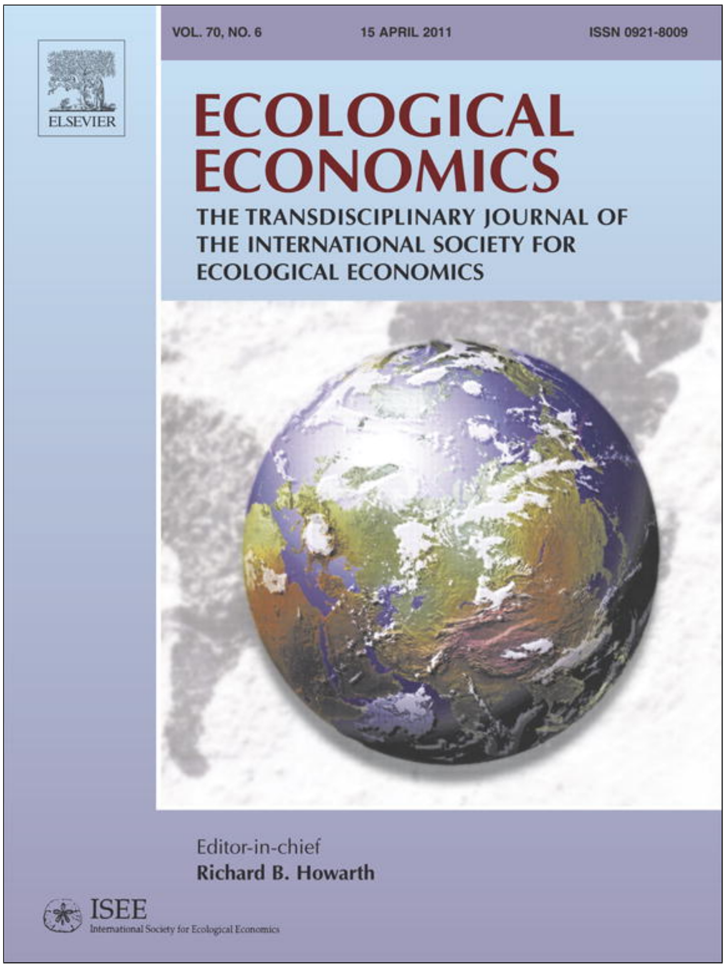
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Analysis

The trade-off between agriculture and biodiversity in marginal areas: Can crofting and bumblebee conservation be reconciled?☆

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ABSTRACT

Crofting is a low intensity agricultural system restricted to the Highlands and Islands of northern Scotland typified by small scale mixed livestock production and rotational cropping activities. As with other low intensity farming systems across Europe, crofting is changing in response to a range of socio-economic factors. This is having a negative impact on the populations of rare bumblebees that are associated with this agricultural system. In this paper we use an ecological–economic modelling approach to examine the likely impacts of introducing two different management options for conserving bumblebees on croft land-use and income. Two linear programming models were constructed to represent the predominant crofting systems found in the Outer Hebrides, and varying constraints on bumblebee abundance were imposed to examine the trade-off between conservation and agricultural incomes. The model outputs illustrate that in some instances it is likely that both agricultural profits and bumblebee densities can be enhanced. We conclude that policy-makers should take into consideration the type of farming system when designing cost-effective agri-environment policies for low intensity farming systems, and that improvements in bee conservation are not necessarily in conflict with maintaining farm income.

1. Introduction

Changing agricultural practices during the latter half of the twentieth century has been identified as an important determinant of declines in a wide range of farmland biodiversity (Chamberlain et al., 2000; Donald et al., 2001; Robinson and Sutherland, 2002). Population declines have been recorded in species belonging to a variety of taxonomic groups ranging from birds and butterflies to plants (Robinson and Sutherland, 2002). Agricultural intensification has also affected populations of pollinating insects, including a number of bumblebee (*Bombus*) species which have declined throughout the UK and Western Europe (Goulson, 2003; Goulson et al., 2008). Bumblebees are frequently associated with wildflower-rich semi-natural habitats, such as permanent unimproved grassland, which provide essential foraging resources (Williams and Osborne, 2009). However, many of these habitats, and therefore their associated forage, have been lost from agricultural landscapes, driving bumblebee declines (Goulson, 2003; Carvell et al., 2006; Goulson et al., 2008). Consequently, of the 25 bumblebee species native to the UK, three are now extinct and a further six are endangered and included on the UK's Biodiversity Action Plan (BAP). Only six species remain common and ubiquitous throughout the UK (Benton, 2006).

The impacts of agricultural intensification have shaped the distribution of UK's bumblebee fauna, with distributions of some of the rarest species now restricted to isolated areas in the far north and west of Scotland where agricultural practices have changed less (Goulson et al., 2006). Crofting is the predominant form of agriculture in these areas and crofted areas provide the last remaining strongholds for two of UK's most endangered bumblebee species: *Bombus distinguendus* and *B. muscorum* (Goulson et al., 2005; Benton, 2006).

Agricultural units in the Outer Hebrides and mainland crofting counties of northern Scotland are known as ‘crofts’ and commonly consist of small areas of enclosed lowland grassland (“inbye”) with shared rights to common grazings on “machair” (a coastal fringe calcareous grassland habitat) and on moorland (Stewart, 2005). Typically crofts are clustered together forming “townships” in which crofters implement small scale arable rotations and livestock production. Grazing regimes traditionally consisted of the inbye and machair being grazed by livestock during the winter, with the movement of livestock to moorland common grazings in the summer (Moisley, 1962; Hance, 1952; Caird, 1987; Love, 2003). Fertilizer inputs were traditionally limited to seaweed and farm yard manure. The nature of traditional crofting has resulted in a high value of croft land for conservation, particularly the coastal wildflower-rich machair grasslands (Love, 2003).

☆ The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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However, crofting practices are changing in response to a variety of factors. Artificial fertilizers are used to an increasing degree, hay production has been superseded by silage production, sheep numbers have risen dramatically, and the area of permanent and improved grassland has increased (Caird, 1979; Willis, 1991; Sutherland and Bevan, 2001). As with many low intensity farming systems across Europe (Caballero, 2007), a range of socio-economic factors are contributing to these changes. For example, the combination of rural depopulation and the increasing age of crofters throughout the region has led to a reduction in the number of crofters actively managing their land, increased the area of rush dominated (and therefore ecologically degraded) land (Crofters Commission, 1991), and accelerated the trend towards sheep production (Willis, 1991). Consequently, many older crofters now view crofting as a purely sheep- based system (Willis, 1991). The number of crofting households fell by 23% throughout the Crofting Counties between the 1950s and 1980s (Crofters Commission, 1991), and now many crofters are responsible for the management of more than one croft, decreasing the mosaic of land-use characteristic of traditional crofting and reducing the value of croft land to biodiversity. In addition, croft income is now largely dependent on the receipt of a range of agricultural subsidies, including the Single Farm Payment (L. Osgathorpe, unpubl. data). With the future of such subsidies currently unclear, the sustainability of crofting in the future is uncertain and this has serious implications for the biodiversity associated with crofted habitats.

The more intensive management practices now employed on crofts in northwest Scotland are of little value to foraging bumblebees (Redpath et al., 2010). Future agricultural policy and socio-economic changes are likely to continue to impact on bumblebee populations. In order for effective conservation measures to be developed ecological *and* economic factors therefore need to be taken into consideration. In this paper we use ecological–economic models to examine the likely impacts of introducing bumblebee conservation measures on the allocation of key crofting resources (e.g. land, labour, and income), and discuss the most cost-effective management options for bumblebee conservation in crofted areas. Trade-offs between croft income and bumblebee densities are identified across a range of bumblebee densities and across croft types.

Linear programming (LP) models were used to simulate croft production decisions. Such models can be used to simulate the impact on land-use at the level of the individual farmer (or crofter in this case) of changes in technology, resources, prices or government policies. Although LP models are subject to several limitations (such as the assumption of rational behaviour on the part of land managers, linearity of constraints, and fixed input-output coefficients), they provide a suitable means of examining the micro-level effects of policy changes on farmer behaviour across different farm types (Acs et al., 2010). LP models also calculate the marginal value product or shadow price associated with fully utilised resources (Hazell and Norton, 1986). Shadow prices are a useful analytical device since they can represent trade-offs between biodiversity and farm income. In our case they show the marginal cost, in terms of farm profits, of increasingly strict constraints on bumblebee abundance. In other words, shadow prices show the supply price of increasing levels of one measure of biodiversity on croft lands.

The combination of LP models with ecological data can be used to examine the impacts on a range of environmental variables (e.g. biodiversity, soil erosion, deforestation) of changes in land manager behaviour, and to optimise land management for the benefit of the environment. For example, Carpentier et al. (2000) used this method to investigate the impacts of changes in farmer behaviour on farm income and deforestation in the western Brazilian Amazon, whilst Saldarriaga Isaza et al. (2007) utilised LP models to examine the relationship between land management practices and huemul (*Hippocamelus bisulcus*) conservation in Chile. We employ a similar approach here.

2. Methods

2.1. Socio-economic croft survey

A croft survey was undertaken to establish which land management practices and production methods are currently employed by crofters in the Outer Hebrides, and to determine which socio-economic factors govern croft management decisions. We required socio-economic data from farmers relating to income and land management decisions to calibrate mathematical models of farmer behaviour, which would allow us to examine the impacts of conservation measures on farm production decisions. Our survey focused on the farming system implemented, the scale of farming operations and the associated input and output prices, and the financial assistance received by farmers.

As our data requirements were very similar to those of Acs et al. (2010), we based our survey on the general structure of the one they used for upland farms in the Peak District, UK. Crofters in the Outer Hebrides were chosen from within the area studied by Redpath et al. (2010) to correspond with their survey of bumblebees utilising croft habitats in the region. This enabled us to collect data from a subsample of crofters ($n = 19$) who participated in both the ecological and economic surveys. Crofters from the islands of North and South Uist, Harris and Lewis were interviewed by the authors during site visits, except for a sub-group (16%) who completed the surveys themselves and returned them by post. All surveys were completed during the spring and summer of 2008. The survey focussed on current management practices, the input costs and output prices associated with agricultural activity, and the subsidies received during the reference period (2007). As crofting practices on both North and South Uist, and on Harris were similar, these are collectively referred to as 'the Uists' in the remainder of the paper, whilst 'Lewis' refers purely to the crofters on that island.

From the survey results we identified two croft types which correspond to the primary production methods utilised by crofters on each island. Store lamb and store calf production (that is, rearing livestock which are then sold to other farmers for fattening and slaughter) with grass and arable silage production was characteristic of the Uists and Harris, although arable production was less common on Harris. Grass crops were primarily cultivated on the improved inbye land, whilst arable cropping consisted of silage cultivated on the machair. Cultivation and fallow periods were organised on a two years cropped, two years fallow rotational basis. In contrast, crofting on Lewis was typified by store lamb production on inbye land. No arable production was carried out and the majority of crofters had no access to moorland grazing, unlike crofters surveyed in the Uists and Harris.

Four land types utilised by crofters in the survey were identified:

1. Machair, a lowland grassland area adjacent to the coast formed from wind-blown shell sand. The sandy soils are low in nutrients and support a diverse variety of wildflowers. The land is primarily used for the cultivation of arable silage and grazing.
2. Semi-improved grassland located on the inbye, forming the main grazings for livestock. Inorganic fertilizers and farm yard manure are applied. This land is also used in the production of grass silage.
3. Improved grassland, which is enhanced with larger amounts of inorganic fertilizers and used for grass silage production.
4. Moorland, which is normally unfenced and often held in common, and to which no inorganic fertilizers or farm yard manure is applied.

All crofters received the Single Farm Payment and payments through the Less Favoured Area Support Scheme (LFASS). Several crofters supplemented this grant income by participating in agri-environment schemes (AES). However, there are currently no prescriptions available in Scotland specifically aimed at conserving bumblebee populations.

2.2. Modelling

Changes in farmer behaviour in response to changing agricultural policy have been studied using ecological–economic models in a range of settings (e.g. Münier et al., 2004; Pacini et al., 2004; Meyer-Aurich, 2005). This approach can be extended to the consideration of conservation issues, with models used to examine the relationship between farm-level decision making and species conservation (e.g. Drechsler et al., 2007). We construct two linear programming land-use optimisation models, one for the type of mixed cattle/sheep and arable crofts found in the Uists and Harris (referred to collectively as 'Uists'; and one for the sheep crofts found on Lewis.

2.2.1. General approach

Farm production models were used to simulate different conservation scenarios. The general structure of the models is shown in Table 1 and takes the form of a standard LP model (Hazell and Norton, 1986), designed to represent the profit maximisation problem of a land manager:

Maximise $(Z = c'x)$
Subject to $Ax \leq b$
And $x \geq 0$

where Z is the gross margin (income from cropping and livestock production net of variable production costs) at the croft level; x is the vector of activities; c is the gross margin or cost per unit of activity; A is a matrix of input use coefficients; and b is the vector of resource endowments or technical constraints. The activities included in the model are based on typical crofting practices, and are shown by the headings in Table 1. Activities are included for different land types, animal production systems, feed production and purchase, fertilizer, hired labour and subsidy payments. The rows of the matrix represent the constraints imposed on croft management in terms of land availability, labour, fertilizer and fodder requirements, and constraints on subsidy payments, e.g. activities associated with qualifying for AES payments. The objective function of the LP model is to maximise the total croft business gross margin (profit excluding fixed costs), i.e. the total revenue from all activities minus the variable costs associated with all crofting activities. The model output provides the optimal croft production plan, detailing optimal land allocations, level and type of production, and labour use. All model simulations were carried out in GAMS (General Algebraic Modelling System) version 23.4.

2.2.2. Production elements

In the Uists model the beef cattle production element is based on continental suckler cows calving between February and April with calves sold as store animals (that is, for fattening) between 12 and 18 months old. This includes 1% cow mortality and 4.5% calf mortality, based on data from the Farm Management Handbook (Beaton et al., 2007). Cattle are generally kept outside throughout the year and their main feed requirements are met through grazing, silage and cattle concentrates. Revenue from cattle production is obtained from direct sales and payments through the Scottish Beef Calf Scheme. Variable costs are calculated per head and consist of the purchase of cattle concentrates, the production of silage on the croft and health care. Costs of bull hire are also included, in addition to other costs listed in the Farm Management Handbook (Beaton et al., 2007), such as levies and tags.

In both the Uists and Lewis models, sheep production activities were based on breeding Blackface and North Country Cheviot ewes producing lambs in the spring which are sold as store animals in the autumn. Some crofters on Lewis also produced fat lambs and this was included in the Lewis model. Feeding requirements were based on the survey results, with grazing and sheep concentrates comprising the majority of the animals' nutritional needs. Hay was used by some

Table 1
Matrix showing the general structure of the linear programming farm models for beef and sheep production. The activities included in the model are shown as column headings, whilst the rows represent the constraints imposed on each activity.

Activities	Improved grassland	Semi-improved grassland	Machair	Fodder production for own use	Sheep production	Beef production	Hired labour	Purchase of fertilizer	Purchase of feed	Animal production for sale	SFP	LFASS	AES	Resource endowments and technical constraints
Constraints														
Land requirements	1	1	1											≤available hectares
Land types for fodder production	−1	−1	−1	1										≤0
Fertilizer and manure requirements	$+a_{ij}$	$+a_{ij}$	$+a_{ij}$		$-a_{ij}$	$-a_{ij}$		$-a_{ij}$						≤0
Animal production for sale					$-a_{ij}$	$-a_{ij}$				$+a_{ij}$				≤0
Labour requirements				$+a_{ij}$	$+a_{ij}$	$+a_{ij}$	−1							≤available fixed labour in hours
Feeding requirements				$-a_{ij}$	$+a_{ij}$	$+a_{ij}$			$-a_{ij}$					≤0
SFP	$+a_{ij}$	$+a_{ij}$									$-a_{ij}$			≤0
LFASS	$+a_{ij}$	$+a_{ij}$										$-a_{ij}$		≤0
AES	$+a_{ij}$	$+a_{ij}$	$+a_{ij}$										$-a_{ij}$	≤0
Livestock constraints for LFASS and AES					$+a_{ij}$	$+a_{ij}$								≥minimum livestock unit
Objective function	Costs (£/ha)	Costs (£/ha)	Costs (£/ha)	Costs (£/ha)	Gross margin (£/head)	Gross margin (£/head)	Costs (£/hour)	Costs (£/kg)	Costs (£/t)	Revenue (£/head)	Revenue (£/ha)	Revenue (£/ha)	Revenue (£/ha)	

*a_{ij} − the technical coefficient that relates the activity $_i$ to the constraint $_j$.

crofters as a supplementary feed. The average number of lambs per ewe was derived from the survey results for each island. No sheep housing requirements were included in the model as this is unusual in the study area. Revenue from sheep production was derived from the direct sale of lambs. Variable costs of production consisted of the purchase of sheep concentrates, hay, healthcare and additional costs (e.g. haulage, levies, and tags). Input and output prices for sheep and beef production varied between the models and were based on averages taken from the survey results for each island.

Croft land can be used for different activities within the models. Silage is rarely purchased and home-grown supplies are used to meet the nutritional needs of livestock, above that provided by grazing and concentrates. Improved grassland is used for the cultivation of grass silage crops. Semi-improved land may also be used for this purpose, but is predominantly utilised as grazing for both cattle and sheep. Similarly, machair areas can be used for grazing or growing arable silage (traditionally a combination of barley, oats and rye). Although the crofts commonly have access to shared areas of moorland grazings in the summer, this land was rarely made use of by the crofters in our survey, and is therefore not included in the baseline Uists model or any of the Lewis models. The use of inorganic fertilizers is included as an activity in the Uists model. Usually only one cut of silage is made per year in late July/August. Rotational constraints were also added.

The labour requirements for each activity were based on standard requirements set out in the Farm Management Handbook (Beaton et al., 2007). These requirements could be met by household labour or by hiring contractors. The availability of household labour varied between the islands, with crofters on the Uists often working on the croft full-time and those on Lewis managing their crofts on a part-time basis.

2.2.3. Incorporating the ecological data

Relationships between croft land management practices and bumblebee densities has been identified by Redpath et al. (2010), using data from the same crofts on which our ecological–economic models are based. All management types found on 22 crofts throughout the Outer Hebrides were surveyed for foraging bumblebees and their forage plants between June and August 2008. The effect of land management on bumblebee abundance was examined using Generalised Linear Models (GLM) with quasipoisson errors in the statistical software package R, version 2.7.2. Eight management types were surveyed and included in the ecological models: arable, bird and bumblebee conservation seed mix, fallow, silage, summer sheep grazed pasture, summer mixed grazed pasture, unmanaged and winter grazed pasture. Croft land management practices supported low densities of foraging bumblebees; however, management was a significant predictor of bumblebee abundance in all months, with silage, fallow and areas sown with a ‘bird and bumblebee’ conservation seed mix the most beneficial activities. Summer sheep grazing was found to have a particularly detrimental effect on bumblebee abundance.

From the GLM results we predicted the median number of foraging bumblebees supported by each management type. We used the data from August when nest development is at its peak and bumblebee abundance greatest. Estimates from the GLMs are incorporated in the LP models as a set of parameters linking bumblebee abundance with the area of each land-use (production) activity. This ensures that the density of bumblebees supported by each activity is also simulated and presented in the model output. This provides a numerical link between the profit-maximising pattern of crofting land-use and predicted bumblebee abundance. Variability in response around these mean effects is not modelled at present.

2.2.4. Subsidy schemes available to crofters

Crofters are eligible to receive payments from a wide range of subsidy schemes that include both direct income support payments and agri-environment payments. Direct subsidy payments were received by all crofters, and provide a substantial additional income above that generated by the main production methods alone. In Scotland, the Single Farm Payment (SFP) is based on the average of the historic subsidy claims made between 2000 and 2002. Farmers or crofters paid under any production based support schemes during this period were allocated entitlements which could be activated after 2005. In order to receive the SFP, all entitlements held must be accompanied by an eligible hectare of land and are subject to the claimant meeting cross-compliance regulations. The LFASS is an area based support scheme implemented in Scotland as part of the Scottish Rural Development Plan from 2007 to 2013, and benefits farmers and crofters in designated Less Favoured Areas (LFAs). Claimants must declare a minimum of 3 ha of eligible land, which is actively farmed for at least 183 days in the period claimed for: this subsidy is also subject to cross-compliance. As all crofters received aid under these schemes, payments were incorporated into the model as a fixed payment per hectare.

Several crofters also participated in Agri-Environmental Schemes (AES) and received payments through these schemes for using environmentally sensitive land management practices. The AES in operation at the time of the survey was the Rural Stewardship Scheme, with management agreements running to 2010/2011. The primary activities undertaken by crofters as part of these agreements were management of open and mown grassland, and the implementation of traditional cropping practices on the machair. Payments were also received under Tier 2 of the Land Management Contracts system for implementing Option 1: the Animal Health and Welfare Management Programme. In order to receive payment under an agri-environment agreement, crofters were required to implement some form of management (e.g. cropping on machair). Each activity had its own fixed payment rate per hectare and the total payment received was calculated in the model as a function of the area of land under the specified management regime.

2.2.5. Model calibration

The models include all aspects of production carried out by crofters in the Outer Hebrides and may therefore be calibrated to represent different scenarios in relation to resources available for crofting in this region. The two croft types (Uists/Harris and Lewis) modelled are based on data derived from the croft survey and are calibrated against the primary production methods (i.e. sheep, beef). To ensure that the models are representative of current crofting practices, the livestock numbers were adjusted to the averages from the survey data and key variables were compared between the model outputs and the survey data (Table 2). The ‘survey adjusted’ model was implemented to simulate currently observed production patterns. As the purpose of the models is to assess the likely changes in resource use on crofts, the key outputs for this validation process were: gross margin; revenue

Table 2
A comparison between the predicted outputs from the optimal (baseline) and survey adjusted models, and the crofter survey data (observed) from the model validation process.

	Optimal (baseline) model (£/ha)	Survey adjusted model (£/ha)	Observed (£/ha)
Mixed livestock — Uists			
Revenue sheep	0	30	32
Revenue beef	190	169	174
Subsidies	289	285	291
Variable costs	106	130	135
Gross margins	373	354	363
Sheep — Lewis			
Revenue sheep	156	62	61
Subsidies	122	122	120
Variable costs	141	56	53
Gross margins	136	128	127

and variable costs associated with livestock production; and, revenue from subsidies (Table 2). Differences emerge between the land-use pattern that would maximise the total farm gross margins and the currently observed patter of land-use (Table 2; discussed later).

2.2.6. Model scenarios

To examine the nature of likely trade-offs between the density of bumblebees per croft and croft income, we introduced a series of binding constraints into the LP model on the total number of bumblebees per hectare above that predicted by the baseline model run. Bumblebee density was increased in a step-wise process at increments of 1 bee ha^{-1} above the baseline for each model. We then examined how crofters should optimally alter their management practices to achieve greater bumblebee abundances and what the consequences for croft income would be. We examined two scenarios based on "bee friendly" management practices identified in the literature (e.g. Pywell et al., 2005; Redpath et al., 2010). The first scenario considered the option of sowing a native wildflower seed mix to attract bumblebees (labelled scenario WM). The seed mix was included in the model as an additional optional costly activity which crofters could choose to include as part of their management regime. The costs involved in this management scenario are subdivided into a one-off capital cost of the initial habitat creation and an annual maintenance cost which would be incurred over the lifetime of the mix (approximately 3-4 years). Devoting land to growing wildflowers also imposes an opportunity cost on the farmer in terms of lost income from alternative uses of this land.

The second scenario considers the impacts of reintroducing moorland grazing in the summer for mixed livestock crofts on the Uists (labelled scenario MG). This scenario was not applicable to sheep crofts on Lewis, as crofters in our survey had no access to moorland. The model enabled crofters to choose to use the moorland for grazing during the summer and predicted the optimal land allocations for each activity to achieve the required bumblebee abundances.

3. Results

The model calibration process highlights that neither mixed livestock crofters (Uists and Harris) nor sheep crofters (Lewis) currently manage their crofts in the most economically efficient way (Table 2). In particular, sheep production is less profitable for crofters in mixed livestock systems (in the Uists and Harris) and this activity is removed from the optimal production plan for this croft type. By continuing to produce store lambs, crofters are reducing the croft's gross margins by £18 ha^{-1}, which equates to an annual loss of over £1000 per annum compared to the optimal model. In addition, from a conservation perspective, the model shows that 10% fewer bumblebees are supported by current crofting practices in this system than if crofters were to operate on a profit maximising basis. In contrast, production on sheep crofts in Lewis is lower than the capacity of the available land and sheep stocking densities would be more than double current levels if crofters were profit maximising (Table 2). The survey adjusted model for sheep based crofts shows that current management practices provide enough habitat to support low densities of foraging bumblebees (0.6 bees ha^{-1} of croft land or an average of 5 bees croft^{-1} for an average sheep croft of 8 ha). However, increasing sheep production to its maximum capacity would require all land to be brought into production, which would result in the loss of any suitable bumblebee foraging habitat, and therefore a complete loss of bumblebees, from this croft type. The absence of profit maximising behaviour from crofters operating in both crofting systems suggests that additional factors to those included in the models, such as age, play an important part in governing croft management decisions. These are discussed later. First, however, we provide more information on simulation results for the bee management schemes modelled.

3.1. Conservation management option A: planting a wildflower mix on croft land

The predicted impacts of increasing bumblebee abundance on croft gross margins vary between croft types and the method of conservation management used. Incorporating a wildflower seed mix reduces the gross margins achieved by crofters in both croft types, although the loss of income is predicted to be greatest for crofters on mixed livestock crofts characteristic of the Uists (Fig. 1a). There is a trade-off between bumblebee density and croft income, although this threshold varies by croft (Fig. 1a and b). Sowing a wildflower mix requires an increase in labour input from the crofter compared to the optimal management plan and, although silage would be a usable by-product of this activity, the opportunity costs incurred though habitat creation alone are substantial — e.g. for a 36% increase in bumblebee abundance across the croft (above the optimal model which results in 8.8 bees ha^{-1}), the crofter would need to sow 1.9 ha of wildflower mix and incur an opportunity cost for habitat creation of £666 in the first year. In addition, there would be associated annual maintenance work for the lifetime of the wildflower mix, which again requires added labour inputs. However, as the purchase of seed is not included in the maintenance cost, the opportunity cost associated with 1.9 ha of wildflowers is much less at £54. The opportunity cost comprises the direct costs associated with implementing this practice (buying seed, cost of labour for sowing, ploughing, etc), and also the costs of converting the land from one use to another in terms of revenue forgone, i.e. from cattle production to wildflowers. Unsurprisingly, purchasing the seed is the most costly element of this practice, with the cost of buying seed accounting for 92% of the direct costs. Stocking rates are also predicted to change under this scenario, with a decline in cattle production (Table 3). The absence of sheep from the optimal production plan remains the same.

Similarly, introducing a wildflower mix to sheep crofts is predicted to have a negative effect on the croft gross margins, with sheep numbers predicted to decline as the constraint on bumblebees is increased (Table 3). Interestingly, our model shows that if crofters in sheep based systems on Lewis were currently operating in an optimal manner, they would reduce their stocking densities and the area of grazed land, thereby increasing the area of winter grazed pasture, rather than incorporating a wildflower mix into their management regimes.

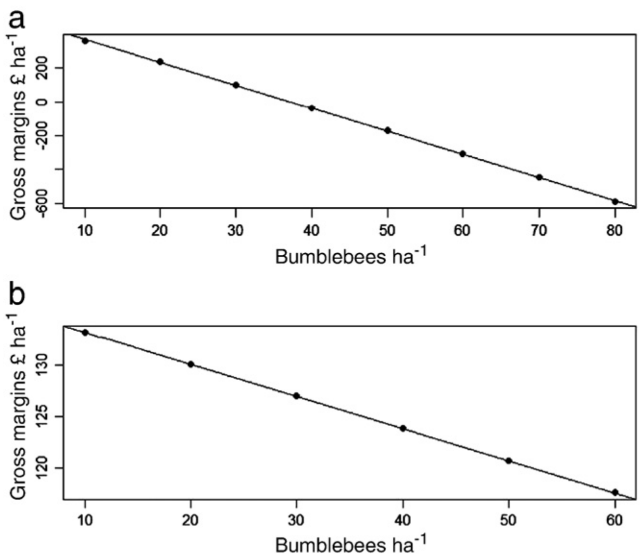

Fig. 1. a–b. The impact of tightening the constraint on bumblebee abundance on croft gross margins for mixed livestock systems on the Uists (Fig. 1a) and sheep production systems on Lewis (Fig. 1b). Gross margins are shown in £/ha and the constraints on bumblebees are shown as the density of bumblebees per hectare of croft land.

Table 3
The percentage change in revenue, costs and land use under the two scenarios. Moorland Grazing is only applicable to the mixed livestock crofts on the Uists and the results are associated with a 30% increase in bumblebee densities. The Wildflower Mix scenario was examined for both systems. The results are also associated with a 30% increase in bumblebees (equivalent to 9.9 bees ha^{-1}). Shown as percentage change in relation to the optimal baseline model.

	Baseline	Uists		Lewis
		Moorland grazing	Wildflower mix–mixed crofts	Wildflower mix–sheep crofts
Croft gross margins	100	11	−4	−4
Total revenue	100	7	0	−6
Total variable costs	100	3	−10	−10
Cattle numbers	100	35	−2	–
Cattle revenue	100	34	−1	–
Cattle variable costs	100	33	−1	–
Sheep numbers	100	0	0	−13
Sheep revenue	100	0	0	−11
Sheep variable costs	100	0	0	−10
Total land used	100	62	10	0
Area inbye grazing	100	−77	0	−20
Area fallow	100	41	35	–
Area silage	100	41	0	–

3.2. Conservation management option B: Use of moorland summer grazing

Bringing moorland back into use for summer grazing is predicted to be the most cost-effective conservation method for mixed livestock crofts on the Uists. Under this scenario, bumblebee abundance increases by 36% above that predicted in the optimal model to 12 bees ha^{-1} of croft land, and the gross margins received by the crofter increases by 11% to £391 ha^{-1}. However, this management option is somewhat limited as bumblebee abundance cannot be increased by more than 36% before the model predicts an infeasible outcome (i.e. there is no single solution that satisfies all the constraints within the model, Hazell and Norton, 1986). Interestingly, the model predicts that crofters should incorporate moorland grazing into their management regimes even without the constraint on bumblebee abundance, in contrast to actual behaviour. By utilising an additional 4.6 ha of moorland crofters would be able to increase cattle production by 35%, and increase their total revenue by 7% (Table 3). An indirect consequence of this change in land management is a 19% increase in bumblebee densities on the inbye to 9.9 bees ha^{-1} of croft land. As no constraint is imposed in this instance the marginal cost is zero. However, increasing bumblebee densities beyond 9.9 bees ha^{-1} of croft land leads to a reduction in overall gross margins compared to the unconstrained MG scenario and generates an opportunity cost of £78.

Interestingly, if crofters in mixed livestock systems are given the choice between the two management options, the models predict that they will only implement moorland grazing if the constraint on bumblebee density is ≤12.6 bees ha^{-1} of croft land, when the availability of moorland grazing becomes a limiting factor. Above this threshold both moorland grazing and a wildflower mix are utilised. However, this has a significant impact on overall croft gross margins, which decrease by 35%, to achieve 12.7 bees ha^{-1} of croft land when compared to the model with no biodiversity constraints.

4. Discussion

4.1. The trade-off between bumblebee abundance and agriculture

Improving the ecological quality of agricultural land often requires a change to current land management practices and results in an opportunity cost to the agent (i.e. farmer or landowner) implementing the desired form of environmental management. Consequently, compensation is usually required. Within the EU this is primarily carried out through Agri-Environment Schemes (AES; e.g. Environmental Stewardship in England, Rural Priorities in Scotland) which reward farmers for employing environmentally sensitive farming methods on the basis of average incomes foregone. Interestingly, the results of our study suggest that in some instances compensation payments may not be required and that farming with a more environmental focus could generate economic, as well as environmental, benefits. In the crofting areas of northwest Scotland, summer grazing by livestock on inbye land has been identified as a particular problem for foraging bumblebees and removing livestock from these areas has been suggested as an appropriate form of conservation management (Redpath et al., 2010). Relocating livestock to moorland grazings in summer is a traditional land management method that could be re-employed to achieve this desired environmental outcome. Re-grazing the moorland would require a change in land management on mixed livestock crofts; however, our models predict that this scenario would actually be more profitable than current crofting practices. Thus, by modifying their management regimes crofters operating in this system would increase their profits whilst providing an environmental good.

That crofters do not engage in this practice suggests that they are not operating on the basis of pure profit maximisation, or that there are other constraints on their choice of management not captured by the model (such as the increasing age of crofters making the use of summer grazing unappealing). In our survey the majority of crofters who did not utilise the moorland grazings did so due to their age, and consequent difficulty in moving livestock between the inbye and hill (L. Osgathorpe, unpubl. data).

The availability and abundance of key foraging resources throughout the flight season are important factors for maintaining bumblebee populations in agricultural landscapes (Bäckman and Tiainen, 2002; Westphal et al., 2006; Goulson et al., 2008). Sowing wildflower seed mixes at field margins is considered an effective means of increasing the abundance of suitable bumblebee flowers in intensively farmed areas (e.g. Carvell et al., 2004; Pywell, et al., 2005), and the inclusion of wildflower mixes into croft management has also been shown to be of value in what has traditionally been seen as a low intensity agricultural system (Redpath et al., 2010). However, these studies have not examined the financial implications to the tax payer of introducing wildflower mixes into farm management practices. We show that the costs of utilising a wildflower mix vary with the type of farming system in operation. Introducing this method to mixed systems in marginal areas is relatively expensive, particularly with respect to the initial capital costs of habitat creation. These costs may make the use of this management tool somewhat prohibitive in such marginal farming systems, especially when less expensive options (e.g. moorland grazing) could be used. However, in sheep based systems the costs of introducing wildflower mixes as part of an AES are considerably less and may provide a more efficient means of increasing bumblebee populations as suitable foraging resources are scarce in this crofting system (Redpath et al., 2010). The density of foraging bumblebees utilising an introduced patch is thought to be determined by landscape context rather than patch size, with greater bumblebee densities on patches in more intensively managed agricultural landscapes with a lack of available foraging resources in adjacent semi-natural habitats (Heard et al., 2007). Therefore, the addition of a small area of bumblebee specific wildflowers to sheep-only crofts could make a significant impact on bumblebee populations, with as little as 0.4 ha of wildflowers having the potential to increase bumblebees densities from an average of zero to 40 bees croft^{-1} (equivalent to 5 bees ha^{-1} of croft land). Although different bumblebee species have different foraging ranges (Knight et al., 2005), the combination of small unit size and the close proximity of sheep-only crofts to one another suggests that even a relatively low uptake of this approach would provide accessible patches for bumblebees with both long and short foraging ranges.

4.2. Considerations for developing agri-environmental payment schemes for bumblebee conservation

Following the Common Agricultural Policy (CAP) Reform in 2005, the calculation of compensation payments for farmers delivering public environmental goods has been based on compensation for the losses incurred in meeting the requirements of agri-environment scheme prescriptions (Mettepennington et al., 2009). Income forgone through scheme participation (ie opportunity cost) is an important factor in this calculation, and has been estimated to account for 56% of total AES scheme costs (Mettepennington et al., 2009). In addition, the transaction costs associated with scheme uptake often impose a significant cost to the farmer, with estimates ranging from a conservative 5% of the total compensation payment to 25% (Falconer, 2000; Mettepennington et al., 2009). Transaction costs are costs incurred by both the farmer (private transaction costs, such as time needed to apply for AES contracts, or legal costs) and the public agency administering the AES in establishing, implementing or monitoring the agreements (public transaction costs). Private transaction costs may significantly affect a farmer's decision to participate in an AES and ultimately influence the success of a scheme (Vanslembrouck et al., 2002). Such costs may be particularly prohibitive for farmers operating small businesses (Falconer, 2000). This is highly relevant to crofting, where income from agriculture often makes a small contribution to total household income. Indeed, transaction costs (either perceived or actual) were often considered as particular obstacles to participating in the latest Scottish AES by crofters managing small agricultural units on Harris and Lewis (L. Osgathorpe, unpubl. data). As highlighted by Falconer (2000), this is worrying as small farms are generally more likely to support high biodiversity. Again, this is highly relevant to crofting due to the association of many rare species with crofted landscapes, e.g. the northern colletes bee (*Colletes floralis*), belted beauty moth (*Lycia zonaria*), and slender naiad (*Najas flexilis*). Measures to reduce transactions costs which deter uptake would include simplifying application processes and payment schemes for farmers, and redistributing private costs to public transactions costs — for example, though publicly-funded advice networks. If transactions costs do indeed disproportionately deter participation on small farms where biodiversity benefits are relatively high, then this is an important issue for policymakers and regulatory agencies to address.

The ecological side effects of altering current management practices to achieve conservation targets such as increases in bees also need to be considered in the creation of any future AES. For example, prior to reintroducing livestock to moorland areas an assessment of the current ecological state of the habitat would be required since heather moorlands are low productivity systems that are easily damaged by inappropriate grazing regimes (Thompson et al., 1995). Overgrazing, in particular, can alter the vegetation structure and composition away from dwarf shrubs to graminoid species (Alonso et al., 2001). Similarly, introducing non-native wildflowers to the machair system could have detrimental effects on the genetic composition of the local flora, thus sourcing of native seeds is essential. Optimal agri-environmental policy would involve the balancing of gains and losses in the value of ecosystem services likely to result from alternative management approaches (Caparros et al., 2010).

The intensification of accessible lowland grasslands and the subsequent abandonment of relatively inaccessible grazing land such as moorlands is a feature of crofting that has been reported in other low intensity grazing systems in Fennoscandia, and the Swiss and Bavarian Alps (Caballero, 2007). Similarly, rural depopulation and the lack of interest from the younger generation in continuing in these traditionally labour intensive farming systems has been highlighted as a common social factor threatening their future across Europe (Caballero, 2007). Much of Europe's High Nature Value (HNV) farmland is found in these Less Favoured Areas (LFA), which account for 56% of the EU's total land mass (Caballero, 2007). These regions receive limited investment due to environmental and social constraints and, worryingly, studies at the European level suggest that current support schemes under the CAP are often not suitable for maintaining human populations in these areas (Caballero, 2007). This suggests that the ecological and economic problems identified in this paper for the Hebridean Islands of Scotland may extend to a much wider area of Europe. Indeed, re-design of agri-environment schemes in other marginal agricultural areas of Europe has been discussed by several authors (Acs et al., 2010; Marini et al., 2011).

Policies are required that take into account the social fragility that is common in these marginal agricultural areas (Acs et al., 2010), and how cultural heritage influences the management of the farming system (Caballero, 2007). The influence of cultural factors is evident to some extent in our study in that the majority of crofters managing mixed crofts persisted with sheep production even though our model shows this to be an unprofitable activity. In most instances sheep had been reared by the family over several generations, and current crofters continue with sheep production in keeping with tradition.

5. Conclusions

Ecological–economic modelling can be usefully employed to examine the trade-offs between socio-economic factors and environmental outcomes for a diverse range of systems. In this paper we use LP based ecological–economic models to show that the cost-effectiveness of two bumblebee conservation measures in the Outer Hebrides varies according to the crofting system in operation. Since current land-use deviates from profit-maximising management, we compare optimal land-use with and without constraints on bumblebee abundance. Promoting the use of traditional summer moorland grazing practices in the mixed crofting systems found in the Uists and Harris would generate a net gain in income from crofting activities and would deliver greater bumblebee abundances on crofts without the need for compensation. Consequently, rather than investing in a traditional AES that may be limited by the associated transaction costs (real or perceived), policy-makers should consider investing in greater advocacy of environmentally beneficial management that also boosts income; and in identifying barriers to management change which might bring about win-win situations for farm incomes and biodiversity. However, more substantial increases in bumblebee numbers on mixed crofts were found to require the introduction of new agri-environment schemes.

In contrast, some form of payment based scheme is required to increase bumblebees on sheep production crofts found in Lewis. Although the payment rate required is relatively low, agricultural income and unit size is typically very small in this system so that transaction costs are likely to be disproportionate to the compensation required. It is essential that policy-makers take this into consideration during the policy design process. Social and cultural factors are also important in shaping land management practices in low intensity farming systems in LFAs, and must also be taken into account when developing agri-environmental policies for these unique areas of the EU.

Several weaknesses behind the approach taken here are acknowledged. Bumblebee conservation is a problem with important spatial aspects due to the nature of foraging ranges and dispersal patterns. This implies that conservation actions by individual farmers can spill-over onto neighbouring farms. It also implies that the optimal pattern of land-use for conservation is best determined at the landscape level. However, the simple optimisation models used here do not reflect this. This is a task for future work.

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