



The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.

Influence of proximity to and type of foraging habitat on value of insect pollination in the tropics, with applications to Kenya

Richard Mulwa*

CASELAP, Faculty of Law & Department of Economics and Development Studies, University of Nairobi, Nairobi, Kenya. E-mail: richard.mulwa@uonbi.ac.ke

Juha Siikamäki

IUCN Economics Unit, Washington DC, USA. E-mail: juha.siikamaki@iucn.org

Michael Ndwiga

Department of Economics and Development Studies, University of Nairobi, Nairobi, Kenya. E-mail: michajairo@gmail.com

Jessica Alvsilver

Swedish Environmental Protection Agency (SEPA), Stockholm, Sweden. E-mail: jessica.alvsilver@naturvardsverket.se

* Corresponding author

Received: September 2022

Accepted October 2022

DOI: [https://doi.org/10.53936/afjare.2022.17\(2\).12](https://doi.org/10.53936/afjare.2022.17(2).12)

Abstract

Insect pollination improves the yield of most crop species and contributes to one-third of global crop production. The importance of this ecosystem service in improving agricultural production has largely been overlooked, however, in favour of practices that improve soil conditions such as fertiliser use and supplementary irrigation. Using economic modelling, this study estimates the value of insect pollination under different land-use types in Kenya. Our model assumes that a combination of land-use type and the foraging distance of insect pollinators influences the intensity of pollination and the value of agricultural output. To demonstrate the hypothesised relationships, areas under different land-use types, e.g. forest, grassland and cropland, and their distances from households were used as proxies for insect pollination. Concentric buffer zones representing foraging distances of pollinators from the land-use types were drawn at 250 m, 500 m, 1 000 m, 2 000 m and 3 000 m from the farms, and areas under each land use in the buffer zones were estimated for the years 2004, 2007 and 2010. Using the random-effects model and an output distance-function stochastic frontier model, the land-use areas, other factors of production and climate variables were regressed on the value of agricultural output in each buffer zone to determine their contribution to agricultural output resulting from insect pollination. The results indicate higher crop productivity on farms bordering forests and grasslands. This implies that insect pollinators are important for crop production, and increasing the number of pollinator habitats closer to the farms will increase food production in the tropics.

Key words: insect pollination; agricultural output; land-use classes (types); multi-output production function; foraging distance; buffer zones

1. Introduction

Improving soil conditions through fertiliser use and irrigation to maximise yields has been given pre-eminence in agriculture in sub-Saharan Africa (SSA) (Gollin 2014; Lema *et al.* 2014; Güneralp *et al.* 2017), whereas the potential contribution of pollination to optimise crop yields has largely been overlooked. Pollination, a key mobile agent-based ecosystem service (MABES), is produced at a local scale both by wild, free-living organisms – mainly bees, but also by many butterflies, moths, flies, beetles and wasps, other invertebrates, birds and mammals; and by commercially managed bee species, primarily the honeybee (Lundberg & Moberg 2003; Sekercioglu 2006; Kremen *et al.* 2007). According to Klein *et al.* (2007), 35% of global food production comes from animal-pollinated crops, while the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has estimated the direct economic contribution of animal pollinators to global agricultural production to be in the range of 5% to 8% (IPBES 2016). The value of the worldwide contribution by pollinators to human food crops has been estimated at €153 billion, with the crops vulnerable to pollinator scarcity being more sensitive to price variation (Gallai *et al.* 2009). Research from 200 countries shows that agricultural productivity of 87 out of 115 of the leading global food crops is dependent upon animal pollination (Klein *et al.* 2007).

Over the last five decades, the volume of production by pollinator-dependent crops has increased by 300%, making livelihoods increasingly dependent on the provision of pollination (Potts *et al.* 2010). In many parts of Africa, the most important cash crops, including coffee, cocoa, sesame, cotton and many pulses and oil crops, are pollinator-dependent (Munyuli 2014), and the negative consequence of any decline in pollinators can cause a reduction in average yield gap to a magnitude of 37% for cotton production and 59% for sesame production (Stein *et al.* 2017). The promotion of pollination services is therefore beneficial to agricultural productivity, food security, and the achievement of the UN's sustainable development goals (Boruff *et al.* 2020; Sawe *et al.* 2020). For the many pollinator-dependent crops in SSA, pollinators provide a free and potentially diverse ecosystem service to farmers (Klein *et al.* 2008; Tibesigwa 2018); and, as the cultivated crop areas continue to increase, the supply of pollinators is becoming increasingly threatened, thus posing pollination-driven declines in food production (Winfrey 2003; Ghazoul 2007; Ollerton 2017). This is because the rich pollinator diversity found in SSA is under threat from potentially damaging practices, such as a growing reliance on fertilisers and pesticides in the region (Eardley *et al.* 2006; Raina *et al.* 2011; Elisante *et al.* 2017). While the risk of falling crop yields due to inadequate pollination services is a key topic of policy importance (Kleijn *et al.* 2015), comparatively little research and policy focus have concentrated on developing countries, where reliance on insect-pollinated or pollinator-dependent crops is increasing (Aizen *et al.* 2019; Fijen *et al.* 2020).

Insects comprise the most diverse and successful group of multicellular organisms on the planet and contribute significantly to vital ecological functions, such as pollination, pest control, decomposition and maintenance of wildlife species (Nee 2004; Losey & Vaughan 2006), and crop pollination is perhaps the best-known ecosystem service performed by insects. Wild or domesticated insects pollinate many fruits, nuts, vegetables, oils and animal forage. They provide pollination services by delivering a sufficient quantity and quality of pollen at the appropriate time and place for fertilisation in about 70% of crop species worldwide (Klein *et al.* 2007). Insect pollination improves the yield of most crop species and contributes to one-third of global crop production (Klatt *et al.* 2014). Several habitats influence the abundance of insect pollinators. These include forests (natural and artificial), shrublands and grasslands, agriculture, e.g. plantations, and settlements (urban and rural). Agriculture and urban settlements cover almost 40% of Earth's ice-

free terrestrial land, with an additional 37% being rangelands and semi-natural habitats that are embedded within agricultural or settled landscapes (Ellis *et al.* 2010). How much habitat is needed and how it should be distributed within agricultural landscapes is not yet known (Kremen *et al.* 2007; Brosi *et al.* 2008). The habitat affinity of most pollinator species is also unknown, although natural or semi-natural landscapes within agricultural landscapes often provide habitat for wild pollinator species, from which they forage on flowering crops and weed plants in agricultural fields (Kremen *et al.* 2007; Ricketts *et al.* 2008). In addition, flowering crops themselves often provide important resources for many pollinator species, although their capacity to support diverse and abundant pollinator communities has been compromised by the short duration of floral availability, the low diversity of floral and nesting resources, and pesticide application and tillage (Potts *et al.* 2010; Williams *et al.* 2010). Therefore, maintaining pollinator habitats and pollinator diversity within agricultural landscapes is essential to ensure food production, quality and security.

Another important factor influencing insect pollination is the foraging distance, which strongly influences the sexual reproduction of most flowering plants and can determine the genetic structure of plant populations (Campbell 1985; Waser *et al.* 1996). For example, pollinators may not visit small or isolated plant populations, leading to plant reproductive failure (Cunningham 2000; Lennartsson 2002). In contrast, long-distance foraging, even by introduced species, may rescue mating in otherwise doomed plants within habitat fragments (Dick 2001). Many wild bees that pollinate crops do nest in their natural habitats and forage on crops within their daily travel distance (Ricketts 2004). Foraging distance therefore determines the spatial scale at which wild bees can provide pollination services to crops (Kremen 2005). According to Greenleaf *et al.* (2007), foraging distance non-linearly increases with body size, with larger bees having disproportionately larger foraging distances than smaller bees.

Over the last few decades, there has been significant habitat transformation due to anthropogenic-induced complex land-use change processes. Pollinator responses to this habitat transformation might be conditioned by the type and extent of land-use changes. According to Tilman *et al.* (2001), the interactions between plants and pollinators are increasingly situated within ecosystems dominated by human land use, which is predicted to increase rapidly over the next few decades as the human population grows. Many scientists are concerned that pollinators are declining globally. This is because there have been drastic shifts in the community composition of insects that visit flowering crops (Bommarco *et al.* 2010; Winfree *et al.* 2011; Bartomeus *et al.* 2013), and declines in the numbers of pollinator species observed in some regions (Potts *et al.* 2010; Carvalheiro *et al.* 2011). Not all pollinator species respond equally to land-use change (Williams *et al.* 2010; Winfree *et al.* 2011), and some even increase in abundance with agricultural intensification (Westphal *et al.* 2008; Carré *et al.* 2009). According to Kennedy *et al.* (2013), pollinator species richness consistently and drastically decays as agricultural landscapes are deprived of natural habitat and are more intensively cultivated (Ricketts *et al.* 2008; Garibaldi *et al.* 2011). However, the fruit set does not fail completely, as the remaining pollinators provide sufficient visitation even in homogenous, intensively cultivated landscapes, especially if the crop has a large degree of autonomous self-pollination. Moreover, intensive landscapes are characterised by harbouring just a few generalist pollinator species (Bartomeus & Winfree 2013), but these might be insufficient numbers to deliver enough crop pollination services. In some cropping systems, this diversity of pollinator responses can buffer a loss of pollination functioning (Cariveau *et al.* 2013), especially if the pollinators are adapted to the ephemeral and patchy resource distribution that is typical of agricultural landscapes.

Given the current era of increasing anthropogenic land-use change, it is important to understand the effects of such land use on insect species that provide pollination. This is because the response of pollinators to human-induced land-use change has important implications for plants and the species that depend on them (Winfree *et al.* 2011) and, by extension, the availability of human food and

animal forage. The composition of the landscape in which the flowering crop field is embedded emerges as an important driver of pollinator community composition, and the landscape context needs to be considered when linking land use to pollination provisioning and benefits in field crops. This will be useful in determining the economic value of pollination and help design policies to maintain the landscape necessary for insect pollinators. For this reason, this study assesses the contribution of insect pollination to agricultural production. Using the different land-use classes (forest, grassland and cropland), insect pollination is modelled as a component of the agricultural production process which, alongside other conventional inputs and climate factors, influences agricultural production. To focus our study, we confined ourselves to the estimation of the economic value of pollination produced by wild (i.e. unmanaged) native insects, especially bees, which are the primary pollinators in most ecological regions of the world (Axelrod 1960; Bawa 1990).

2. Methodological approaches

Several studies have attempted to value wild pollinators, with a much larger body of literature focusing on the value of honey-bee pollination (Winfree *et al.* 2011). These evaluations have focused on the benefits to producers, which have been estimated as either the cost of alternative pollination sources (Allsopp *et al.* 2008) or the value of production resulting from insect pollination (Losey & Vaughan 2006). The cost of alternative pollination sources assumes a situation where insect pollination is substituted by an alternative technology, such as managed pollinators, hand pollination or pollen dusting, but offers a similar service, i.e. a replacement-value method (De Groot *et al.* 2002; Winfree *et al.* 2011). However, according to Gallai *et al.* (2009), the value-of-production approach is problematic because it attributes a crop's full value to pollination, while the production of most crops suffers only to some degree in the absence of insect pollinators. The value of wild pollination services has also been estimated using rental fees paid for them (Rucker *et al.* 2003), but this fails to capture consumer willingness to pay to ensure quality pollination and ignores production costs (National Research Council 2007). Other attempts have been to calculate the total value of insect-pollinated crops (Levin 1984; Robinson *et al.* 1989; Costanza *et al.* 1997; Pimentel *et al.* 1997).

An improvement on the value-of-production approach is the bioeconomic approach, in which the crop's total value is multiplied by a coefficient representing the crop's dependence on pollination (Robinson *et al.* 1989; Morse & Calderone 2000; Gallai *et al.* 2009). The bioeconomic approach is more widely used and focuses on the value of crop production attributable to pollination. The logic is that, for pollination-dependent crops, production, or yield, is assumed to fall when pollinators decline. The reduction in production or yield is approximated using studies of the dependence of fruit set on the presence of insect pollinators (Klein *et al.* 2007). The expected fractional yield loss in the absence of pollinators is then multiplied by the market value of production (Robinson *et al.* 1989; Morse & Calderone 2000). The general framework, which was also used by Winfree *et al.* (2011), assumes that the change in the value of pollination, V , is given by

$$V = (pY - cY) \cdot D \cdot \rho, \quad (1a)$$

where p is the price of the output Y , and c is the variable cost of production. D is the dependence of the crop on insect pollination, while ρ is the proportion of or percentage reduction in pollinators. Although widely applied (Robinson *et al.* 1989; Morse & Calderone 2000; Losey & Vaughan 2006; Gallai *et al.* 2009), this approach gives only a general picture of how much the value of pollination is expected to change if the proportion of pollinators reduces. The shortfall of this method is that it attributes crop market value solely to pollination, ignoring the contribution of other inputs (National

Research Council 2007). Hein (2009) improves on the bioeconomic approach by introducing other factors of production. His formulation estimates the influence of pollination on welfare as

$$W = S \cdot \Delta q(pQ - cQ), \quad (1b)$$

where W is welfare, S is area under production (ha), Δq is the increase in productivity due to pollination, p is the farmgate price of output, c are the variable costs of production, and Q is the output. An increase in productivity due to pollination (Δq) can be estimated from an appropriate production function to determine the marginal effects of a unit change in pollination services on agricultural output. The value of crop pollination cannot be separated from the agricultural production process, since agricultural production depends on a range of inputs. These include labour, capital, land, inputs (e.g. seeds, fertilisers) and, for some crops, pollination. For this reason, pollination can be interpreted as one of the ‘inputs’ into agricultural production (Hein 2009); therefore, the production function approach method best suits this service (Freeman 1993).

2.1 Proposed modelling of insect pollination and agricultural output

To extend the production function, we propose an approach where insect pollination services influence agricultural output and therefore should enter the farm’s production function in some form. Our theoretical model follows the damage control function of Lichtenberg and Zilberman (1986). In their model, they argued that pesticides that control pests cannot be treated the same as fertilisers, because fertilisers are used directly in crop production, while pesticides are used to control any pests that might attack the plant, hence are damage control inputs. They discuss the special nature of damage control inputs (pesticides, herbicides, etc.) by using a built-in ‘damage control function’ in the production function. The same argument can be used for pollination services, which cannot enter the production function directly as a conventional input, although they have a bearing on the level of production through their support of pollination. This calls for the specification of a ‘pollination service function’ alongside the usual production function. Lichtenberg and Zilberman (1986) modelled the damage control function using a separate structure, given as:

$$y = F(x^D, g(x^P, z)), \quad (2)$$

where x^D is a vector of M direct inputs (labour, seed, fertilisers and other inputs), x^P is the vector of R damage control inputs (such as pesticides), and z is the vector of S damage factors (pests). Using the same argument in a pollination service setup, we assume ($k = 1, \dots, K$) farming households operating in time periods denoted $t = (1, \dots, T)$, using technology subset Γ . The households use a vector of direct inputs (labour, seed, fertilisers and other inputs), denoted by $x = (x_1, \dots, x_n) \in \mathbb{R}^{N+}$, which are used to produce a non-negative vector of farm outputs (e.g. fruits, cereals, vegetables, legumes, etc.), denoted by $y = (y_1, \dots, y_m) \in \mathbb{R}^{M+}$, which may or may not depend on insect pollination. The K households are located in specific agro-ecological zones with different climate variables, e.g. rainfall and temperature, as in $w = (w_1, \dots, w_q) \in \mathbb{R}^{Q+}$, and land-use types, e.g. forests, grasslands and croplands, denoted as $l = (l_1, \dots, l_d) \in \mathbb{R}^{D+}$, which are expected to influence the level of pollination as they harbour insect pollinators at various concentrations. Borrowing from Lichtenberg and Zilberman (1986) and Kuosmanen *et al.* (2006), we assume that agricultural production is subject to farm inputs, climatic variables and pollination services, and can be modelled by production function f and climate-pollination function g , with a separable structure expressed as:

$$y = F((x), g(w, l)) \quad (3)$$

In practice, the functional forms f and g are not usually known, and the common approach has been to assume certain parametric forms (e.g. Cobb-Douglas, CES, translog, etc.) and use either OLS or MLE to estimate the function. However, there is no theoretical reason for assuming a certain functional form *a priori*. The output \mathbf{y} in the production function can be a single output – as is the case with most conventional estimations – or a vector of more than one output, in which case the standard estimation technique may not suffice. For example, in this study, the value of agricultural output (dependent variable) has been treated as a vector with three categories of values of outputs. These are: a) value of pollination-dependent crops; b) value of pollination-independent crops; and c) value of pollination-indeterminate crops. This categorisation of the dependent variable requires the adoption of a multi-output multi-input production function specification.

2.2 Extending into multi-output production function

Many production processes produce more than one output, which are often aggregated into one. For example, in mixed cropping agriculture, a household may produce cereals, legumes, fruits and vegetables on the same plot, while using common inputs like fertiliser, labour, herbicides, etc. It might, for instance, be difficult to separate the inputs due to a specific output. The most natural way to handle this kind of production problem is to aggregate output into a single output using some monetary measure, e.g. profit, revenue, etc. In other cases, however, this aggregation, although feasible, may not achieve the desired results, hence the need to handle different outputs separately. In such instances, the multi-output distance function formulation is used. To motivate this formulation, we define the production set of the farming household using the transformation function, $AT(\mathbf{x}, \mathbf{y})$, which represents the set of all output vectors, $\mathbf{y} \in R_+^M$, which can be produced using the input vector $\mathbf{x} \in R_+^N$. The A term captures the influence of observed and unobserved factors that affect the transformation function neutrally. The production technology can therefore be expressed as

$$AT(\mathbf{x}, \mathbf{y}) = P(\mathbf{x}) = \{\mathbf{y} \in R_+^M : \mathbf{x} \text{ can produce } \mathbf{y}\} \quad (4)$$

From this transformation function we can either define an output distance function or an input distance function (Coelli *et al.* 1998; Coelli & Perelman 1999, 2000). However, for the purposes of this study, we only explore the output distance function (Shephard 1970), which is defined on the output set, $P(\mathbf{x})$, as

$$AT(\mathbf{x}, \mathbf{y}) = D^o(\mathbf{x}, \mathbf{y}) = \min[\delta : (\mathbf{y}/\delta) \in P(\mathbf{x})] \quad (5)$$

The output distance function, $D^o(\mathbf{x}, \mathbf{y})$, is non-decreasing, positively linearly homogeneous and convex in \mathbf{y} , and decreasing in \mathbf{x} . It will take a value less than or equal to one if the output vector, \mathbf{y} , is an element of the feasible production set, $P(\mathbf{x})$. That is, $D^o(\mathbf{x}, \mathbf{y}) \leq 1$ if $\mathbf{y} \in P(\mathbf{x})$. In addition, the output distance takes a value of one if \mathbf{y} is located on the outer boundary of the production possibility set. That is, $D^o(\mathbf{x}, \mathbf{y}) = 1$ if $\mathbf{y} \in \text{Isoq } P(\mathbf{x})$ (Lovell *et al.* 1994). If the transformation function is separable (i.e. the output function is separable from the input function), we rewrite Equation (5) as

$$ATy(\delta\mathbf{y}).Tx(\mathbf{x}) = D^o(\mathbf{x}, \mathbf{y}) \quad (6a)$$

If we assume that both $Ty(\cdot)$ and $Tx(\cdot)$ are of Cobb-Douglas¹ functional form, then, if producers use a vector of N inputs to produce M outputs in t different periods, the output-oriented distance frontier is defined as follows:

¹ Note that this can be relaxed to accommodate other flexible functional forms.

$$A \prod_m \lambda \{y_{mt}\}^{\alpha_{mt}} \cdot \prod_n \{x_{nt}\}^{\beta_{nt}} = D_{kt}^O(\mathbf{x}, \mathbf{y}, \mathbf{t}), \quad (6b)$$

where α_m and β_n parameters are of opposite signs. That is, either $(\alpha_m < 0 \forall m)$ or $(\beta_n < 0 \forall n)$, and vice versa. There is an identification issue in Equation (6b), viz. (A, α_m, β_n) cannot be separately identified without further restrictions. Therefore, we can always rescale \mathbf{y} or \mathbf{x} along with A and still obtain 1. To circumvent this issue, we select one parameter to fix for the normalisation. For the output distance function, $(\delta = 1)$, the linearisation of Equation (6b) gives

$$\ln A + \sum_{m=1}^M \alpha_m \ln y_{mkt} + \sum_{n=1}^N \beta_n \ln x_{nkt} = \ln D_{kt}^O(\mathbf{x}, \mathbf{y}, \mathbf{t}). \quad (7)$$

In order to qualify as an output-oriented distance frontier, Equation (7) must fulfil the following regularity conditions: symmetry, monotonicity, positive linear homogeneity, non-decreasing and convex in outputs (\mathbf{y}), and decreasing in inputs (\mathbf{x}) (Lovell *et al.* 1994). The convexity condition ensures that the distance frontier displays diminishing marginal rates of technical substitution. Empirically, the homogeneity restriction can be imposed by normalising all outputs in the function by an arbitrary output (e.g. y_1), which, according to Coelli and Perelman (2000), yields

$$\ln A + \sum_{m=1}^M \alpha_m \ln \frac{y_{mkt}}{y_{1kt}} + \sum_{n=1}^N \beta_n \ln x_{nkt} = \ln \frac{D_{kt}^O(\mathbf{x}, \mathbf{y}, \mathbf{t})}{y_{1kt}} \quad (8)$$

Note that the inputs remain constant in this transformation, and we are seeking to expand output by the largest margin feasible while holding the inputs constant. Equation (8) can be rewritten as

$$\ln A + \sum_{m=1}^{M-1} \alpha_m \ln \frac{y_{mkt}}{y_{1kt}} + \sum_{n=1}^N \beta_n \ln x_{nkt} = \ln D_{kt}^O(\mathbf{x}, \mathbf{y}, \mathbf{t}) - \ln y_{1kt}, \quad (9a)$$

which can be rearranged to

$$-\ln y_{1kt} = \ln A + \sum_{m=1}^{M-1} \alpha_m \ln \frac{y_{mkt}}{y_{1kt}} + \sum_{n=1}^N \beta_n \ln x_{nkt} - \ln D_{kt}^O(\mathbf{x}, \mathbf{y}, \mathbf{t}), \quad (9b)$$

where $-\ln D_{kt}^O(\mathbf{x}, \mathbf{y}, \mathbf{t})$ corresponds to the radial distance function from the boundary of the frontier. From Equation (9b), we can select parameter values for the Cobb-Douglas function that ensure the function fits the observed data as closely as possible, while maintaining the requirement that $0 \leq D^O(\mathbf{x}, \mathbf{y}) \leq 1$, which implies that $-\infty \leq \ln[D^O(\mathbf{x}, \mathbf{y})] \leq 0$. In a stochastic frontier framework (Aigner *et al.* 1977; Meeusen & Van den Broeck 1977), the distance from each observation to the frontier is defined as inefficiency and can be expressed as $[-\ln D_{kt}^O(\mathbf{x}, \mathbf{y}, \mathbf{t}) = u_{kt}]$ (Coelli & Perelman 1999, 2000). If the symmetric error term, v_{kt} , is added to Equation (9b), the normalised output-oriented distance frontier can be written as:

$$\ln y_{1kt} = - \left[\ln A + \sum_{m=1}^{M-1} \alpha_m \ln \frac{y_{mkt}}{y_{1kt}} + \sum_{n=1}^N \beta_n \ln x_{nkt} + v_{kt} + u_{kt} \right] \quad (9c)$$

In a non-stochastic frontier framework, the formulation takes the form $(v_{kt} + u_{kt} = \varepsilon_{kt})$. In line with the way Equation (9c) is specified, a negative sign in front of the input distance elasticities is interpreted as a positive contribution of the inputs (\mathbf{x}) to the production of the output (\mathbf{y}). Similarly, a positive sign in front of other outputs' distance elasticity implies a negative shadow share contribution of other outputs relative to the dependent output in the overall production (i.e. reflecting the degree of substitution) (Mensah & Brümmer 2016). However, to avoid confusion in interpretation, we will express the dependent variable in absolute terms.

Given the forgoing discussion, we can now express Equation (3) in the form of a multi-output Cobb-Douglas production function. We do this by expressing conventional factors of production, $f(\mathbf{x})$, and climate variables, $g(\mathbf{w})$, differently from pollination services variables. From Equation (9c), pollination service variables $g(\mathbf{l})$ are modelled as exponential functions of \mathbf{y} in a multi-output production framework. That is,

$$|\mathbf{y}| = A \prod_{m=1}^{M-1} \left(\frac{y_m}{y_1} \right)^{\alpha} \cdot \prod_{n=1}^N (\mathbf{x})^{\beta} \cdot \prod_{q=1}^Q (\mathbf{w})^{\mu} \cdot \prod_{d=1}^D \exp(\gamma_d \mathbf{l}_{dkt}) \cdot \exp(\epsilon) \quad (9d)$$

Including time (t) and individual farm (k) notations, Equation (9d) can be expressed in the following linear additive form:

$$\ln|y_{1kt}| = \ln A + \sum_{m=1}^{M-1} \alpha_m \ln \frac{y_{mkt}}{y_{1kt}} + \sum_{n=1}^N \beta_n \ln x_{nkt} + \sum_{q=1}^Q \mu_q \ln w_{qkt} + \sum_{d=1}^D \gamma_d \ln l_{dkt} + \epsilon_{kt}, \quad (9e)$$

where y_{1kt} is dependent and normalising output, \mathbf{y}_{mkt} is a vector of other outputs, \mathbf{x} is a vector of conventional production inputs (seed, fertiliser, etc.), \mathbf{w} is a vector of climate variables (rainfall and temperature), \mathbf{l} is a vector of land-use classes used to proxy pollination, and $\alpha, \beta, \mu, \gamma$ are parameters to be estimated. Note that, for multi-output functions, the parameter estimates do not change, irrespective of the output chosen (i.e. you can recover model information from one equation, so it is not necessary to estimate all the equations). For instance, in this study, by estimating one equation (e.g. pollination-dependent equation), one can recover information for the remaining two.

3. Data

This study used Kenya's rural household survey datasets for the periods 2000, 2007 and 2010. The Tegemeo Institute of Agricultural Policy and Development (a research institute of Egerton University, Kenya) conducted the surveys in collaboration with Michigan State University.² The collected data were from 2 297, 1 342 and 1 313 households in the three years respectively, spread over 24 districts in the country. For our analysis, however, 1 301 households for each period (a balanced panel of a total 3 903 households for the three panels) from 22 districts across the country were used. The districts were drawn from six of the eight provinces in Kenya and covered four main agroecological zones and their sub-categorisations. These included coastal lowlands, lowlands, lower and upper midlands, and highlands (lower and upper). The districts vary in a range of agroclimatic conditions (i.e. rainfall, temperature, drought conditions or precipitation-evapotranspiration index, and elevation). The data captured socio-economic characteristics, including age, education and household size. Household income sources, besides crop and livestock, include salary earning and individual business activities. The survey data were also complemented by data on climate variables, namely rainfall and temperature. Rainfall data were obtained from CHIRPS³ (the Climate Hazards Group InfraRed Precipitation with Stations) data archive. Temperature data were sourced from the Global Historical Climatology Network version 2 dataset and the Climate Anomaly Monitoring System (GHCN CAMS).⁴ The dependent variable in the model is the agricultural value of harvested crops, categorised into pollination-dependent, pollination-independent and pollination-indeterminate categories. This classification of the different

² <http://www.tegemeo.org/>

³ CHIRPS is a 30+ year quasi-global rainfall dataset that incorporates satellite imagery with in situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring (Funk *et al.* 2014).

⁴ GHCN CAMS contains high-resolution analysed global land surface temperatures from 1948 to the present, and captures the most common temporal-spatial features in the observed climatology and anomaly fields over both regional and global domains (Fan & Van den Dool 2008).

pollination classes is after Klein *et al.* (2007), who sorted crops by impact of biotic pollination (increased fruit set, weight and/or quality, seed volume and/or quality, and/or pollen deposition) into five categories: a) essential (pollinator loss would lead to production loss of at least 90%); b) great (potential production loss of 40% to 90%); c) modest (potential production loss of 10% to 40%); d) little (potential production loss of 0% to 10%); and e) no increase (pollinators do not increase production).

Our categorisation aggregated all crops that depend on pollination for any proportion of their production into one category, i.e. the classes essential, great, modest and little pollination dependency were grouped under pollination dependent. In this category are most fruits and vegetables. The second category included those that showed no increase in production, even with pollination. These were categorised as pollination independent. This category comprises most cereals. The third category is the value of crops for which the effect of pollination is not known. These were categorised under pollination indeterminate, and consisted of crops like tobacco, amaranth, spinach, etc. The aggregated values and the total agricultural value are shown in Table 1. The total mean revenue for the farms considered in this study was Ksh 27 129 (US\$ 271.29) per acre, which comprised of Ksh 10 019 (US\$ 100.19) per acre from pollination-dependent crops, Ksh 13 143 (US\$ 131.43) per acre from pollination-independent crops, and Ksh 1 919 (US\$ (19.19) per acre from pollination-indeterminate crops.

To produce the values of agricultural output presented in Table 1, households require conventional inputs, which include seed, fertiliser, labour and other consumable inputs (pesticides, herbicides, etc.). The mean values in Ksh per acre for the inputs is given in Table 2.

Table 1: Insect pollination dependence of agricultural values (Ksh) per acre/year

Year	2004		2007		2010		Overall	
Statistic	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Increase	4 310.08	10 552.81	4 697.24	10 524.65	7 649.21	17 763.18	5 552.50	13 467.38
Essential	451.52	1 520.39	315.90	1 455.37	256.06	1 140.72	341.14	1 384.15
Great	506.21	2 013.58	463.49	1 726.41	524.15	1 494.39	497.96	1 757.34
Little	1 844.44	3 395.63	1 941.32	5 719.20	3 066.02	5 430.56	2 284.01	4 986.95
Moderate	938.24	6 969.62	1 171.16	5 457.25	1 932.09	8 472.24	1 347.16	7 085.18
Dependent	8 045.32	16 006.24	8 585.77	16 108.88	13 425.64	24 072.72	10 018.91	19 254.34
Independent	9 881.63	15 783.56	11 797.34	17 646.76	17 751.34	26 814.10	13 143.44	20 916.99
Indeterminate	766.01	4 437.52	2 410.35	5 741.48	2 579.88	4 793.33	1 918.87	5 086.16
Total farm value	21 672.43	32 564.80	24 143.91	29 611.45	35 572.86	42 975.81	27 129.73	36 019.89

1US\$ = Ksh 100

Table 2: Cost of conventional inputs (Ksh per acre/year)

Year	2004		2007		2010		Overall	
Statistic	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Seed	282.84	587.54	399.28	753.91	1 117.03	1 942.42	599.80	1303.00
Fertiliser	1 012.43	3 774.28	51.74	72.20	665.20	2 036.52	576.45	2507.44
Labour	2 560.94	8 691.38	2 943.37	5 674.48	2 904.88	3 084.45	2803.07	6252.53
Others	507.21	3 124.87	2 664.78	4 744.69	3 665.76	6 756.08	2279.80	5263.13

1US\$ = Ksh 100

Pollinators inhabit different land-use types, which were identified using regional land-cover maps. The areas under different land-use types were divided into concentric buffer zones of 250 m, 500 m, 1 000 m, 2 000 m and 3 000 m. The rationale for creating these buffer zones was informed by the fact that pollinators fly from different distances to forage, and the proximity of the farm to the pollinator habitat influences the frequency and number of pollinators on a farm. Six major categories of land-use classes (forest, shrub/grassland, cropland, settlement/bare, wetlands and

water) were defined from regional land-cover maps. Our concern, however, was with pollinator habitats, and land-use types deemed unimportant for pollinators, such as settlement/bare, wetlands and water, were dropped from the analysis. For the remaining land-use types, we estimated the areas (in square kilometre) in each buffer zone and calculated the proportions of the different areas in each buffer zone.

The Tegemeo data for the different households had geographical coordinates that provided us with their latitude and longitude. This tabular data was converted into a spatial format using a geographical information system (GIS). The GIS platform used in this study was the ESRI ArcGIS 10.1 suite. The household location data were stored as a point feature shapefile in a projected coordinate reference system. Buffers were generated around these point features using the buffer geoprocessing tool of ArcGIS. These buffers were generated separately for different distances from the household point. The distances specified were 250, 500, 1 000, 2 000 and 3 000 metres. Each buffer was maintained pristinely by not merging buffers, even where they overlapped. The buffers were named by using a unique household identity of their point features.

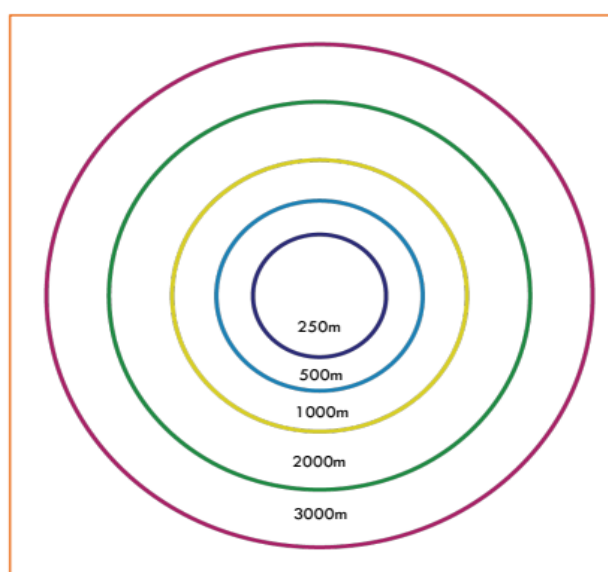


Figure 1: An illustration of habitat buffers

The other data used in this study were land-cover maps, showing the coverage of different land-cover classes regionally. These maps were created by the European Space Agency using imagery from Earth-observation satellite sensors. Satellite imagery was processed to produce representations of the different land covers and map their spatial distribution across the land surface. These data were provided in raster format, with each grid cell having a value representing the land-cover class it represented. Land-cover maps of the years 2004, 2007 and 2010 were obtained to represent the years included in the study. The many land-use classes in these maps were amalgamated into six principal classes, viz. forest, croplands, wetlands, shrubs and grasslands, settlement and bare areas, and water. This generalisation was done using the Lookup tool of the Reclassify toolset of the Spatial Analyst toolbox. The reclassified rasters were converted to integer format using the Copy tool of the Raster Dataset toolset of the Data Management toolbox. The integer rasters were then converted into polygons using the Raster to Polygon tool of the From Raster toolset of the Conversion toolbox. The value of the grid cells was the chosen field for assigning value from the raster cells to the polygons. The outlines of the raster cells were not simplified in order to retain the spatial dimensions of the original datasets.

The Tabulate Intersection tool of the Statistics toolset of the Analysis toolbox was configured to analyse the described datasets. The buffers for each household were the input for the zone features, while the land-cover polygons were the input for the class features. A script was developed to compute a geometrical intersection of the feature classes and to cross-tabulate the areas and proportions of the intersecting features. This configuration allowed the calculation of how much of each buffer was intersected by each class. The resultant table specified the area of a buffer taken up by each -and cover class and the proportion this area represented. This analysis was iterated to exhaustively combine the five differently sized buffers and the three different years of land-cover data.

The mean areas in hectares under the different buffer zones are as shown in Table 3. Our hypothesis is that insect pollinators originate from the different land-use classes, and that there is a decaying exponential relationship between household farm revenue and the insect foraging distance, such that the further the land-use type from the household, the lower the revenue from insect pollination.

Table 3: Buffer areas for different land-use classes in hectares

Year	2004		2007		2010		Overall	
Statistic	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Forest 250 m	8.96	9.1	9.02	9.08	9.01	9.08	9.00	9.09
Forest 500 m	26.9	25.86	26.97	25.89	27.24	25.96	27.04	25.9
Forest 1 000 m	107.9	97.18	107.80	97.06	109.40	97.46	108.36	97.21
Forest 2 000 m	433.97	367.7	435.39	368.49	439.18	367.18	436.18	367.71
Forest 3 000 m	725.81	591.16	727.30	594.23	732.02	592.10	728.38	592.35
Grassland 250 m	3.46	7.13	3.60	7.20	3.45	7.12	3.50	7.15
Grassland 500 m	10.43	20.68	10.84	20.95	10.36	20.70	10.54	20.77
Grassland 1 000 m	42.53	79.33	43.94	80.66	42.00	79.42	42.82	79.79
Grassland 2 000 m	176.63	304.7	177.97	306.25	173.85	302.78	176.15	304.51
Grassland 3 000 m	293.71	483.95	295.64	489.55	289.98	483.11	293.11	485.43
Crop area 250 m	6.95	8.7	6.71	8.54	6.84	8.64	6.83	8.63
Crop area 500 m	20.77	24.75	20.14	24.35	20.30	24.53	20.40	24.54
Crop area 1 000 m	81.66	92.23	79.80	90.87	80.12	91.39	80.52	91.48
Crop area 2 000 m	316.79	342.13	312.52	340.54	312.53	339.76	313.95	340.73
Crop area 3 000 m	525.69	545.68	520.66	545.12	520.31	542.41	522.22	544.27

Besides for conventional inputs, it is expected that climate variables, such as rainfall and temperature, also influence crop production, and therefore revenue. The mean temperatures (°C) and rainfall (mm), both at levels and quadratic for the different years, are shown in Table 4. These also need to be controlled for so as to obtain the net effect of pollination on production.

Table 4: Climate variables

Year	2004		2007		2010		Overall	
Statistic	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Temp (°C)	20.24	2.54	20.10	2.62	20.60	2.64	20.31	2.61
Rainfall (mm)	93.32	27.8	112.51	30.8	109.72	37.57	105.18	33.4

4. Results

Estimates of Equation (9e) were done using both the linear model and the stochastic frontier (which uses MLE) in R statistical software. In the linear model, we estimated the pooled panel data model, the fixed-effects model and the random-effects model. Initial tests indicate that the random-effects model is consistent with the data compared to fixed effects. The results are therefore presented for random effects and the output distance function stochastic frontier models, as shown in Tables 5 and 6. In the estimations, we present the results of each buffer separately. The variables in all the

models remain the same across all buffers, except for areas under land-use classes, which change for each buffer. In total, five random-effects and stochastic frontier models are presented (one for each buffer). The aim of estimating each buffer separately was to avoid any possible confounding effects of areas under different land-use types if estimation was done in the same model.

Table 5: Model coefficients for the random-effects model

Random-effects Models					
Dependent variable: Log of value of agricultural output					
	Buffer 250 m	Buffer 500 m	Buffer 1 000 m	Buffer 2 000 m	Buffer 3 000 m
Seed	0.0762***	0.0762***	0.0763***	0.0761***	0.0761***
Fertiliser	0.0985***	0.0986***	0.0985***	0.0986***	0.0987***
Inputs	0.0246***	0.0246***	0.0245***	0.0245***	0.0245***
Labour	0.1854***	0.1855***	0.1856***	0.1856***	0.1855***
Temperature	-0.4687**	-0.4671**	-0.4639**	-0.4667**	-0.4606**
Rainfall	0.2949***	0.2963***	0.2968***	0.2974***	0.2976***
Forest	0.0202**	0.0072*	0.0020**	0.00050**	0.00030*
Grassland	0.0237**	0.0089**	0.0025**	0.00062**	0.00037**
Cropland	0.0191*	0.0065*	0.0018*	0.00044*	0.00026*
Pollination independent	-0.384***	-0.384***	-0.384***	-0.384***	-0.384***
Pollination indeterminate	-0.085***	-0.085***	-0.085***	-0.085***	-0.085***
Pollination dependent	-0.531***	-0.531***	-0.531***	-0.531***	-0.531***
Constant	7.049***	7.069***	7.093***	7.099***	7.111***
Observations	3 903	3 903	3 903	3 903	3 903
Adjusted R ²	0.864	0.864	0.864	0.864	0.864
F-statistic	2 256.79***	2 258.13***	2 258.79***	2 258.34***	2 257.97***

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Note that, in all the models, the coefficients of the covariates do not change significantly across buffers, as only the buffer areas change while the other variables remain constant. From the random effects and output distance function (ODF) stochastic frontier models, all conventional inputs are significant and positive, indicating that increasing any of them would improve the agricultural output value. The random-effects model shows that a 1% increase in temperature decreases the agricultural output value by close to 0.47%, while a 1% increase in rainfall increases output by 0.3%. The substitution between the different output values shows that an increase in the value of pollination-dependent output by 1% decreases the value of the pollination-independent and the value of pollination-indeterminate outputs by 0.384% and 0.085% respectively. This shows a strong substitution between pollination-dependent and pollination-independent crops. In the stochastic frontier model, the influence of conventional inputs on agricultural outputs is comparable to the results of the random-effects model.

On climate change-related variables, a percentage increase in temperature by one degree reduces the value of output by 0.08% to 0.15%, depending on the buffer, while an increase in rainfall by 1 mm increases output by 0.22%. Substitution between outputs shows that a percentage increase in pollination-dependent output decreases pollination-independent and pollination-indeterminate outputs by 0.434% and 0.076% respectively.

Table 6: Model coefficients for the output distance function stochastic frontier

MLE: Stochastic frontier					
Dependent variable: Log of agricultural output value					
	Buffer 250 m	Buffer 500 m	Buffer 1 000 m	Buffer 2 000 m	Buffer 3 000 m
Seed	0.0975***	0.0945***	0.0943***	0.0945***	0.0940***
Fertiliser	0.1535***	0.1552***	0.1550***	0.1549***	0.1555***
Inputs	0.0795***	0.0751***	0.0765***	0.0761***	0.0753***
Labour	0.1916***	0.1965***	0.1966***	0.1942***	0.1958***
Temperature	-0.1500	-0.0833	-0.1221	-0.1073	-0.0886
Rainfall	0.2033***	0.2270***	0.2168***	0.2167***	0.2234***
Forest	0.0132*	0.0041*	0.0012*	0.00028*	0.00016*
Grassland	0.0143*	0.0047*	0.0013*	0.00032*	0.00018*
Cropland	0.0114	0.0034	0.0010	0.00025	0.00015
Pollution independent	-0.4342***	-0.4345***	-0.4342***	-0.4338***	-0.4342***
Pollution indeterminate	-0.0746***	-0.0749***	-0.0750***	-0.0751***	-0.0749***
Pollution dependent	-0.4902***	-0.4896***	-0.4898***	-0.4903***	-0.4899***
Sigma squared	5.424***	5.198***	5.896***	5.093***	5.211***
Gamma	0.8501***	0.8415***	0.8335***	0.8367***	0.8433***
μ	-4.295***	-4.183***	-4.125***	-4.129***	-4.193***
Time	-0.7495***	-0.7244***	-0.715***	-0.722***	-0.724***
Constant	6.042***	5.751***	5.895***	5.864***	5.772***
Observations	3,903	3,903	3,903	3,903	3,903
Log likelihood	-5571.15	-5571.28	-5570.55	-5571.03	-5571.94

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Following Equation (9d), the areas covered by different land-use types in different buffers were modelled as an exponential function of the output. Therefore, the relationship between agricultural production value and area of a land-use type in any buffer takes the form $[y = Ae^{-\beta x}]$ or $[\ln y = \ln A - \beta x]$, where $(-\beta)$ is the decay rate of agricultural production value as the area of a specific buffer changes. In the exponential relationship, β is regarded as intrinsically positive, thus negative coefficients of β s are ignored and the coefficients read as positive. It can be seen that the relationship is given by the coefficients of forest, grassland and crop land areas, as shown in Table 5 (random-effects model) and Table 6 (maximum likelihood estimates – stochastic frontier).

To interpret these coefficients, one would like to know by how much agricultural value would change if a certain land-use class changed (increased or decreased). To linearise the exponential relationship between agricultural output and pollination, we adopted the loglinear function interpretation. The marginal effects of pollination on agricultural output from this relationship are from the multiplication of land-use class coefficients in Table 5 and Table 6 above by a factor of 100, as shown in Table 7a and Table 7b.

Table 7a: Marginal effects (%) of pollination services (random effects)

Land-use type	Buffers				
	250 m	500 m	1 000 m	2 000 m	3 000 m
Forest	2.02	0.72	0.20	0.050	0.030
Grassland	2.37	0.89	0.25	0.062	0.037
Cropland	1.91	0.65	0.18	0.044	0.026

Table 7b: Marginal effects (%) of pollination services (ODF stochastic frontier)

Land-use type	Buffers				
	250 m	500 m	1 000 m	2 000 m	3 000 m
Forest	1.32	0.41	0.12	0.028	0.016
Grassland	1.43	0.47	0.13	0.032	0.018
Cropland	1.14	0.34	0.10	0.025	0.015

From Table 7a it can be seen that a 1% increase in forest area in the 250 m buffer increases the value of pollinated agricultural output by 2.02%, while a similar increase in grassland area in the same buffer increases the value of pollinated agricultural output by 2.37%. Still in the same buffer, a 1% increase in the cropland class increases the same value (pollinated agricultural output) by 1.91%. Our expectation was that forest would have a greater impact than grassland and cropland, but it was only higher than cropland. The other buffers can be interpreted in the same manner. Estimates from the stochastic frontier (MLE) are lower than those from the random-effects model, although the trends are similar (Table 7b). The declining influence of pollination on output as distance increases could be explained by the limit of insects' forage distance, which for most bee species is about 1 000 m.

One of the commitments of Kenya's nationally determined contributions (NDCs) to emissions reductions under the Paris Agreement is to increase forest area by 10%. Using this argument, we calculated what an increase in 10% of the current land-use classes would mean changes in the values of agricultural output for pollination-dependent crops only. The results are shown in Table 8a and Table 8b. Assuming a situation where the forest land-use class in each buffer zones increases by 10%, the results of the random-effects model indicate that the value of pollinated agricultural output would increase by Ksh 2020 (US\$ 20.2) per acre for the 250 m buffer and Ksh 30.1 (US\$ 0.3) per acre for 3 000 m. Using the stochastic frontier approach (maximum likelihood estimation), a 10% increase in forest area would increase pollination-dependent agricultural value by Ksh 1 320 (US\$ 13.2) per acre for the 250 m buffer. This amount declines significantly, to Ksh 16 (US\$ 0.16) per acre at a distance of 3 000 m. The results demonstrate that the effect of insect pollination on agricultural output declines with distance.

Table 8a: Change in agricultural value (Ksh/acre) due to a 10% change in land-use classes (random effects)

Land-use class	Buffers				
	250 m	500 m	1 000 m	2 000 m	3 000 m
Forest	2 020	720	200	50	30
Grassland	2 370	890	250	62	37
Cropland	1 910	650	180	44	26

Table 8b: Change in agricultural value (Ksh/acre) due to a 10% change in land-use classes (ODF stochastic frontier)

Land-use class	Buffers				
	250 m	500 m	1 000 m	2 000 m	3 000 m
Forest	1 320	410	120	28	16
Grassland	1 430	470	130	32	18
Cropland	1 140	340	100	25	15

The results in Table 8a and Table 8b indicate that the value of output declines as the distance of the farm from the land-use class increases. The value of the output is highest if there is a higher percentage of forests, grassland or cropland around the farm. The explanation for the high contribution of croplands could be that insects would most likely pollinate crops on the neighbouring farms. These farm values are shown in Figures 2a and 2b. The surprising result was that an increase in grasslands contributes more to pollination than forests. This result suggests that area matters more for foraging by insect populations in less dense vegetation like grasslands than in the denser forest cover, i.e. the marginal contribution of an extra unit area of dense vegetation like forest is smaller than the same extra unit of grassland area. This strengthens the case for the increased recognition of grasslands ecosystems, which have largely remained underappreciated in the ecosystem services framework (Frélichová *et al.* 2014) and have sometimes been combined with other rangelands, including shrubland, deserts and savannas (see Sala *et al.* 2017). Similarly,

grasslands have received substantially less attention in the multiple ecosystem services framework compared to other production systems, such as forest (Gamfeldt *et al.* 2013) and cropland (Robertson *et al.* 2014), and have also, for the most part, been neglected in global policy discussions concerning ecosystem services (e.g. Parr *et al.* 2014; Díaz *et al.* 2015; Bond 2016). This is despite grasslands having been highlighted as important for the maintenance of biodiversity and food production, pollination, water regulation and climate regulation (Reyers *et al.* 2005; Turpie *et al.* 2008; Bullock *et al.* 2011; Egoh *et al.* 2016).

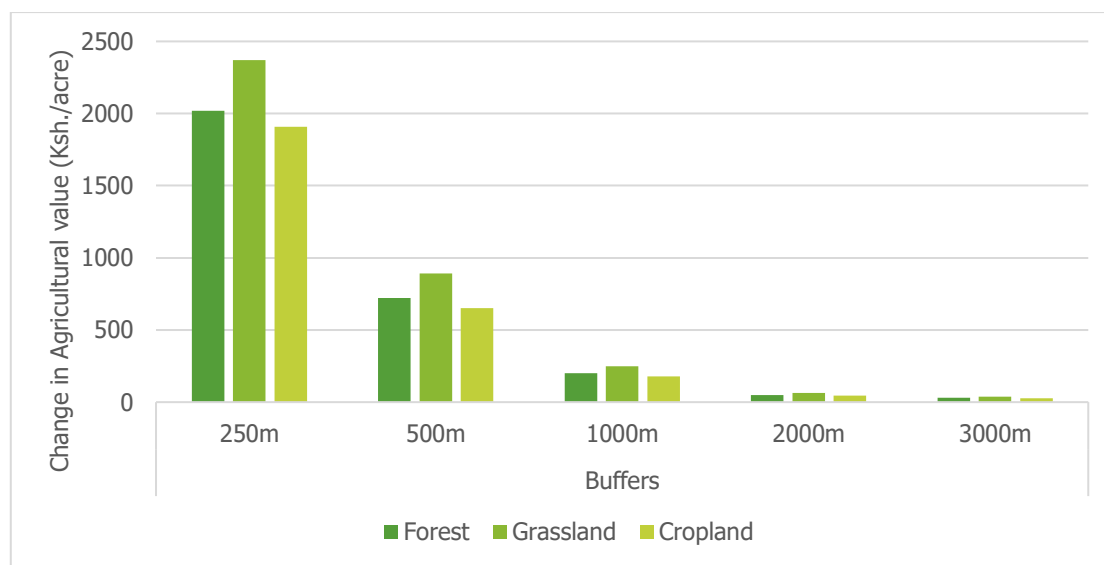


Figure 2a: Change in output value due to change in foraging distance (random effects)

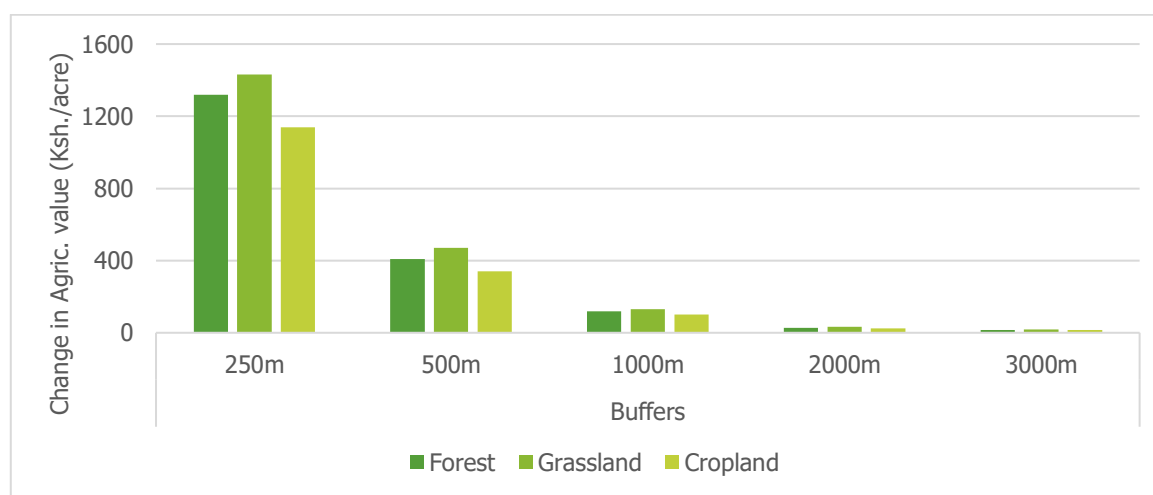


Figure 2b: Change in output value due to change in foraging distance (ODF stochastic frontier)

The same information presented in Figures 2a and 2b is presented in Figures 3a and 3b, but in a line graph that presents the agricultural revenue as a decreasing function of pollination as distance increases. The increments of crop value due to pollination at distances of 2 000 m and 3 000 m from the farm are almost negligible.

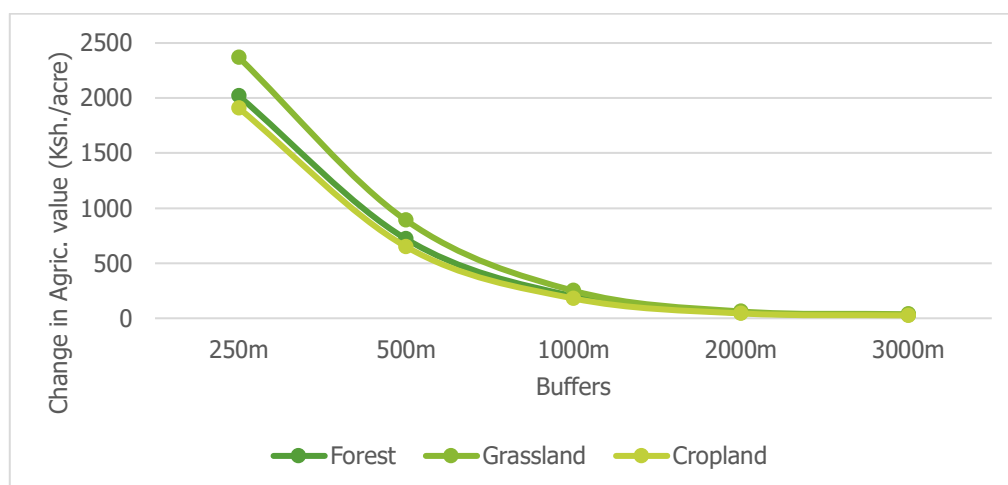


Figure 3a: Change in output value due to change in foraging distance (random effects)

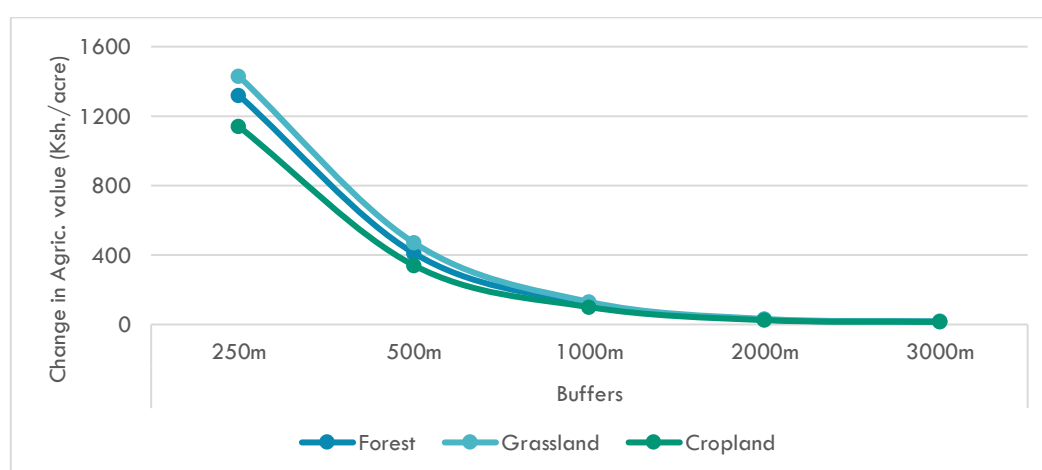


Figure 3b: Change in output value due to change in foraging distance (ODF stochastic frontier)

5. Conclusions and recommendations

This study used three-wave panel data to estimate the effect of insect pollination on agricultural output using data from Kenya. Due to complexities in smallholder production, different crops are grown on the same or different plots, but on the same farm, either for diversification, hedging against risks, or for other, individual reasons. It therefore is challenging to separate the actual inputs used for each output of the farm. To overcome this challenge, we used a multiple-output production function approach to estimate the effect of insect pollination on the value of agricultural output. Since insect pollinators are expected to originate from or inhabit different land-use classes surrounding the farms, such as other croplands, grassland or forests, buffer zones were drawn around the farms at distances of 250 m, 500 m, 1 000 m, 2 000 m and 3 000 m, and the areas under the different land-use classes in each buffer zone were estimated as proxies for pollination services. The results indicate that changing the area under the different land-use classes in the different buffer zones by 1% would, on average, increase farm revenue by 2.1% at 250 m and 0.03% at 3 000 m.

At present, the policy in Kenya is to increase tree cover by 10%. We therefore assumed a situation in which each land-use class in each buffer zone increased by 10%. The results indicate that the value of agricultural output would increase by about Ksh 2 100 (US\$ 21.0) per acre at 250 m and Ksh 30 (US\$ 0.3) per acre for 3 000 m. Using the output distance function stochastic frontier approach (MLE), a 10% increase in forest area would increase pollination-dependent revenue by

Ksh 1 320 (US\$ 13.2) per acre for the 250 m buffer. This amount declines significantly, to Ksh 16 (US\$ 0.16) per acre, at a distance of 3 000 m. This is an indication that insect pollinators are more effective if they travel shorter distances, and that distances of over 1 000 m greatly reduce the effectiveness of the pollinators. In addition, forest, grassland and cropland land-use classes are important habitats for insect pollinators. From a policy perspective, it would pay to increase forest and grassland around farms. If Kenya's 10% tree cover policy is realised, the country will increase pollinator habitats and improve insect pollination. Further, given the importance of cropland as a habitat for insect pollinators, it is also advisable for farmers to cultivate close to other farms so as to maximise pollination across farms. We have also demonstrated that grasslands are important habitats for insect pollinators, and that larger grassland vegetation areas contribute to higher pollination values than larger forest areas. Therefore, individual farmers may need to plan for relatively smaller land areas if forest vegetation is the habitat choice for pollinator foraging compared to a grassland ecosystem. Finally, having contiguous areas of farms next to forests or grasslands would be better for pollinators than having a mosaic of farms scattered all over the landscape. Realising this, however, will depend on the land tenure system, which as currently constituted in Kenya does not allow for the clustering of farms in one area, but prefers continued fragmentation.

Acknowledgements

The authors would like to thank the Swedish International Development Agency (SIDA), which funded this study through the Environment for Development Initiative (EfD) of Gothenburg University, Sweden.

References

- Aigner DJ, Lovell CAK & Schmidt P, 1977. Formulation and estimation of stochastic frontier production function models. *Journal of Econometrics* 6(1): 21–37.
- Aizen MA, Aguiar S, Biesmeijer JC, Garibaldi LA, Inouye DW, Jung C, Martins DJ, Medel R, Morales CL, Ngo H, Pauw A, Paxton RJ, Sáez A & Seymour CL, 2019. Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. *Global Change Biology* 25(10): 3516–27.
- Allsopp MH, Lange WJD & Veldtman R, 2008. Valuing insect pollination services with cost of replacement. *PloS One* 3(9): e3128.
- Axelrod DI, 1960. The evolution of flowering plants. In Tax S (ed.), *Evolution after Darwin Vol. I: Evolution of life*. Chicago IL: University of Chicago Press.
- Bartomeus I & Winfree R, 2013. Pollinator declines: Reconciling scales and implications for ecosystem services. *F1000 Research* 2: 146.
- Bartomeus I, Ascher JS, Gibbs J, Danforth BN, Wagner DL, Hedtke SM & Winfree R, 2013. Historical changes in northeastern US bee pollinators related to shared ecological traits. *Proceedings of the National Academy of Sciences* 110(12): 4656–60.
- Bawa KS, 1990. Plant-pollinator interactions in tropical rain forests. *Annual Review of Ecology and Systematics* 21: 399–422.
- Bommarco R, Biesmeijer JC, Meyer B, Potts SG, Pöyry J, Roberts SPM, Steffan-Dewenter I & Öckinger E, 2010. Dispersal capacity and diet breadth modify the response of wild bees to habitat loss. *Proceedings of the Royal Society B, Biological Sciences* 277(1690), 2075–82.
- Bond WJ, 2016. Ancient grasslands at risk. *Science* 351(6269): 120–2.
- Brosi BJ, Daily GC, Shih TM, Oviedo F & Duran G, 2008. The effects of forest fragmentation on bee communities in tropical countryside. *J. Appl. Ecol.* 45:773–83.

- Bullock JM, Jefferson RG, Blackstock TH, Pakeman RJ, Emmett BA, Pywell RJ, Grime P, Silvertown J, Church A, McMullan M *et al.*, 2011. Chapter 6: Semi-natural grasslands. In UK National Ecosystem Assessment: Technical Report. Cambridge: UNEP-WCMC.
- Campbell DR, 1985. Pollen and gene dispersal: The influences of competition for pollination. *Evolution* 39(2): 418–31.
- Cariveau DP, Williams NM, Benjamin FE & Winfree R, 2013. Response diversity to land use occurs but does not consistently stabilise ecosystem services provided by native pollinators. *Ecology Letters* 16(7): 903–11.
- Carré G, Roche P, Chifflet R, Morison N, Bommarco R, Harrison-Cripps J, Krewenka K, Potts SG, Roberts SPM, Rodet G, Settele J, Steffan-Dewenter I *et al.*, 2009. Landscape context and habitat type as drivers of bee diversity in European annual crops. *Agriculture, Ecosystems & Environment* 133(1–2), 40–7.
- Carvalho LG, Veldtman R, Shenkute AG, Tesfay GB, Pirk CWW, Donaldson JS & Nicolson SW, 2011. Natural and within-farmland biodiversity enhances crop productivity. *Ecology Letters* 14(3), 251–59.
- Coelli TJ & Perelman S, 1999. A comparison of parametric and non-parametric distance functions: With applications to European railways. *European Journal of Operational Research* 117(2): 326–39.
- Coelli TJ & Perelman S, 2000. Technical efficiency of European railways: A distance function approach. *Applied Economics* 32(15): 1967–76.
- Coelli TJ, Rao DSP & Battese GE, 1998. An introduction to efficiency and productivity analysis. Boston: Kluwer Academic Publishers.
- Costanza R, D'Arge R, De Groot R, Farber S, Grasse M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin R, Sutton P & Van den Belt M, 1997. The value of the world's ecosystem services. *Nature* 387: 253–60.
- Cunningham SA, 2000. Effects of habitat fragmentation on the reproductive ecology of four plant species in mallee woodland. *Conservation Biology* 14(3): 758–68.
- De Groot RSD, Wilson MA & Boumans RM, 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics* 41(3): 393–408.
- Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie An, Adhikari JR, Arico S, Báldi A, Bartuska A, Baste IA, Bilgin A *et al.*, 2015. The IPBES Conceptual Framework – Connecting nature and people. *Current Opinion in Environmental Sustainability* 14: 1–16.
- Dick CW, 2001. Genetic rescue of remnant tropical trees by an alien pollinator. *Proceedings of the Royal Society B: Biological Sciences* 268(1483): 2391–96.
- Eardley C, Roth D, Clarke J, Buchmann S & Gemmill B, 2006. Pollinators and pollination: A resource book for policy and practice. Second edition. Pretoria: African Pollinator Initiative.
- Egoh B, Bengtsson J, Lindborg R, Bullock JM, Dixon AP & Rouget M, 2016. The importance of grasslands in providing ecosystem services: Opportunities for poverty alleviation. In Potschin M, Haines-Young R, Fish R & Turner RK (eds.), *Routledge handbook of ecosystem services*. London and New York: Routledge.
- Elisante F, Mbega ER & Ndakidemi PA, 2017. Significance of pollination services in crop and plant diversity in tropical Africa. *Journal of Biodiversity and Environmental Sciences* 11(6): 206–23.
- Ellis EC, Goldewijk KK, Siebert S, Lightman D & Ramankutty N, 2010. Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography* 19(5): 589–606.
- Fan Y & Van den Dool H, 2008. A global monthly land surface air temperature analysis for 1948–present. *Journal of Geophysical Research* 113(D1). <https://doi.org/10.1029/2007JD008470>
- Fijen TPM, Scheper JA, Vogel C, Van Ruijven J & Kleijn D, 2020. Insect pollination is the weakest link in the production of a hybrid seed crop. *Agriculture, Ecosystems & Environment* 290: 106743.

- Freeman AM III, 1993. The measurement of environmental and resource values: Theory and methods. Washington DC: Resources for the Future.
- Frélichová J, Vackár D, Pártl A, Loucková B, Harmácková ZV & Lorencová E, 2014. Integrated assessment of ecosystem services in the Czech Republic. *Ecosystem Services* 8: 110–7.
- Funk C, Hoell A, Shukla S, Bladé I, Liebmann B, Roberts JB, Robertson FR & Husak G, 2014. Predicting East African spring droughts using Pacific and Indian Ocean sea surface temperature indices. *Hydrology and Earth System Sciences* 18: 4965–78.
- Gallai N, Salles J-M, Settele J & Vaissiere BE, 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics* 68(3): 810–21.
- Gamfeldt L, Snäll T, Bagchi R, Jonsson M, Gustafsson L, Kjellander P, Ruiz-Jaen MC, Fröberg M, Stendahl J, Philipson CD, Mikusiński G *et al.*, 2013. Higher levels of multiple ecosystem services are found in forests with more tree species. *Nature Communications* 4: Article no. 1340.
- Garibaldi LA, Aizen MA, Klein AM, Cunningham SA & Harder LD, 2011. Global growth and stability in agricultural yield decrease with dependence on pollinator services. *Proceedings of the National Academy of Sciences* 108(14): 5909–14.
- Ghazoul J, 2007. Challenges to the uptake of the ecosystem service rationale for conservation. *Conservation Biology* 21(6): 1651–2.
- Gollin D, 2014. Smallholder agriculture in Africa: An overview and implications for policy. IIED Working Paper, International Institute for Environment and Development (IIED), London. <https://www.iied.org/sites/default/files/pdfs/migrate/14640IIED.pdf>
- Greenleaf SS, Williams NM, Winfree R & Kremen C, 2007. Bee foraging ranges and their relationship to body size. *Oecologia* 153(3): 589–96.
- Güneralp B, Lwasa S, Masundire H, Parnell S & Seto KC, 2017. Urbanization in Africa: Challenges and opportunities for conservation. *Environmental Research Letters* 13(1): 015002. <https://doi.org/10.1088/1748-9326/aa94fe>
- Hein L, 2009. The economic value of the pollination service, a review across scales. *The Open Ecology Journal* 2: 74–82.
- IPBES, 2016. Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. In Potts SG, Imperatriz-Fonseca VL, Ngo HT, Biesmeijer JC, Breeze TD, Dicks LV, Garibaldi LA, Hill R, Settele J, Vanbergen AJ *et al.* (eds.), *The assessment report on pollinators, pollination and food production: Summary for policymakers*. Bonn, Germany: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.
- Kennedy CM, Lonsdorf E, Neel MC, Williams NM, Ricketts TH, Winfree R, Bommarco R, Brittain C, Burley AL, Cariveau D, Carvalheiro LG *et al.*, 2013. A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecology Letters* 16(5): 584–99.
- Klatt BK, Holzschuh A, Westphal C, Clough Y, Smit I, Pawelzik E & Tschardt T, 2014. Bee pollination improves crop quality, shelf life and commercial value. *Proceedings of the Royal Society B: Biological Sciences* 281(1775). <https://doi.org/10.1098/rspb.2013.2440>
- Kleijn D, Winfree R, Bartomeus I, Carvalheiro LG, Henry M, Isaacs R, Klein, A-M, Kremen C, M'Gonigle LK, Rader R, Ricketts TH *et al.*, 2015. Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nature Communications* 6: Art. #7414.
- Klein AM, Vaissiere BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C & Tschardt T, 2007. Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society of London. Series B: Biological Sciences* 274(1608): 303–13.
- Kremen C, 2005. Managing ecosystem services: What do we need to know about their ecology? *Ecology Letters* 8(5): 468–79.
- Kremen C, Williams NM, Aizen MA, Gemmill-Herren B, LeBuhn G, Minckley R, Packer L, Potts SG, Roulston T, Steffan-Dewenter I, Vázquez DP *et al.*, 2007. Pollination and other ecosystem

- services produced by mobile organisms: A conceptual framework for the effects of land-use change. *Ecology Letters* 10(4): 299–314.
- Kuosmanen T, Pems D & Wesseler J, 2006. Specification and estimation of production functions involving damage control inputs: A two-stage, semiparametric approach. *American Journal of Agricultural Economics* 88(2): 499–511.
- Lema E, Machunda R & Njau KN, 2014. Agrochemicals use in horticulture industry in Tanzania and their potential impact to water resources. *International Journal of Biological and Chemical Sciences* 8(2): 831–42.
- Lennartsson T, 2002. Extinction thresholds and disrupted plant–pollinator interactions in fragmented plant populations. *Ecology* 83(11): 3060–72.
- Levin MD, 1984. Value of bee pollination to United States agriculture. *American Bee Journal* 124: 184–6.
- Lichtenberg E & Zilberman D, 1986. The econometrics of damage control: Why specification matters. *American Journal of Agricultural Economics* 68(2): 261–73.
- Losey JE & Vaughan M, 2006. The economic value of ecological services provided by insects. *BioScience* 56(4): 311–23.
- Lovell CAK, Richardson S, Travers P & Wood L, 1994. Resources and functionings: A new view of inequality in Australia. In Eichhorn W (ed.), *Models and measurement of welfare and inequality*. Berlin: Springer.
- Lundberg J & Moberg F, 2003. Mobile link organisms and ecosystem functioning: Implications for ecosystem resilience and management. *Ecosystems* 6: 87–98.
- Meeusen W & Van den Broeck J, 1977. Technical efficiency and dimension of the firm: Some results on the use of frontier production functions. *Empirical Economics* 2: 109–22.
- Mensah A & Brümmer B, 2016. A multi-output production efficiency analysis of commercial banana farms in the Volta region of Ghana: A stochastic distance function approach. *African Journal of Agricultural and Resource Economics* 11(4): 305–16.
- Morse RA & Calderone NW, 2000. The value of honeybees as pollinators of US crops in 2000. *Bee Culture* 128: 1–15.
- Munyuli BMT, 2014. Social and ecological drivers of the economic value of pollination services delivered to coffee in central Uganda. *Journal of Ecosystems* 2014: Art. #298141.
- National Research Council, 2007. *Status of pollinators in North America*. Washington DC: National Academies Press.
- Nee S, 2004. More than meets the eye: Earth’s real biodiversity is invisible, whether we like it or not. *Nature* 429(6994): 804–5.
- Ollerton J, 2017. Pollinator diversity, distribution, ecological function, and conservation. *Annual Review of Ecology, Evolution, and Systematics* 48: 353–76.
- Parr CL, Lehmann CER, Bond WJ, Hoffmann WA & Andersen AN, 2014. Tropical grassy biomes: Misunderstood, neglected, and under threat. *Trends in Ecology and Evolution* 29(4): 205–13.
- Patel V, Pauli N, Biggs E, Barbour L & Boruff B, 2020. Why bees are critical for achieving sustainable development. *Ambio* 50: 49–59.
- Pimentel D, Wilson C, McCullum C, Huang R, Dwen P, Flack J, Tran Q, Saltman T & Cliff B. 1997. Economic and environmental benefits of biodiversity. *BioScience* 47(11): 747–57.
- Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O & Kunin WE, 2010. Global pollinator declines: Trends, impacts and drivers. *Trends in Ecology & Evolution* 25(6): 345–53.
- Raina SK, Kioko E, Zethner O & Wren S, 2011. Forest habitat conservation in Africa using commercially important insects. *Annual Review of Entomology* 56: 465–85.
- Reyers B, Nel J, Egoh B, Jonas Z & Rouget M, 2005. National Grasslands Biodiversity Program: Grassland biodiversity profile and spatial biodiversity priority assessment. CSIR Report Number ENV-S-C 2005–102, CSIR, Stellenbosch.
- Ricketts TH, 2004. Tropical forest fragments enhance pollinator activity in nearby coffee crops. *Conservation Biology* 18: 1262–71.

- Ricketts TH, Regetz J, Steffan-Dewenter I, Cunningham SA, Kremen C, Bogdanski A, Gemmill-Herren B, Greenleaf SS, Klein AM *et al.*, 2008. Landscape effects on crop pollination services: Are there general patterns? *Ecology Letters* 11(5): 499–515.
- Robertson GP, Gross K, Hamilton S, Landis D, Schmidt T, Snapp S & Swinton S, 2014. Farming for ecosystem services: An ecological approach to production agriculture. *BioScience* 64(5): 404–15. <https://doi.org/10.1093/biosci/biu037>
- Robinson WS, Nowogrodzki R & Morse RA, 1989. The value of honeybees as pollinators of US crops: Part II. *American Bee Journal* 129(7): 477–87.
- Rucker RR, Thurman WN & Burgett M, 2003. Internalizing reciprocal benefits: The economics of honeybee pollination markets. Unpublished manuscript, Department of Agricultural and Resource Economics, North Carolina State University, Raleigh NC.
- Sala OE, Yahdjian L, Havstad K & Aguiar MR, 2017. Rangeland ecosystem services: Nature's supply and humans' demand. In Briske DD (ed.), *Rangeland systems*. Cham, Switzerland: Springer.
- Sawe T, Eldegard K, Totland Ø, Macrice S & Nielsen A, 2020. Enhancing pollination is more effective than increased conventional agriculture inputs for improving watermelon yields. *Ecology and Evolution* 10(12): 5343–53. <https://doi.org/10.1002/ece3.6278>
- Sekercioglu CH, 2006. Avian ecosystem services. *Trends in Ecological Evolution* 21(8): 464–71.
- Shephard RW, 1970. *Theory of cost and production function*. Princeton: Princeton University Press.
- Stein K, Coulibaly D, Stenchly K, Goetze D, Porembski S, Lindner A, Konaté S & Linsenmair K, 2017. Bee pollination increases yield quantity and quality of cash crops in Burkina Faso, West Africa. *Scientific Reports* 7: Art. # 17691.
- Tibesigwa B, 2018. Naturally available pollinator decline will decrease household food security and increase the gender gap in nutrition between men and women who head smallholder farm households in Sub-Saharan Africa. *ERSA Working Paper 741*, Economic Research Southern Africa, Cape Town.
- Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D & Swackhamer D, 2001. Forecasting agriculturally driven global environmental change. *Science* 292(5515): 281–4.
- Turpie JK, Marais C & Blignaut JN, 2008. The working for water programme: Evolution of payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. *Ecological Economics* 65(4): 788–98.
- Waser NM, Chittka L, Price MV, Williams N & Ollerton J, 1996. Generalization in pollination systems, and why it matters. *Ecology* 77(4): 1043–60.
- Westphal C, Bommarco R, Carré G, Lamborin E, Morison N, Petanidou T, 2008. Measuring bee diversity in different European habitats and biogeographical regions. *Ecological Monographs* 78(4), 653–71.
- Williams NM, Crone EE, Roulston TH, Minckley RL, Packer L & Potts SG, 2010. Ecological and life-history traits predict bee species responses to environmental disturbances. *Biological Conservation* 143(10): 2280–91.
- Winfree R, Bartomeus I & Cariveau DP, 2011. Native pollinators in anthropogenic habitats. *Annual Review of Ecology, Evolution and Systematics* 42: 1–22.