3190.66	21.843
		Lime	5.11	247.90	1.697
		Trace Elements	62.81	3046.39	20.855
		Rebates	(3.36)	(162.91)	(1.115)
		Seed / Plants	18.58	901.30	6.170
		Variable Costs	**295.47**	**14330.32**	**98.103**
		Primary Output	441.16	21396.11	146.475
		Outputs	**441.16**	**21396.11**	**146.475**
		Establishment	202.77	9834.49	67.325
		Harvest	75.77	3675.07	25.159
		Fixed Costs	**278.55**	**13509.55**	**92.484**
		Gross Margin	145.69	7065.79	48.371
		Net Margin	(132.86)	(6443.76)	(44.113)
		Output quantity	3.01	146.07 t	
Total	48.500	**Gross Margin**	145.69	7065.79	
		Net Margin	(132.86)	(6443.76)	

Glossary of Terms

Term	Definition
Akaike's Information Criterion (AIC)	A parsimonious quantitative description of model fit by incorporating both deviance explained and number of parameters used
Ecosystem Services	Ecosystem services are the direct and indirect benefits that ecosystems provide to humans, and are classified according to four categories: supporting, regulating, provisioning and cultural services
Linear mixed model	Statistical models that assume the error to be normally distributed and which includes both fixed and random factors
Meta-analysis	Set of statistical techniques for the quantitative synthesis of the results of independent experiments to reach general conclusions
Model selection	A series of approaches to determine the best set of candidate statistical models, which uses information-theoretic approaches based on the Akaike's Information Criterion (AIC). This approach also allows model averaging to be performed
Pollination	Process whereby plant pollen is transferred from the male reproductive organs (anthers) to the female reproductive organs (stigma) to enable fertilization and reproduction. In flowering plants this is done either by wind (anemophily) or by animals (zoophily)
Pollinator	A regular flower visitor that transfers pollen between plants, leading to successful pollination and ultimately the production of seeds
Pollination Services	Regulating ecosystem services consisting in the transfer of pollen between male and female flower organs to enable fertilization. They contribute to human well-being through the production of food, maintenance of ecosystems and through their aesthetic values
Plant reproductive success	Measurement of pollination performance which quantifies the contribution to seed set
Pseudoreplication	The use of inferential statistics to test for treatment effects with data from experiments where either treatments are not replicated or replicates are not statistically independent
Systematic review	Standardized method for collating, reviewing and appraising published scientific data. The data collated through systematic review can be synthesized either narratively or quantitatively by performing meta-analysis