

Ecosystem service and dis-service impacts of increasing tree cover on agricultural land by land-sparing and land-sharing in the Welsh uplands

Hardaker, Ashley; Pagella, Tim; Rayment, Mark

Ecosystem Services

DOI:

[10.1016/j.ecoser.2021.101253](https://doi.org/10.1016/j.ecoser.2021.101253)

Published: 01/04/2021

Peer reviewed version

[Cyswllt i'r cyhoeddiad / Link to publication](https://doi.org/10.1016/j.ecoser.2021.101253)

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):

Hardaker, A., Pagella, T., & Rayment, M. (2021). Ecosystem service and dis-service impacts of increasing tree cover on agricultural land by land-sparing and land-sharing in the Welsh uplands. *Ecosystem Services*, 48, Article 101253. <https://doi.org/10.1016/j.ecoser.2021.101253>

Hawliau Cyffredinol / General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1 Ecosystem service and dis-service impacts of increasing tree cover on
2 agricultural land by land-sparing and land-sharing in the Welsh uplands
3

4 Ashley Hardaker^a, Tim Pagella^a and Mark Rayment^a
5

6 ^a*School of Natural Sciences, Bangor University, Bangor, Wales, LL57 2UW*
7

8 Email of Ashley Hardaker (corresponding author): afpb0d@bangor.ac.uk

9 Email of Tim Pagella: t.pagella@bangor.ac.uk

10 Email of Mark Rayment: m.rayment@bangor.ac.uk

Ecosystem service and dis-service impacts of increasing tree cover on agricultural land by land-sparing and land-sharing in the Welsh uplands

Abstract

Increasing tree cover on agricultural land is recognised as a potential mechanism to enhance ecosystem services. In this case study, we assessed and mapped the impacts on ecosystem services and dis-services of different land-sparing and land-sharing strategies for tree cover expansion on grassland and arable land in the Welsh uplands. In addition, we modelled the impacts of widespread adoption of these strategies on grassland and arable land on the total basket of ecosystem services derived from the Welsh uplands. Our modelling over a 120-year period suggests land-sharing strategies (agroforestry options) could lead to the greatest potential increase in ecosystem service benefits (+£2.62 billion for the Agroforestry - in field trees option). Such land-sharing strategies deliver a basket of ecosystem services primarily focused on private provisioning benefits, with only modest increases in public regulation and maintenance benefits. In contrast, land-sparing strategies (full afforestation options) deliver the highest level of public regulation and maintenance benefits (£7.60 billion), but at the cost of provisioning benefits (-£17.13 billion). Land-sharing strategies (agroforestry options) provide the highest level of *in-situ* ecosystem service benefits. Land-sparing strategies (full afforestation options) primarily provide *ex-situ* ecosystem service benefits and are likely to require livelihood shifts for private landowners and occupants.

Keywords: *Agriculture, Tree Cover, Land-sparing/sharing, Ecosystem Service Assessment, Economic Valuation*

1. Introduction

Expansion or restoration of tree cover on agricultural land is recognised as a potential mechanism for improving regulating ecosystem functions and enhancing ecosystem service (ES) provision. Expanding tree cover (in any form) on agricultural land is complex due to competing stakeholder priorities, often requiring significant trade-offs (Burton *et al.*, 2018a; Lawrence *et al.*, 2010; Lawrence and Dandy, 2014; Swanwick, 2009). Whilst it is generally acknowledged that restoration and expansion of woodland cover through land-sparing strategies can lead to increases in regulation and maintenance ESs and in some cases ecosystem dis-services (EDSs) the evidence base surrounding the effect of different modes of afforestation on ESs and EDSs to inform future land use decisions is still lacking (Burton *et al.*, 2018b; Cord *et al.*, 2017). Land-sharing measures such as small woodland patches within agricultural landscapes have been found to deliver a wide range of *in-situ* (e.g., food production) and *ex-situ* (e.g., carbon sequestration and flood mitigation) ES benefits, demonstrating the value of integrating trees with agricultural production (Burton *et al.*, 2018b; Decocq *et al.*, 2016), but this evidence is limited. In addition, little is known generally about how much agricultural landscapes and the benefits derived from them would have be modified to accommodate significant increased tree cover (Fairhead *et al.*, 2012).

Meli *et al.* (2019) argue that promoting restoration of tree cover within principally agricultural landscapes requires assessing and addressing the problem through both land-sparing and land-sharing approaches. Increasing tree cover on agricultural land does not necessarily need to involve complete

transformation of land use to full woodland cover but can occur on a more integrated basis such as farm woodland and agroforestry. Given this, the land-sparing/sharing model (LSSM)—originally a model for quantifying the implications of land use and food production on biodiversity (Balmford *et al.*, 2005; Green *et al.*, 2005; Phalan *et al.*, 2011)—provides a powerful heuristic for considering the value of trees for improving ES provision. The application of the LSSM to modelling the changes in ESs is based on the view there are two main ways to increase tree cover on agricultural land, either retaining agricultural production alongside tree cover within a parcel of land or complete removal and displacement of agriculture in favour of complete afforestation of a parcel of land (Fischer *et al.*, 2008; Phalan *et al.*, 2011). The LSSM acknowledges there are often significant trade-offs between these two types of strategies (Phalan, 2018) and provides a means for quantifying them. Such an approach has value in gauging the effects of landscape transformation on large scale ecological processes affecting ESs, the ES benefits derived from them and the livelihoods of people living and working in these landscapes (Chazdon *et al.*, 2017).

Recent political activity in the UK associated with withdrawal from the EU has put the future direction of agricultural land use into question, particularly in areas dominated by extensive livestock agriculture such as the Welsh uplands (Hubbard *et al.*, 2018). Land use changes in the Welsh uplands involving increases in tree cover as a response to climate change adaption targets or to restore greater regulating ecosystem functions could bring about a significant shift in the balance of ESs delivered from these systems. Historically the expansion of woodland cover in the Welsh uplands was facilitated by significant growth of the public forest estate through land sparing means by replacement of agricultural production (Forest Research, 2017a, 2017b; Wong *et al.*, 2015). Increasingly, the debate surrounding future expansion of tree cover in Wales has shifted towards needs for multiple benefits and its closer integration with agriculture through land-sharing means, such as trees on farms and agroforestry systems (Forestry Commission Wales, 2009; UKCCC, 2020; Welsh Government, 2018a, 2018b).

The primary evidence base available to inform tree-based land use change in upland agricultural landscapes in Wales is predominantly focused around ESs from existing woodland cover and on a single or a few ESs; notably timber production and its relation to carbon sequestration (Bateman and Lovett, 2000; Brainard *et al.*, 2009), recreational use (Scarpa, 2003; Sen *et al.*, 2011) and hydrological services (Willis, 2002). Other authors have made attempts at estimating the total ES value of the UK forest resource (Eftec, 2010; Europe Economics, 2017; Saraev *et al.*, 2017; Willis *et al.*, 2003). The assessment of ESs from agroforestry systems is currently underrepresented, with the UK only featuring as a single *landscape* within two wider European studies (Crous-Duran *et al.*, 2020; Kay *et al.*, 2019). Only two studies have undertaken economic valuation and mapping of ESs from woodland based land use change in Wales, comparing agriculture and hypothetical expansion of multipurpose broadleaf and coniferous woodland

(Bateman, 1996; Cosby *et al.*, 2019). These studies are based primarily around replacement of agriculture through land-sparing measures with no attention paid to more integrated land-sharing approaches such as farm woodland and agroforestry. The evidence base also does little to show who benefits or disbenefits from increasing tree cover.

With this in mind, we present an approach for using the LSSM as a formalisation framework for modelling the impacts of increasing tree cover on agricultural land on ESs and EDSs using the Welsh uplands as a case study. The Welsh uplands offer a particularly interesting case study as a) upland areas account for a significant proportion of the total land area of Wales, b) they are the likely target location for interventions to restore regulating ecosystem functions by increasing tree cover and c) it is largely understudied.

1.1 Aim and objectives

Here we present an approach that aims to address the knowledge gap surrounding the potential impacts on ES benefits and EDS costs associated with different modes of tree cover expansion in agricultural systems, using the Welsh uplands as a case study. The principal objectives of this study were to:

1. Compare how ES delivery changes under a range of tree-based land-sparing and land-sharing strategies on agricultural land in the Welsh uplands.
2. Compare the economic impacts of widespread adoption of different forms of tree cover expansion (based on changes to ESs and EDSs delivery across all categories of ESs and EDSs).
3. Suggest which land use options are potentially most suitable for improving ES benefits through increasing tree cover on grassland and arable land in the Welsh uplands.

2. Materials and methods

2.1 The study area

In this case study we investigated the impacts of expanding tree cover on agricultural land in the Welsh uplands. It is challenging to robustly define the system boundaries for *uplands* (Mansfield, 2011). Here we defined the *Welsh uplands* as the area encompassed by the Severely Disadvantaged Area (SDA) under the Less Favoured Area (LFA) designation (EC Directive 75/268) – panel *a* in Figure 1. Land use in the Welsh uplands is dominated by low-intensity sheep and cattle grazing (covering approximately 80% of the area), with smaller amounts of high-volume low quality softwood timber production interspersed with areas of unproductive amenity woodland (covering the remaining 20%) (Armstrong, 2016; National Assembly for Wales, 2013). In Wales, the majority of the upland area is managed through extensive livestock grazing on a mix of permanent grassland and semi-natural habitats with sheep and beef cattle (Armstrong, 2016; National Assembly for Wales, 2013). In this case study we explored the consequences

of increasing tree cover on improved, semi-improved, unimproved grassland and arable land (as defined by the Terrestrial Phase 1 Habitat Survey (Natural Resources Wales, 2018)) within the Welsh uplands on ESs and EDSs. The total area of these land cover types is 569,477 ha, of which 433,171 ha is improved grassland, 36,565 ha is semi-improved grassland, 92,589 ha unimproved grassland and 7,151 ha is arable (Natural Resources Wales, 2018) – see panel *b* Figure 1. We focused our modelling of land use changes on these areas of grassland and arable land as they were identified in Hardaker *et al.* (2020) as an opportunity space for tree cover expansion. In addition they are generally contiguous with enclosed farmland and are not sensitive priority habitats such as heathland or mire where tree planting may be problematic (Natural Resources Wales, 2016).

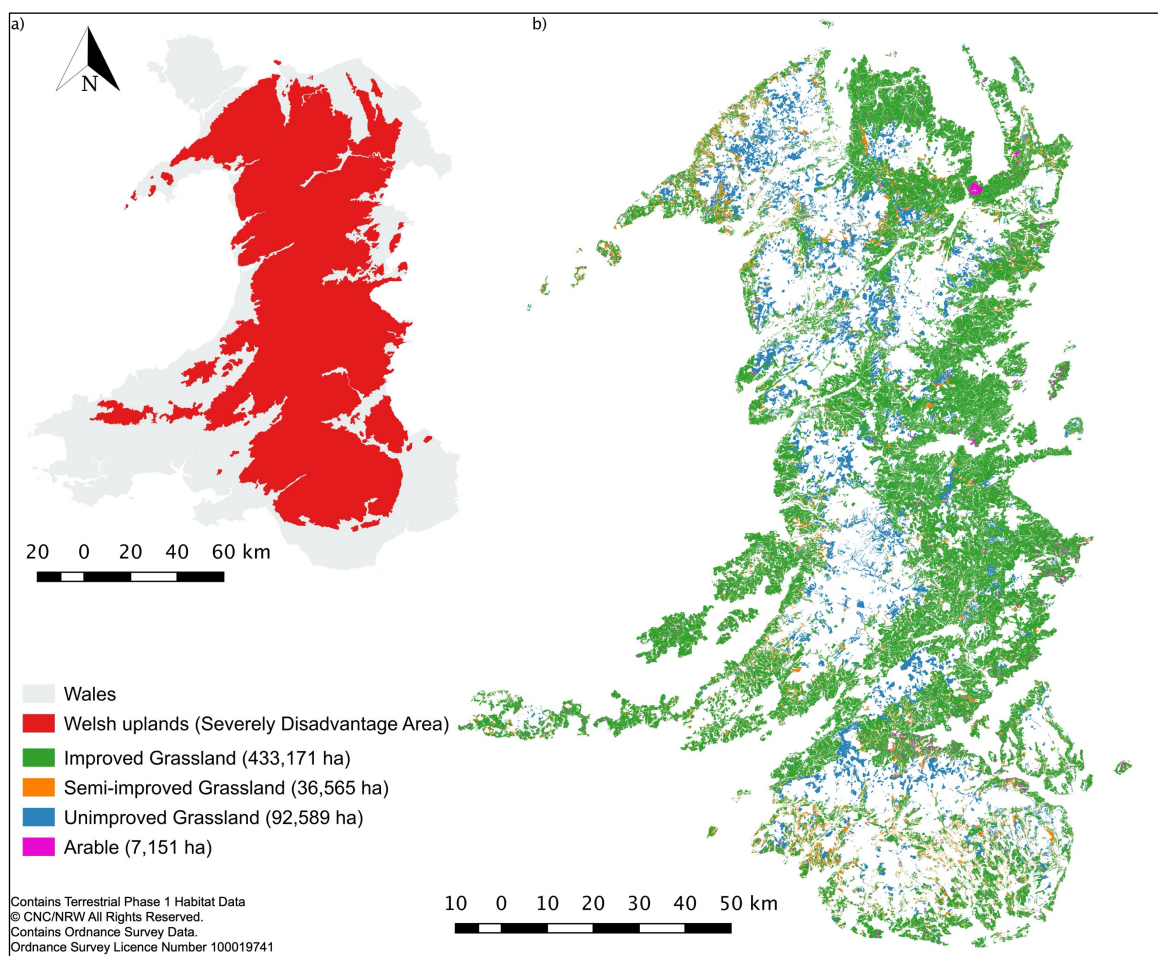


Figure 1: a) Extent of the Welsh Severely Disadvantaged Area (SDA) and b) distribution of improved, semi-improved-unimproved grassland and arable land in Wales's SDA derived from the Terrestrial Phase 1 Habitat Survey (Natural Resources Wales, 2018) .

2.2 Ecosystem services framework and some key terms

In this study we focused on the actual supply (or flow) of ESs from the Welsh uplands and how land use changes (involving greater tree cover) may alter this flow. The actual supply or flow of ESs is the combination of potential supply and the associated human demand (Fisher *et al.*, 2009, 2008; Goldenberg

et al., 2017; Verhagen *et al.*, 2015). With this in mind we defined ESs as the flows of services and goods from ecosystems that provide benefits to humans (de Groot *et al.*, 2010; Haines-Young and Potschin, 2010). To classify the ESs to be investigated in this study we used the Common International Classification for Ecosystem Services (CICES) (Haines-Young and Potschin, 2017).

As a development of similar work we also considered the actual supply of EDSs, which are the result of the functions, processes and management of ecosystems that lead to negative impacts on humans (Blanco *et al.*, 2019; Campagne *et al.*, 2018; Dunn, 2010; Schaubroeck, 2017; Shackleton *et al.*, 2016). In this study EDSs are defined as the flows of dis-services from ecosystems that provide costs to humans. By including EDSs in our analysis, we hope to present a more balanced view of the net benefits of land use and potential land use changes (Wegner and Pascual, 2011). The CICES classification does not explicitly include EDS, however an EDS may manifest a negative externality of different land uses and their associated management activities (Campagne *et al.*, 2018). It is in this manner that EDS are classified in this study. In this study we used a relevant subset of the ESs and EDSs outlined in Table 1.

Table 1: Ecosystem services and dis-services included within the economic valuation

CICES Section	Final ecosystem services and dis-services included in the economic valuation
Provisioning services	Livestock production
	Arable crops
	Timber production
	Water supply for consumptive use
Provisioning dis-services	Potable water quality reduction
Regulation and maintenance services	Carbon sequestration
	Local flood risk mitigation
	Livestock shelter and shade
Regulation and maintenance dis-services	GHG emissions
Cultural services	Employment

2.3 Methodological framework

In this study we conducted a spatially explicit economic assessment of the potential performance of a range of land-sparing and land-sharing strategies for increasing tree cover on agricultural land in the Welsh uplands in terms of ES benefits and EDS costs. We also simulated the potential impact of widespread adoption of these strategies on the total basket of ES benefits and EDS costs from the Welsh uplands as a whole.

2.3.1 Assessing the performance of land-sparing and land-sharing strategies for increasing tree cover on agricultural land in the Welsh uplands

In the first part of the analysis, we assessed and mapped the potential ES benefits and EDS costs from grassland and arable land in the Welsh uplands under a range of land-sparing and land-sharing strategies

to identify how this performance varied spatially across the Welsh uplands. Within the land-sparing and land-sharing strategies, we considered seven different land use options covering a spectrum of tree canopy coverages from no increase in canopy coverage through to conversion to full canopy coverage within a land parcel. The land-sparing strategies were split into land use options that involve either a) no increase in canopy coverage where tree cover does not replace agricultural production (*Business as usual* option) or b) complete canopy coverage where tree cover completely replaces agricultural production is displaced (*Full afforestation – conifer/broadleaf* options). The land-sharing strategies describe partial canopy coverage where land is shared, and agricultural production continues alongside tree cover. The land-sharing strategies are split into land use options where either a) trees are intimately integrated alongside agricultural production (*Agroforestry – in field trees/shelterbelts* options) or b) trees are coarsely integrated alongside agricultural production (*Farm woodland – conifer/broadleaf* options). The land use options are illustrated in Figure 2 and described in Table 2. A full breakdown of the land use option specifications is provided in Supplementary Material Table 1 describing modelling assumptions, indicative species mixes, indicative planting spacings, thinning/felling regimes and full descriptions of the options.

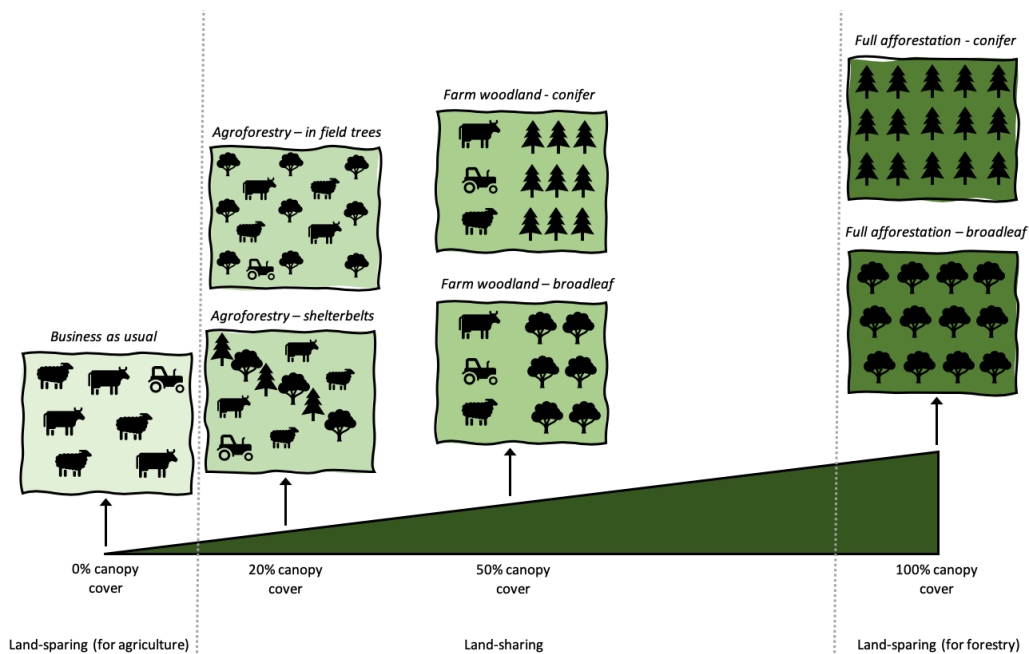


Figure 2: Land use options (option name in *italic*) describing the modelled percentage tree cover in each parcel on improved, semi-improved and unimproved grassland, and arable land used to estimate the potential impact of increasing tree cover on ecosystem service benefits and ecosystem dis-services costs.

172 Table 2: Summary and description of the land use options

Option name	Shorthand	Land-sparing/sharing	Canopy cover (%)	Description
Business as usual	BAU	Land-sparing (for agriculture)	0	No tree canopy cover expansion.
Agroforestry – in field trees	AF-IF	Land-sharing (light)	20	Addition of agroforestry systems, modelled as an in-field trees (silvopasture and silvoarable) planting arrangement.
Agroforestry – shelterbelts	AF-SH	Land-sharing (moderate)	20	Addition of agroforestry systems modelled as a shelterbelt planting arrangement.
Farm woodland – conifer	FW-CO	Land-sharing (heavy)	50	Addition of farm woodland modelled as a primarily conifer planting scheme (to reflect a biomass focused management system).
Farm woodland – broadleaf	FW-BR	Land-sharing (heavy)	50	Addition of farm woodland modelled as a mixed primarily broadleaf planting scheme (to reflect an ecosystem services/public goods focused management system).
Full afforestation – conifer	FA-CO	Land-sparing (for forestry)	100	Replacement of agricultural production with complete canopy cover modelled as a productive mixed primarily conifer planting scheme (to reflect a timber focused management system).
Full afforestation – broadleaf	FA-BR	Land-sparing (for forestry)	100	Replacement of agricultural production with complete canopy cover modelled as a broadleaf planting scheme using native broadleaves (to reflect an ecosystem services/public goods focused management system).

2.3.2 Assessing the potential impacts of widespread adoption of the land sparing and land-sharing strategies on ecosystem services and dis-services from the Welsh uplands as a whole

Land use in the Welsh uplands consists of primarily two types, agriculture and forestry (Armstrong, 2016; National Assembly for Wales, 2013) with agricultural land use split across a) rough grazing and b) grassland and arable land cover – as shown in Figure 3. In the second part of the analysis, we assessed the how the total basket of ES benefits and EDS costs from the Welsh uplands as a whole could be affected by widespread adoption of each of the seven land use options on all grassland and arable land. In essence this simulated the impacts of 0%, 20%, 50% and 100% afforestation of grassland and arable land in the Welsh uplands. In this study we also assessed the ES benefits and EDS costs from forestry land use and agricultural land use on rough grazing modelled *ceteris paribus*. We used these values plus the values of ES benefits and EDS costs from grassland and arable land under the range of land use options to estimate the potential maxima impacts that widespread increases of tree cover on agricultural land could have on the total basket of ES benefits and EDS costs from the Welsh uplands as a whole – as shown in Figure 3.

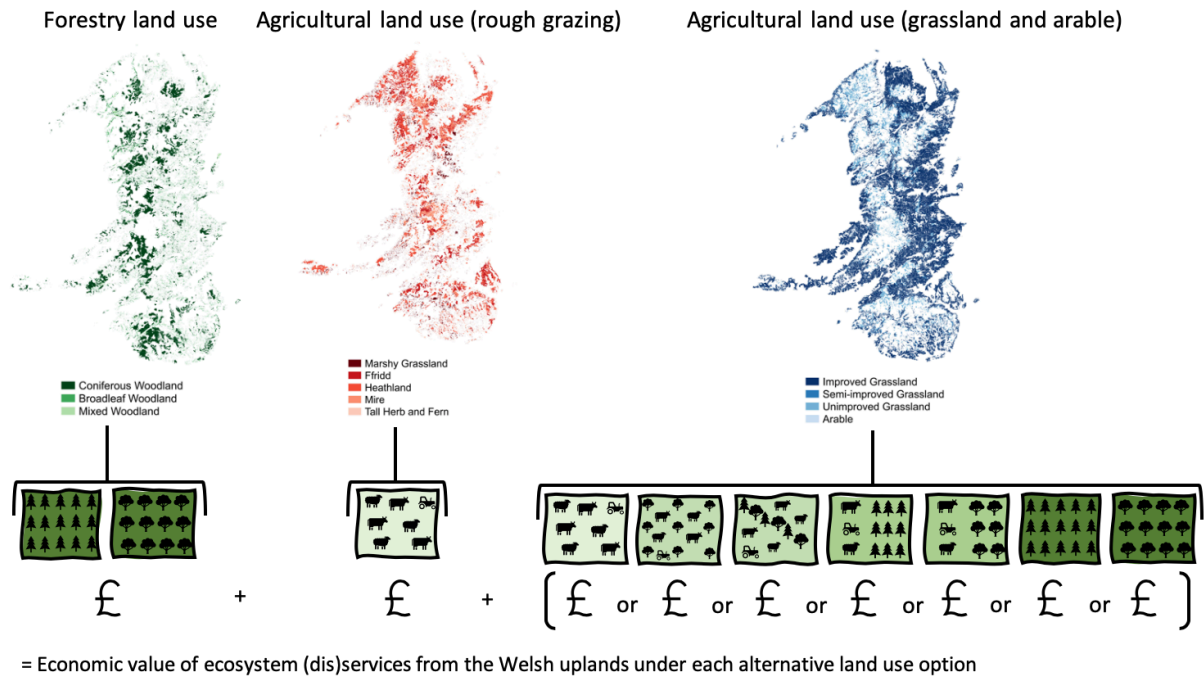


Figure 3: Differentiation of the land use types present in the Welsh uplands (and their constituent land cover classes) and the procedure for estimating the economic value of ecosystem services and dis-services from the Welsh uplands as a whole under each land use option.

2.4 Economic assessment approach

For the monetary valuation of ES benefits and EDS costs over the 120-year assessment period we followed a benefit transfer approach (Ferrini *et al.*, 2015; Johnston and Wainger, 2015) using land cover proxies for ES generation potential. To estimate economic values, we used areas of ES and EDS supply (derived from land cover data) combined with biophysical quantities (derived from simple mathematical models or existing country specific data) and economic unit values. We estimated of the economic value (EV) of ES benefits, EDS costs and net ES (NES) benefits (which is the economic value of ES benefits less the EDS costs) from:

1. Grassland and arable land under each of the seven land use options as described in Section 2.3.1.
2. The Welsh uplands as a whole following the hypothetical transformation of land use on grassland and arable land as described in Section 2.3.2.

We included EDS costs and NES benefits because whilst the value of ES benefits shows the positive importance of land use in the Welsh uplands these values neglect the costs associated with different land uses (Wegner and Pascual, 2011). We limited the economic valuation in this study to the ESs and EDSs included in the baseline economic valuation undertaken in Hardaker *et al.* (2020) plus an additional ES (*livestock shelter and shade*) for which demand could be determined from the alternative land use options (as outlined in Table 1). In order to determine which of the 10 ESs and EDSs were supplied by each of the alternative land use options we conducted a brief review of relevant literature; for an overview of the reviewed literature and the ESs and EDSs supplied by each option see Supplementary Material Table 2.

2.4.1 Identifying ecosystem service and dis-service demand

We used the Terrestrial Phase 1 Habitat Survey (Natural Resources Wales, 2018) spatial shapefile data to delineate the land parcels within the Welsh uplands and identify ESs and EDSs demand as a basis for the quantification and mapping of actual supply. Each polygon within the dataset represents an individual parcel of land. The actual supply or flow of ESs or EDSs from a parcel of land is the combination of potential supply and the associated human demand. For some ESs (i.e., *livestock production, arable crops, water supply for consumptive use, carbon sequestration, livestock shelter and shade*) the associated demand is not spatially dependent. Where this is the case, all land parcels were tagged with a *yes* for demand for these particular ESs and EDSs.

For some ESs and EDSs in this study the associated demand is spatially dependent (i.e., *timber production, local food risk mitigation, employment, potable water quality reduction and greenhouse gas emissions*). Where this is the case, we used a range of spatial proxies for demand to determine where actual supply is realised (see Supplementary Material Tables 3 and 4). To define the land parcels within the Welsh uplands where spatially dependent demand for certain ES and EDS was present, we performed spatial queries using GIS to tag land parcels based on their spatial relationship (in this case where they overlap) with the spatial proxies for ES and EDS demand (e.g., shapefiles charting acid sensitive catchments as a proxy for *potable water quality reduction* from forestry land use). Where demand for these ES or EDS exists in a land parcel, we tagged it with a *yes* and where demand was not present, we tagged it with a *no*.

2.4.2 Economic analysis

Similarly to Hardaker *et al.* (2020) we focused on monetary valuation of direct and indirect use values as defined under the Total Economic Value (TEV) Framework; where the economic value of ES benefits includes all elements of utility provided by the direct and indirect use of ESs using monetary accounting units (Freeman, 2003; Pearce and Turner, 1990; Pearce, 1993). Non-use values were disregarded due to the lack of available data to infer their supply from land cover data. Therefore, we refer to the results of our economic valuation as the “*economic value*” not the “*total economic value*” as we do not include non-use values such as existence value or bequest value. We also include the EV of dis-utility provided EDS costs. The impacts of land use changes on ESs and EDSs will take some time into the future to arise. It is well established that given the time value of money the value of ES benefits and EDS costs in the present are worth more than the same amount in the future. In other words, the benefits accrued in the future won’t be worth as much as those earned in the present (Freeman, 2003; Pearce and Turner, 1990; Pearce, 1993). Discounting the future value of flows of ES benefits and EDS costs to their present-day equivalents or Present Value (PV) is a way to account for this. We took a multi-period assessment approach where

we estimated the annual EVs over an extended projection period (120 years)—which is the length of the longest single rotation in any of the land use options—and discounted the future flow of annual EVs to their PV. To discount the future value of benefits and costs to their PV we used a standard real discount rate of 3% based on the recommendations of (Hepburn and Koundouri, 2007) due to the uncertainty of future revenues and costs over the length of the projection.

2.4.2.1 Economic values of ecosystem service benefits and dis-service costs across grassland and arable land under each of the land use options

We estimated and created a lookup table of the EV ha⁻¹ of ES benefits and EDS costs from grassland and arable land cover types under each of the land use options. We calculated the per hectare EV of each ES_k or EDS_k supplied by grassland and arable land under each of the land use options using the following formula:

$$PVha^{-1}_k = \sum_{t=1}^n \left(\frac{s_k ha^{-1} \cdot p_k}{(1+i)^t} \right) \quad (Eq. 1)$$

where t is the year in projection period (t ranges from 1 to 120), i = real discount rate and n = number of time periods, $s_k ha^{-1}$ is the biophysical supply of ES_k or EDS_k from a hectare of each constituent land cover type, e.g., m³ timber ha⁻¹ during a single period t and p_k is the market or shadow price of ES_k or EDS_k, e.g., £m³ timber during a single period t (Howarth and Farber, 2002).

We used the look up table of per hectare economic values of ES benefits and EDS costs and GIS to create a set of maps comparing the economic values across grassland and arable land under each of the land use options. We used the Terrestrial Phase 1 Habitat Survey (Natural Resources Wales, 2018) spatial shapefile data tagged with ES and EDS demand as described in Section 2.4.1 to create our maps. Where demand for a particular ES or EDS exists in a land parcel, and was tagged with a *yes*, we assigned it the corresponding economic values ha⁻¹ for each ES benefit and EDS cost for each land cover type from the lookup table derived using equation 1. Where no demand existed for each ES or EDS in a land parcel, and tagged with a *no*, we assigned a zero value. We summed the individual ES and EDS values in each land parcel to provide an EV for ES benefits, EDS costs and NES benefits.

2.4.2.2 Economic values of ecosystem service benefits and dis-service costs from the Welsh uplands as a whole under each of the land use options

We calculated the EV of each ES benefit and EDS cost supplied by each land use (forestry, agricultural (rough grazing) and agricultural (grassland and arable)) using the following formula:

$$PV_k = \sum_{t=1}^n \left(\frac{s_k p_k}{(1+i)^t} \right) \quad (Eq. 2)$$

where t is the year in projection period (t ranges from 1 to 120), i = real discount rate and n = number of time periods, s_k is the biophysical supply of ES_k or EDS_k e.g., tonnes of CO^2 (total area of land parcels supplying ES_k or EDS_k (as described in section 2.4.1)) multiplied by the per hectare biophysical unit of ES_k or EDS_k) during a single period t , and p_k is the market or shadow price of ES_k or EDS_k , e.g., £tonne⁻¹ CO^2 during a single period t (Howarth and Farber, 2002).

We calculated to the total EV of ES benefits and EDS costs for each land use using the following formula:

$$EV_{ES/EDS} = \sum_{k=1}^n PV_k \quad (Eq. 3)$$

where $EV_{ES/EDS}$ is the sum of the present values of all n ES benefits or EDS costs that each land use (forestry, agricultural (rough grazing) and agricultural (grassland and arable)) generates. We calculated the total aggregated EV of ESs and EDS from the Welsh uplands as whole (forestry, agricultural (rough grazing) and agricultural (grassland and arable) combined) as the sum of the totals for each land use – as shown in figure 3.

Most existing valuation studies of multiple ESs aggregate the separate values of each individual ES into a single figure cited as the total societal benefits derived from the particular study site (Eftec, 2010; Europe Economics, 2017; Häyhä *et al.*, 2015; Willis *et al.*, 2003). This overlooks issues surrounding the distribution of benefits across the spectrum of different beneficiary groups (Hein *et al.*, 2006). As such, we disaggregated the EV of ES benefits and EDS costs from the Welsh uplands as a whole into the different value bundles for each beneficiary group (identified in Hardaker *et al.* (2020)) in order to identify the impacts of transformations of upland grassland and arable land use on the beneficiary bundles. We disaggregated the total EV into beneficiary bundles by the population of the relevant beneficiary groups using population data as at 2011 taken from Population Reference Bureau (2011); Reis *et al.* (2017). For the relevant beneficiary groups for each ES and EDS see Supplementary Material Table 5.

2.4.2.1.1 Uncertainty analysis

This assessment was based on national level economic data and other data from the wider literature and is therefore also subject to non-negligible uncertainty. We undertook an uncertainty analysis to detect the influence of uncertainty in the market and calculated shadow prices would have on the economic values. We used the Monte Carlo simulation method (Metropolis and Ulam, 1949) to determine the

combined effects of the input data uncertainties based on the distribution functions of the input data parameters. Using the Monte Carlo simulation method, we employed a uniform random function using a range of $\pm 20\%$ for market and calculated shadow prices and ran this over 10,000 simulations. A uniform random function was chosen as the best probability distribution for the input data as the input variable variation is unknown and only its minimum and maximum values can be estimated (Sivia, 1996).

2.4.4 Economic valuation methods

For the economic valuation of ES benefits and EDS costs we used pricing techniques; specifically, a combination of market price observations and non-market pricing methods (Howarth and Farber, 2002). We used the market price method to estimate the value of ES benefits (*livestock production, arable crops, timber production, water supply for consumptive use and employment*) that are tradeable on markets that are well functioning and individual unit market prices are well defined (Dasgupta, 2008; Bateman *et al.*, 2014). The market price method assumes that prevailing market prices are a reflection of the minimum willingness to pay (WTP) for ESs that are tradeable on competitive markets and provide a conservative lower bound estimate of WTP (Howarth and Farber, 2002). For ES benefits and EDS costs without observable or specific market prices, we used non-market pricing methods to estimate shadow prices (Dasgupta, 2008; Flores, 2003; Howarth and Farber, 2002). We used the replacement cost (Bateman *et al.*, 2014; Dixon *et al.*, 1997) for *carbon sequestration, local flood risk reduction and livestock shelter and shade* and averting behaviour methods (Dickie, 2003; Flores, 2003; Bateman *et al.*, 2014) for *GHG emissions and potable water quality reduction*. These methods assume that the costs of mitigating damages or replacing ecosystem functions are equivalent to the minimum WTP for ES benefits and willingness to avoid (WTA) EDS costs. We calculated the EV of ES benefits and EDS costs using calculation procedures adapted from Hardaker *et al.* (2020). The biophysical and economic units of the ES benefits and EDS costs are outlined in Supplementary Material Table 5 and economic parameter values are outlined in Supplementary Material Table 6. The valuation of ES benefits and EDS costs as described in Section 2.4.2 are based on 2018 figures and represent the PV of the stream of future annual EVs across the extended projection period. For a full overview of the calculation procedures of individual ES benefits and EDS costs (including the specific data sources) used in the economic valuation see Supplementary Material Section 4.

3. Results

3.1 Inter-option differences in the economic value of ecosystem service benefits and ecosystem dis-service costs

Our results show quite significant inter-option differences in performance in terms of potential ES benefits and EDS costs – see Figure 4. The land use strategies where tree cover replaces agricultural production (FA-BR and FA-BR options) perform the worst in terms of ES benefits representing a potential major drop in ES benefits compared to the BAU option (panel *a* in Figure 4). The FA-BR and FA-BR options perform the best in terms of EDS costs leading to significant potential reductions compared to the BAU option (panel *b* in Figure 4). The land use strategies where tree cover is intimately integrated with agricultural production (AF-IF and AF-SH) generally perform the best in terms of ES benefits, representing major potential increases in ES benefits in the case of the AF-IF option and moderate increases in the case of the AF-SH option (panel *a* in Figure 4). The AF-SH option leads to sizeable potential reductions in EDS costs compared to the BAU option, whereas the AF-IF option generally leads to an increase in EDS costs (panel *b* in Figure 4). The land use strategies where trees are coarsely integrated alongside agricultural production (FW-CO and FW-BR options) generally perform worse than the BAU option in terms of ES benefits (panel *a* in Figure 4) but do lead to potential reductions in EDS costs (panel *b* in Figure 4).

On improved grassland and semi-improved grassland both the AF-IF and AF-SH options leads to an increase in ES benefits whereas the FW-CO, FW-BR, FA-BR and FA-BR options lead to a decrease in ES benefits (panel *a* in Figure 4). On unimproved grassland all of the land use options return higher EV of ES benefits than the BAU option (panel *a* in Figure 4). In terms of EDS costs, on improved, semi-improved and unimproved grassland the AF-IF option leads to an increase whereas all other options lead to a decrease in EDS costs compared to the BAU option (panel *b* in Figure 4). Although, on semi-improved grassland the increase in EDS costs from the AF-IF option is not as large as on improved and unimproved grassland. On arable land, only the AF-IF option leads to an increase in ES benefits compared to the BAU, all other options lead to a decrease (panel *a* in Figure 4). On arable land all options (including the AF-IF option) lead to a decrease in EDS costs compared to the BAU option.

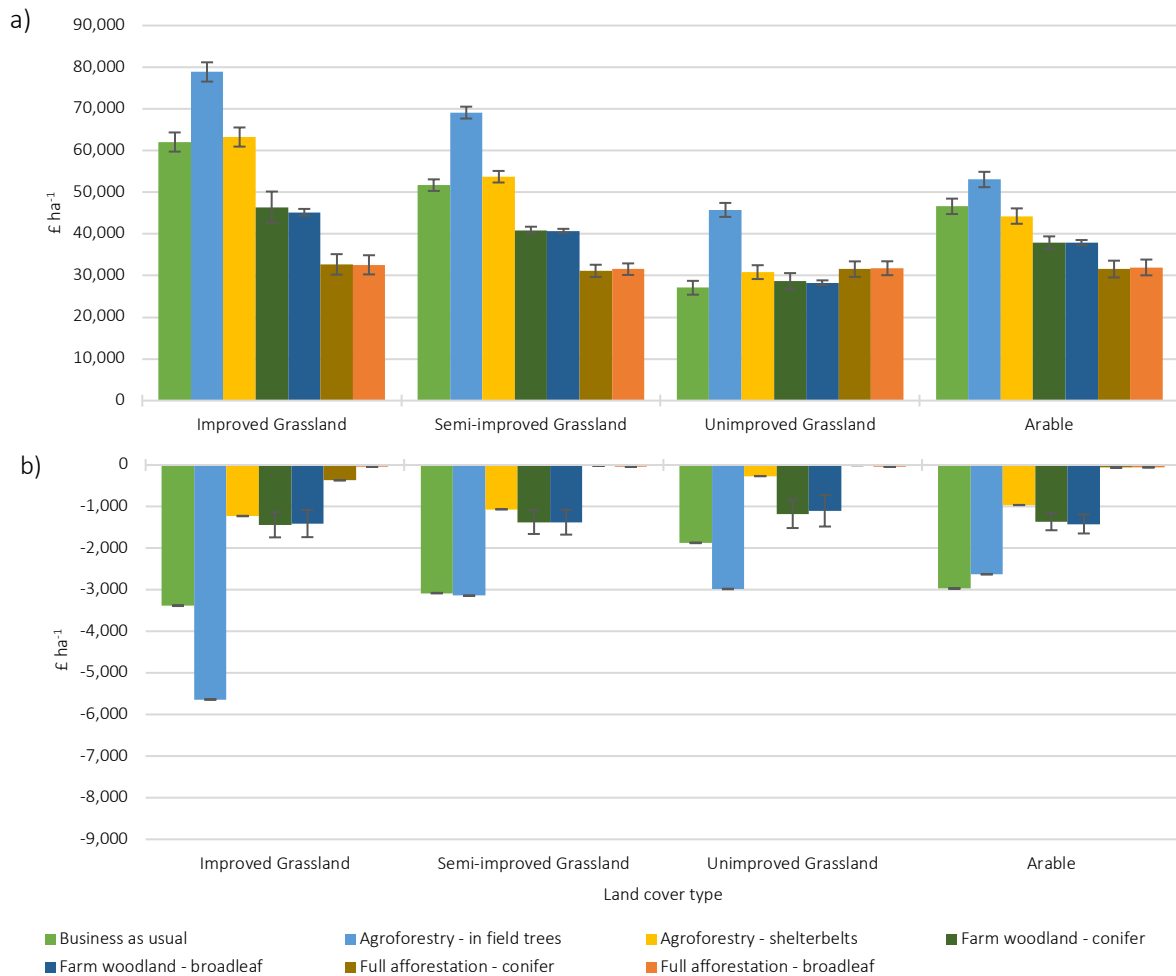


Figure 4: Mean economic value ha^{-1} of a) ecosystem service benefits and b) ecosystem dis-service costs by antecedent land cover type across each of the seven land use options. Error bars show standard deviation. The ecosystem services comprise livestock production, arable crops, timber production, carbon sequestration, local flood risk mitigation, livestock shelter and shade and employment. The ecosystem dis-services comprises GHG emissions and reduction of potable water quality. The economic values are the present value of the future flows of benefits and costs and are based on 2018 market and shadow prices and calculated over 120 years at a discount rate of 3%.

3.2 Intra-option differences in the economic value of ecosystem service benefits, ecosystem dis-service costs and net ecosystem service benefits

The mapping of ES benefits, EDS costs and NES benefits highlights some quite distinct intra-option differences in performance between land parcels depending on their spatial location within the study area. Generally higher EVs of ES benefits are supplied from land parcels located in the east of the study area and in lower lying areas around the margins and in valley bottoms (Figure 5). Land parcels in these areas also supply some of the highest EVs of EDS costs (Figure 6). Overall, there is much greater spatial intra-option differences in performance between land parcels under the BAU option along with the AF-IF and AF-SH options and the FW-CO and FW-BR options (with areas of quite defined difference in performance) compared with the FA-BR and FA-BR (Figure 5, Figure 6 and Figure 7).

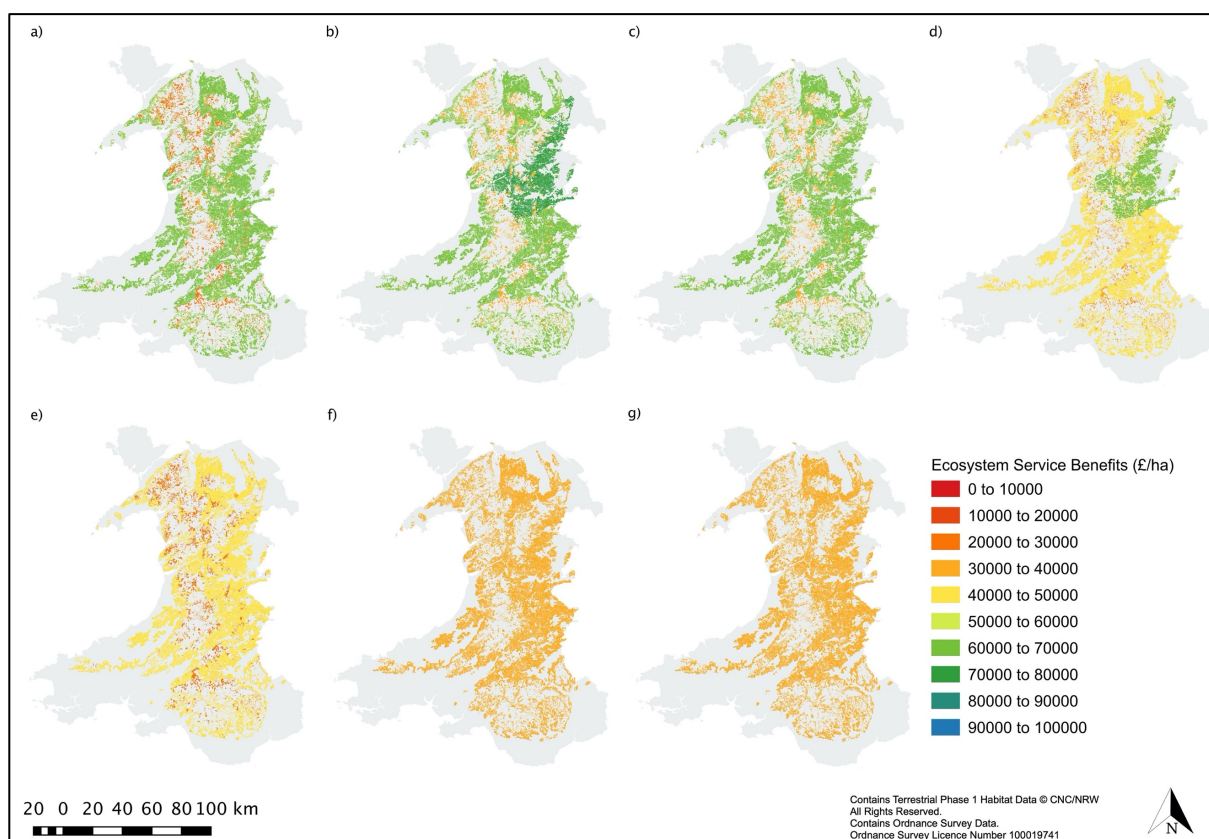


Figure 5: Economic value ha^{-1} of ecosystem service benefits from SDA grassland and arable land in Wales under the a) Business as usual, b) Agroforestry – in field trees, c) Agroforestry – shelterbelts, d) Farm woodland – conifer, e) Farm woodland – broadleaf, f) Full afforestation – conifer and g) Full afforestation – broadleaf options. The economic value ha^{-1} of ecosystem services comprises livestock production, arable crops, timber production, carbon sequestration, local flood risk mitigation, livestock shelter and shade and employment. The economic values are the present value of the future flows of benefits and costs and are based on 2018 market and shadow prices and calculated over 120 years at a discount rate of 3%.

3.2.1 Business as usual option

Under the BAU option there are two distinct areas of land parcels where performance differs. The majority of land parcels (primarily in the east of the region) fall into the £60,000 to 70,000 ha^{-1} category for ES benefits with patches of parcels in the higher altitude areas of the north west and south falling in to the lower £20,000 to 30,000 ha^{-1} category (panel a in Figure 5). For EDS costs the majority of land parcels fall into either the £2,000 to 3,000 ha^{-1} or the £0 to 1,000 ha^{-1} categories following a similar pattern to ES benefits (panel a in Figure 6). However, in terms of NES benefits there are three distinct areas where performance differs the majority of land parcels fall into the £50,000 to 60,000 ha^{-1} category for NES benefits with some parcels at higher altitudes in primarily in north western areas falling in to the lower £40,000 to 50,000 ha^{-1} category and now the best performing parcels (falling into the higher £60,000 to 70,000 ha^{-1} category) located in a distinct patch in the eastern area (panel a in Figure 7).

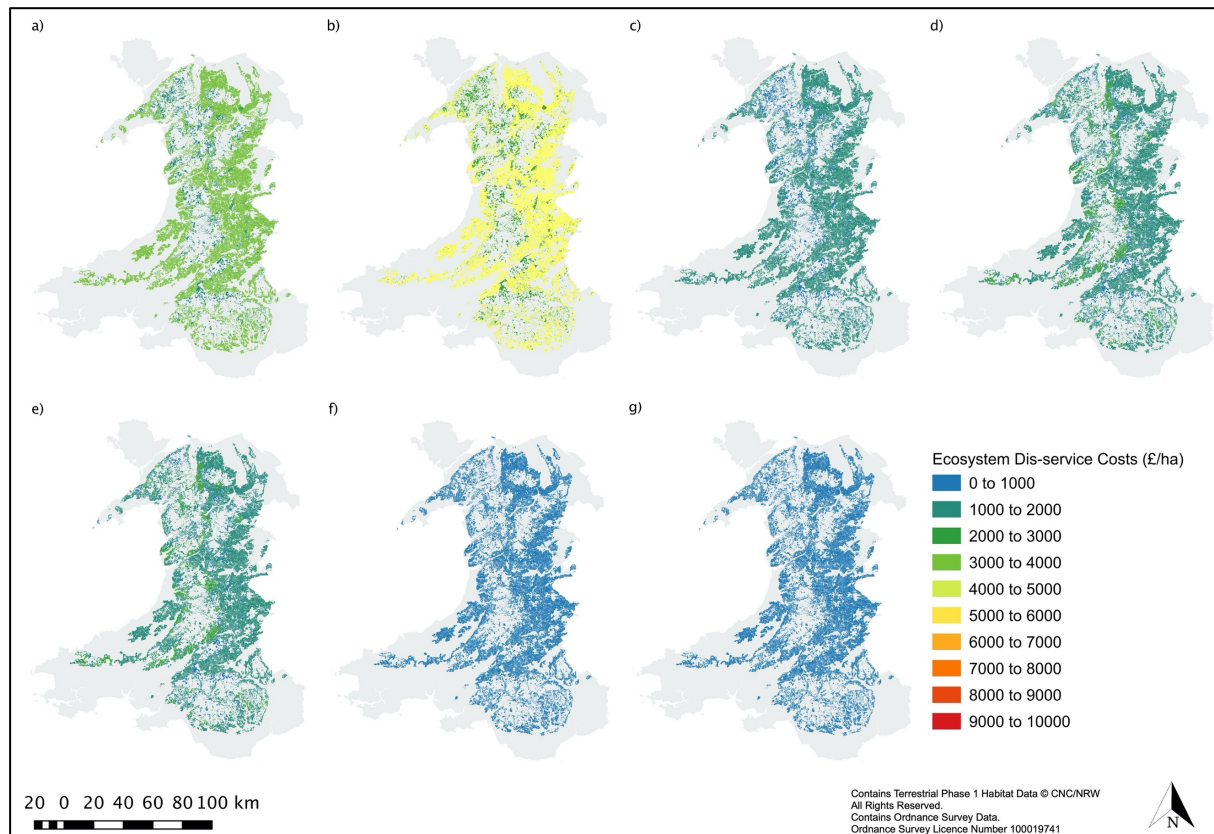


Figure 1: Economic value ha^{-1} of ecosystem dis-service costs from SDA grassland and arable land in Wales under the a) Business as usual, b) Agroforestry – in field trees, c) Agroforestry – shelterbelts, d) Farm woodland – conifer, e) Farm woodland – broadleaf, f) Full afforestation – conifer and g) Full afforestation – broadleaf options. The economic value ha^{-1} of ecosystem dis-services comprises GHG emissions and reduction of potable water quality. The economic values are the present value of the future flows of benefits and costs and are based on 2018 market and shadow prices and calculated over 120 years at a discount rate of 3%.

3.2.2 Agroforestry – in field trees option

The AF-IF option is one of the options where performance across land parcels in different location across the Welsh uplands is more heterogenous with three distinct areas of land parcels where performance varies. In terms of ES benefits the majority of land parcels fall into the £60,000 to 70,000 ha^{-1} category primarily in the east with some parcels at higher altitudes in the north west and south falling into the £30,000 to 40,000 ha^{-1} category (panel b in Figure 5). The best performing parcels are located in a discrete patch in the east falling into the higher £70,000 to 80,000 ha^{-1} category (panel b in Figure 5). For EDS costs the differences following a similar pattern to the BAU option most land parcels falling into the £4,000 to 5,000 ha^{-1} primarily in the east or at higher altitudes in the west into the £2,000 to 3,000 ha^{-1} categories (panel b in Figure 6). Given the higher level of EDS costs under the AF-IF option (compared to all other options) there is a shift in the relative performance of land parcels in terms of NES benefits. The best performing parcels now falling into the £60,000 to 70,000 ha^{-1} category are also not just located in a discrete patch in the east of the region but also in other low-lying areas around the margins (panel b in Figure 7). The parcels at higher altitudes in north western and southern areas now fall into the £20,000

to 30,000 ha⁻¹ category and the remainder of parcels in the east falling into the £50,000 to 60,000 ha⁻¹ (panel *b* in Figure 7).

3.2.3 Agroforestry – shelterbelts option

The differences in performance of the AF-SH option across land parcels in different locations follows a similar pattern to the BAU option. Under the AF-SH option the majority of land parcels fall into the £60,000 to 70,000 ha⁻¹ category for ES benefits with some parcels at higher altitudes in the north west and south falling into the £30,000 to 40,000 ha⁻¹ category (panel *c* in Figure 5). In terms of EDS costs the majority of land parcels fall into either the £1,000 to 2,000 ha⁻¹ or at higher altitudes in the West in the £0 to 1,000 ha⁻¹ categories (panel *c* in Figure 6). In terms of NES benefits the majority of land parcels still fall into the £60,000 to 70,000 ha⁻¹ category but there is some shift with the parcels at higher altitudes in the north west and south now falling into the lower £20,000 to 30,000 ha⁻¹ category (panel *c* in Figure 7).

3.2.4 Farm woodland – conifer option

The FW-CO option is also one of the options where performance across land parcels in different locations is more heterogeneous, again with three distinct areas of variation. Under the FW-CO option the majority of land parcels fall into the lower £40,000 to 50,000 ha⁻¹ category (compared to the BAU option) in terms of ES benefits (panel *d* in Figure 5). Some parcels at higher altitudes in north western areas fall into the higher £30,000 to 40,000 ha⁻¹ category (compared to the BAU option) and a discrete patch in the east of the area falling into the £60,000 to 70,000 ha⁻¹ category (panel *d* in Figure 5). In terms of EDS costs the majority of land parcels fall into either the £1,000 to 2,000 ha⁻¹ category or at higher altitudes in the west into the £0 to 1,000 ha⁻¹ categories (panel *d* in Figure 6). Due to the relatively low levels of EDS costs across the majority of land parcels still fall into the £40,000 to 50,000 ha⁻¹ category in terms of NES benefits (panel *d* in Figure 7). The best performing parcels are still located in a discrete patch in the east of the area still falling into the £60,000 to 70,000 ha⁻¹ category for NES benefits (panel *d* in Figure 7). However, there is some shift with parcels at higher altitudes in north western areas now falling into the lower £20,000 to 30,000 ha⁻¹ category (panel *d* in Figure 7).

3.2.5 Farm woodland – broadleaf option

The performance of the FW-BR option across land parcels in different locations also follows a similar pattern to the BAU option. Under the FW-BR option the majority of land parcels fall into the lower £40,000 to 50,000 ha⁻¹ category (compared to the BAU option) in terms of ES benefits with some parcels at higher altitudes in primarily the north western areas falling into the £20,000 to 30,000 ha⁻¹ category (panel *e* in Figure 5). In terms of EDS costs, the majority of land parcels fall into either the £1,000 to 2,000 ha⁻¹ category or in the higher altitude areas in the north west into the £0 to 1,000 ha⁻¹ categories (panel

e in Figure 6). Due to the relatively low levels of EDS costs across all land parcels in the SDA the majority of land parcels still fall into the £40,000 to 50,000 ha⁻¹ category in terms of NES benefits with the parcels in the higher altitude areas in the north west still falling in to the £20,000 to 30,000 ha⁻¹ category (panel e in Figure 7).

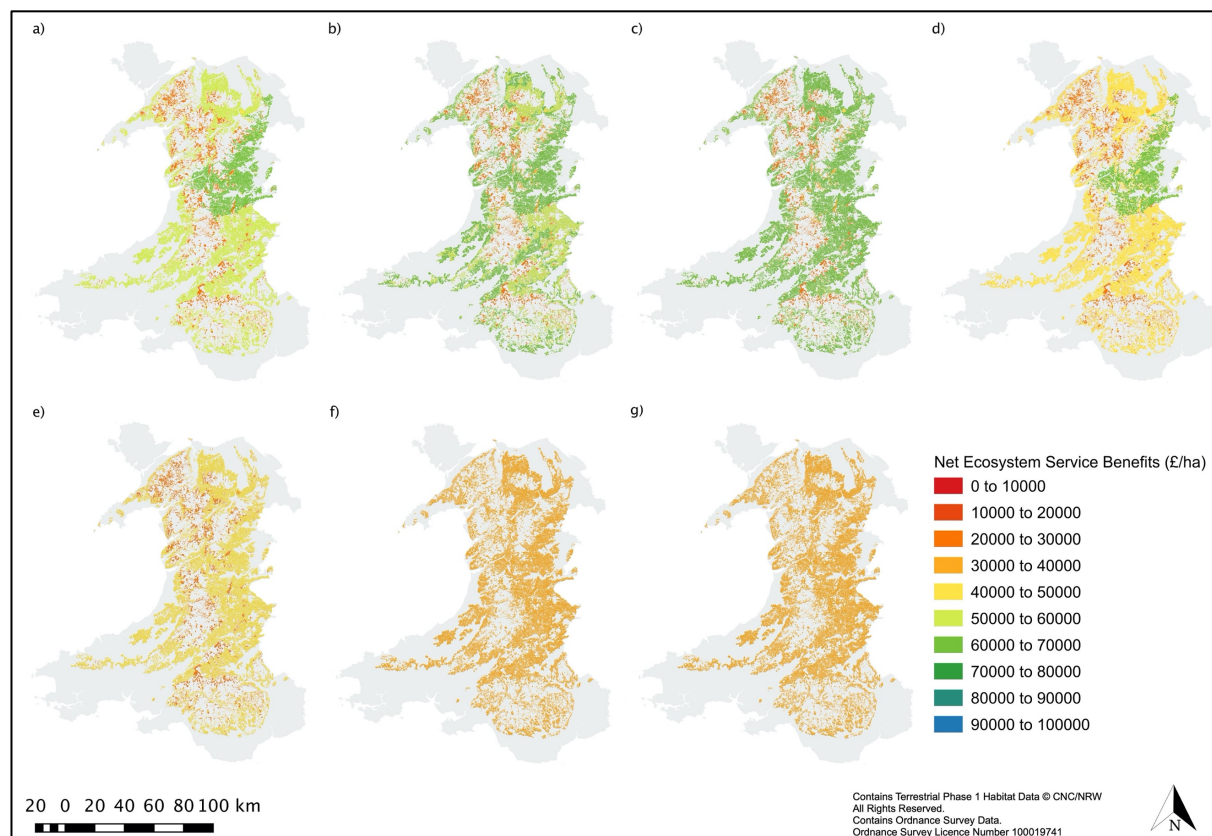


Figure 7: Economic value ha⁻¹ of net ecosystem service benefits from SDA grassland and arable land in Wales under the a) Business as usual, b) Agroforestry – in field trees, c) Agroforestry – shelterbelts, d) Farm woodland – conifer, e) Farm woodland – broadleaf, f) Full afforestation – conifer and g) Full afforestation – broadleaf options. The economic value ha⁻¹ of net ecosystem service benefits comprises ecosystem service benefits less ecosystem dis-service costs. The ecosystem services comprise livestock production, arable crops, timber production, carbon sequestration, local flood risk mitigation, livestock shelter and shade and employment. The ecosystem dis-services comprises GHG emissions and reduction of potable water quality. The economic values are the present value of the future flows of benefits and costs and are based on 2018 market and shadow prices and calculated over 120 years at a discount rate of 3%.

3.2.4 Full afforestation – conifer and full afforestation – broadleaf options

The performance of the FA-CO and FA-BR options is homogenous across the entirety of the Welsh uplands with all land parcels performing worse than the BAU option in terms of ES benefits but better than the BAU option in terms of EDS costs. In terms of ES benefits all of the land parcels within the SDA fall into the £30,000 to 40,000 ha⁻¹ category under both the FA-CO and FA-BR options (panel f and g in Figure 5). In terms of EDS costs all of the land parcels fall into the £0 to 1,000 ha⁻¹ category (panel f and g in Figure 6) and in terms of NES benefits all of the land parcels fall into the £30,000 to 40,000 ha⁻¹ category (panel f and g in Figure 7).

440 Table 3: Economic value of ecosystem service benefits, dis-service costs and net ecosystem service benefits from the Welsh uplands (forestry, agricultural (rough grazing) and
441 agricultural (grassland and arable) land use combined) following increasing of tree cover on grassland and arable land. The economic values are the present value of future flows
442 of benefits and costs based on market and shadow prices correct as at 2018 and calculated over 120 years at a discount rate of 3%.

Ecosystem service and dis-service	Economic value (£M)						
	Business as usual	Agroforestry – in field trees	Agroforestry – shelterbelts	Farm woodland – conifer	Farm woodland – broadleaf	Full afforestation – conifer	Full afforestation – broadleaf
Provisioning services							
Livestock production	18,047.42	16,697.81	17,447.68	9,581.61	9,581.61	1,115.80	1,115.80
Arable crops	195.48	187.66	156.38	97.74	97.74	0.00	0.00
Timber production	1,297.92	2,846.00	1,297.92	2,106.84	1,455.32	3,675.45	1,768.65
Water supply for consumptive use	16,433.11	16,433.11	16,433.11	16,433.11	16,433.11	16,433.11	16,433.11
Regulation and maintenance services							
Carbon sequestration	5,375.47	7,350.90	5,803.12	5,933.80	6,050.52	6,787.11	7,056.14
Local flood risk mitigation	163.23	163.23	469.21	346.64	346.64	541.70	545.78
Livestock shelter and shade	0.00	544.84	760.75	0.00	0.00	0.00	0.00
Cultural services							
Employment	1,658.73	4,591.80	5,041.59	5,575.26	5,575.26	6,464.71	6,464.71
Ecosystem service benefits	46,198.44	48,815.36	47,409.76	40,075.00	39,540.20	35,017.86	33,384.18
Provisioning dis-services							
Reduction of potable water quality	1,336.03	1,086.65	503.30	803.55	803.55	689.28	502.65
Regulation and maintenance dis-services							
GHG emissions	1,553.06	2,898.34	1,216.38	916.82	914.14	657.61	640.86
Ecosystem dis-service costs	2,889.09	3,984.99	1,719.68	1,720.37	1,717.69	1,346.89	1,143.51
Net ecosystem service benefits	43,309.35	44,830.37	45,690.08	38,354.63	37,822.51	33,670.97	32,240.67

3.3 Potential impacts of widespread adoption of the land use options on the economic value of ecosystem services and dis-services from the Welsh uplands as a whole

Widespread adoption of the FW-CO, FW-BR, FA-CO and FA-BR options could lead to a potential decrease in the EV of ES benefits from the Welsh uplands as a whole compared to the BAU option, but it is only adoption of the AF-IF and AF-SH options that may lead to an increase – as shown in Table 3. The highest potential increase of +£2.67 billion (bn) in the EV of ES benefits could come from a widespread adoption of the AF-IF option. The highest potential decrease of -£1.75bn in the EV of ES benefits would come from a widespread transformation of land use on grassland and arable land from the BAU option to the FA-BR option. Widespread adoption of all of the land use options except the AF-IF option could potentially lead to reduction in the EV of EDS costs compared the BAU option – as shown in Table 3. The highest potential reduction of -£12.81bn in the EV of EDS costs would also come from widespread adoption of the FA-BR option. The highest potential increase of +£1.10bn in the EV of EDS costs would also come from widespread adoption of the AF-IF option. In terms of NES benefits, the results are similar to the impacts on ES benefits, widespread adoption of the FW-CO, FW-BR, FA-CO and FA-BR options could lead to a potential decrease in the EV of NES benefits compared to the BAU option, it is only adoption of the AF-IF and AF-SH options that may lead to an increase in the EV of NES benefits – as shown in Table 3. However, due to the significant increase in EDS costs under the AF-IF option, the highest potential increase in the EV of NES benefits could actually come from a widespread adoption of the AF-SH option. The AF-SH option could lead to a +£2.38bn increase in the EV of NES benefits. For a breakdown of the changes to the economic values see Supplementary Section 5.

Table 4: Monte Carlo simulation of the economic value of ecosystem service benefits, dis-service costs and net ecosystem service benefits from the Welsh uplands (forestry, agricultural (rough grazing) and agricultural (grassland and arable) land use combined) following increasing of tree cover on grassland and arable land. The economic values are the present value of future flows of benefits and costs based on market and shadow prices correct as at 2018 and calculated over 120 years at a discount rate of 3%.

Land use option	Economic value £M (mean and standard deviation)		
	Ecosystem service benefits	Ecosystem dis-service costs	Net ecosystem service benefits
Business as usual	46,130.53 ±5,300.26	2,885.66 ±332.46	43,396.14 ±5,025.74
Agroforestry – in field trees	48,895.32 ±5,655.48	3,988.00 ±462.34	44,826.01 ±5,166.35
Agroforestry - shelterbelts	47,394.15 ±5,452.30	1,720.44 ±198.09	45,562.54 ±5,271.16
Farm woodland - conifer	40,106.54 ±4,628.59	1,722.77 ±197.74	38,374.28 ±4,452.04
Farm woodland - broadleaf	39,535.85 ±4,562.31	1,717.13 ±198.90	37,862.90 ±5,271.16
Full afforestation - conifer	35,033.43 ±4,035.73	1,347.29 ±155.85	33,699.33 ±4,452.04
Full afforestation – ecosystem services	33,330.45 ±3,846.77	1,145.30 ±132.46	32,215.73 ±4,394.62

The results of the uncertainty analysis using a Monte Carlo simulation based on $\pm 20\%$ variation in the market and shadow prices of ES benefits and EDS costs are shown in Table 4. These results suggest that uncertainty in the market and shadow prices of ES benefits and EDS costs could result in significant variability in the EV of ES benefits, of EDS costs and of NES benefits. These results suggest that the estimates for the BAU, AF-IF and AF-SH options are subject to the highest potential variation. Given this uncertainty in the market and shadow prices, the results of the Monte Carlo simulation highlight that our EV estimates presented in Table 3 fall within a potentially broad range and readers should be cognisant of this when considering the results.

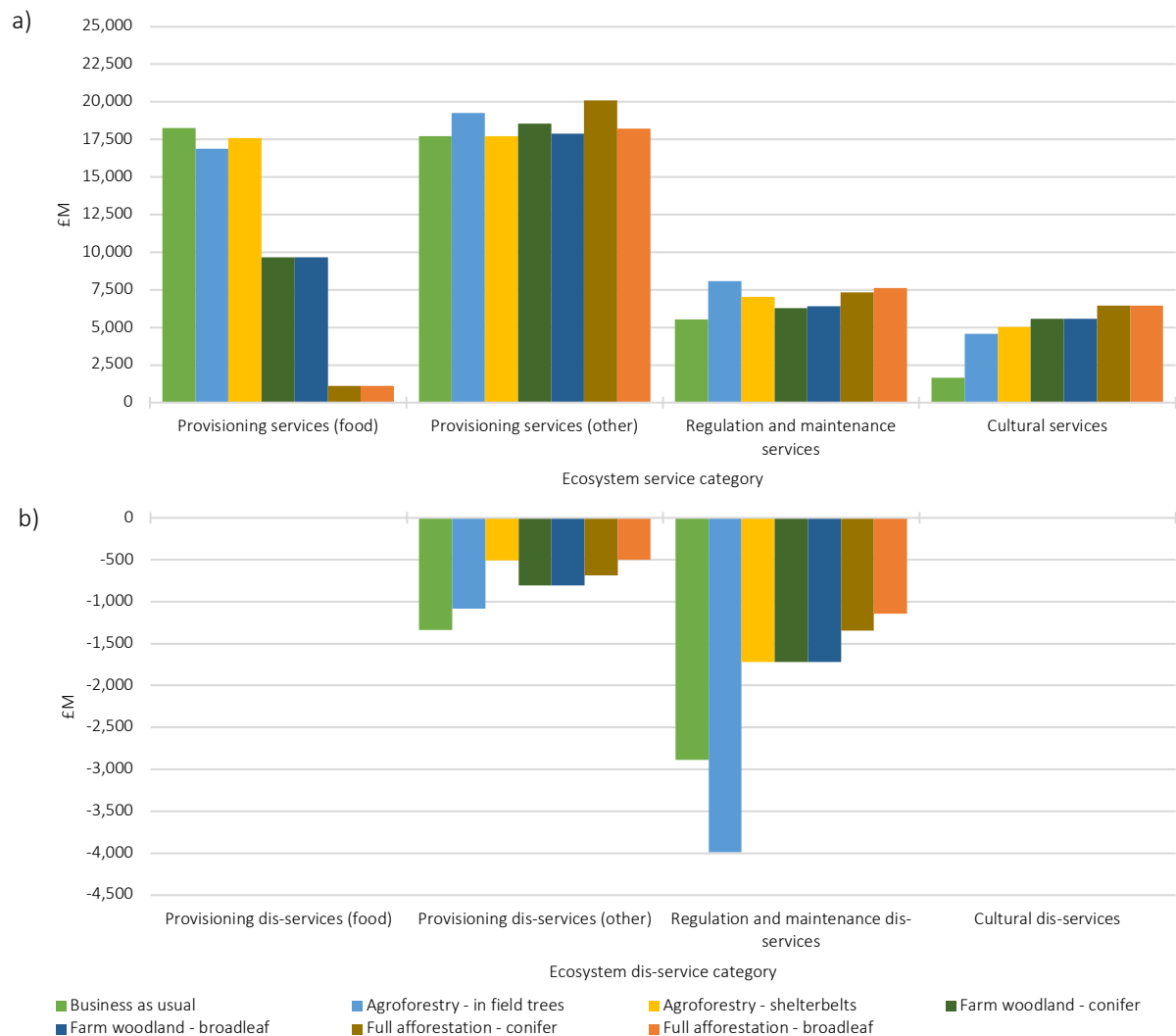


Figure 2: Breakdown of the economic value of a) ecosystem service benefits from the Welsh uplands into ecosystem service categories and b) ecosystem dis-service costs from the Welsh uplands into ecosystem dis-service categories from the Welsh uplands. Each column shows the portion of the total economic value of ecosystem service benefits contributed by each ecosystem system service category (provisioning (food and other), regulation and maintenance, and cultural) for each of the seven land use options. The columns show changes in the economic value of the ecosystem service benefits from each category and the contribution of each category to the economic value of all ecosystem service benefits. The economic values are the present value of the future flows of benefits and costs and are based on 2018 market and shadow prices and calculated over 120 years at a discount rate of

3.3.1 Breakdown of economic values by ecosystem service and dis-service categories

Widespread adoption of all the land use options would lead to a potential drop in the EV of ES benefits coming from provisioning (food) services compared to the BAU option (panel *a* in Figure 8). The biggest reductions would be under the FW-CO and FW-BR options (where trees partially replace agricultural production on grass and arable land) and the FA-CO and FA-BR options (where trees replace livestock and arable production on grass and arable land) (See Table 3). Provisioning (other) benefits increase in their proportion of total ES benefits except under the AF-SH option (panel *a* in Figure 8) where there is no additional timber production. The biggest potential increases in provisioning (other) benefits are under the FA-CO and FA-BR options. Regulation and maintenance ESs take up an increasingly larger portion of the total ES benefits, most evident in the AF-IF and AF-SH options and the FA-CO and FA-BR options (panel *a* in Figure 8). Compared to the BAU option there are potential increases in the EV of ES benefits coming from cultural ESs under all of the other land use options. The biggest potential increases are under the FA-CO and FA-BR options where there is a replacement of lower value agricultural employment with higher value forestry employment (panel *a* in Figure 8 or see Table 3). Under all land use options there is a potential decrease in the proportion of the total EDS costs supplied by provisioning (other) dis-services (panel *b* in Figure 8), this is mainly attributable to decreasing water quality costs. There is an overall potential decrease in the proportion of total EDS costs coming from regulation and maintenance EDS costs except under the AF-IF option where there is a potential significant increase (panel *b* in Figure 8).

3.3.2 Public versus private ecosystem service benefits and ecosystem dis-service costs

Widespread adoption of the AF-IF and AF-SH options could lead to a slight increase in the EV of private ES benefits compared to the BAU option (panel *a* in Figure 9). Whereas switches of land use from the BAU option on grassland and arable land to the FW-CO, FW-BR, FA-CO and FA-BR options could lead to significant decreases in the EV of private ES benefits (panel *a* in Figure 9). Compared to the BAU option widespread adoption of all of the land use options on grassland and arable land could lead to an increase in the EV of public ES benefits, with the largest potential increases attributable to the AF-IF, FA-CO and FA-BR options (panel *a* in Figure 9). Shifts in land use on grassland and arable land from the BAU option to all of the other land use options could decrease the EV of private EDS costs, with the largest potential reduction attributable to the AF-SH option (panel *b* in Figure 9). There is potential for the EV of public EDS costs to be reduced by widespread switches in land use from the BAU option to all of the other land use options except the AF-IF option, which could almost double the public EDS costs (panel *b* in Figure 9).

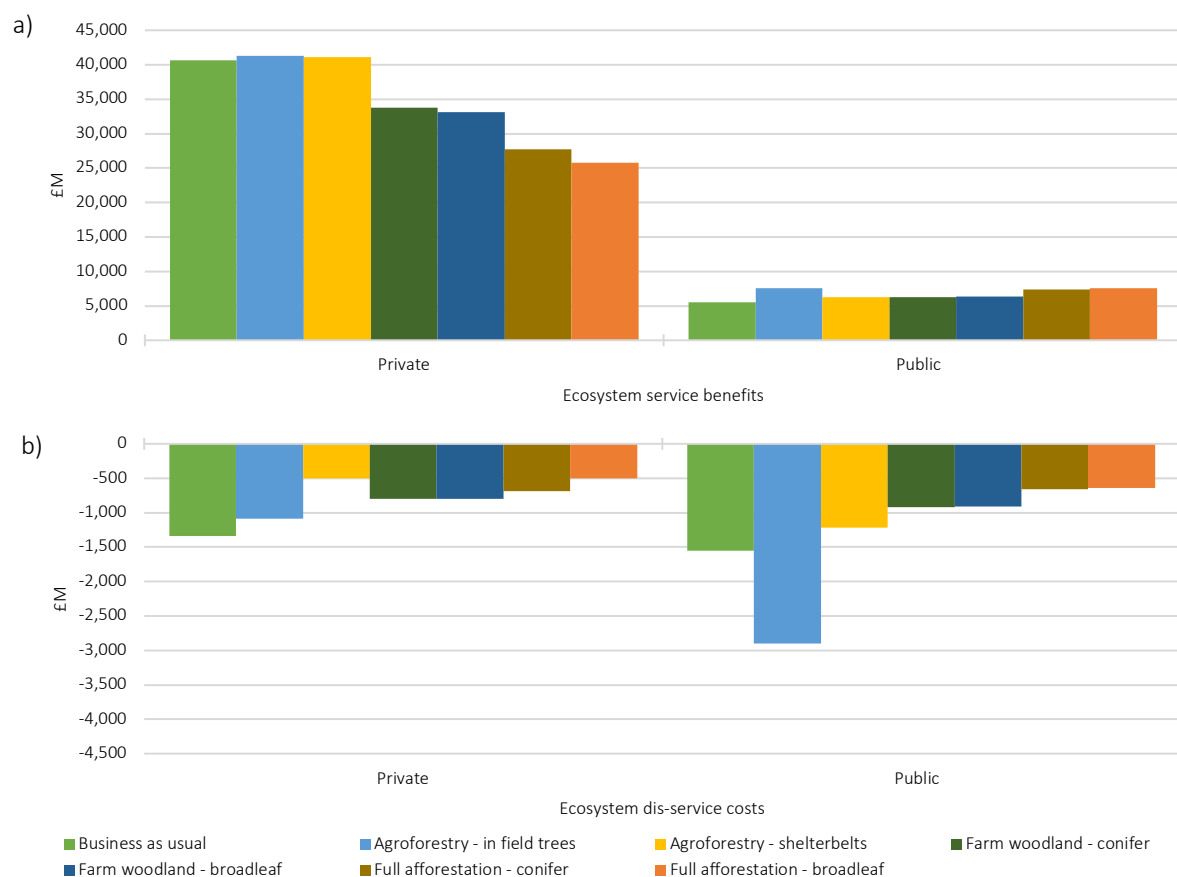


Figure 9: Comparison of the public and private a) ecosystem service benefits and b) ecosystem dis-service costs from the Welsh uplands under each land use option. The private ecosystem services include livestock production, arable crops, timber production, water supply for consumptive use, livestock shelter and shade and employment. The public ecosystem services include carbon sequestration and local flood risk mitigation. The private ecosystem dis-services includes reduction of potable water quality and the public ecosystem dis-services includes GHG emissions. The economic values are the present value of the future flows of benefits and costs and are based on 2018 market and shadow prices and calculated over 120 years at a discount rate of 3%.

3.3.3 Disaggregation of benefits and costs into beneficiary specific bundles

Widespread shifts in land use from the BAU option to the other six land use options could potentially lead to increases in the EV of the bundles of ES benefits for rural and urban communities within and outside the SDA and also for global society but could lead to reductions for private landowners and occupants (panel a in Figure 10). Changes in land use has no effect on the bundles of ES benefits for public body landowners and water companies (panel a in Figure 10). Adoption of the FA-BR option could lead to the greatest potential increase in the EV of the bundles of ES benefits for rural and urban communities within and outside the SDA and also for global society. In contrast the FA-BR also leads to the largest potential decrease in the EV of the bundle of ES benefits for private landowners and occupants. The AF-IF option is the only option that lead to potential increases in the bundle of ES benefits for private landowners and occupants. The beneficiary groups receiving the smallest potential increases in the EV of their bundle of ES benefits are rural and urban communities within and outside the SDA. Changes in land use from the BAU option to all of the other land use options could lead to significant reductions in the EV of the bundle

of EDS costs for the water companies, which could be more than halved through widespread adoption of the AF-SH or FA-BR options (panel *b* in Figure 10). Changes in land use from BAU to the other land use options—except the AF-IF option—could lead to potential reductions in the EV of the bundles of EDS costs that accrue to rural and urban communities within and outside of the SDA and for global society (panel *b* in Figure 10). Widespread adoption of the AF-IF option on grassland and arable land could lead to a significant increase in the EV of the bundle of EDS costs for rural and urban communities within and outside of the SDA and for global society (panel *b* in Figure 10).

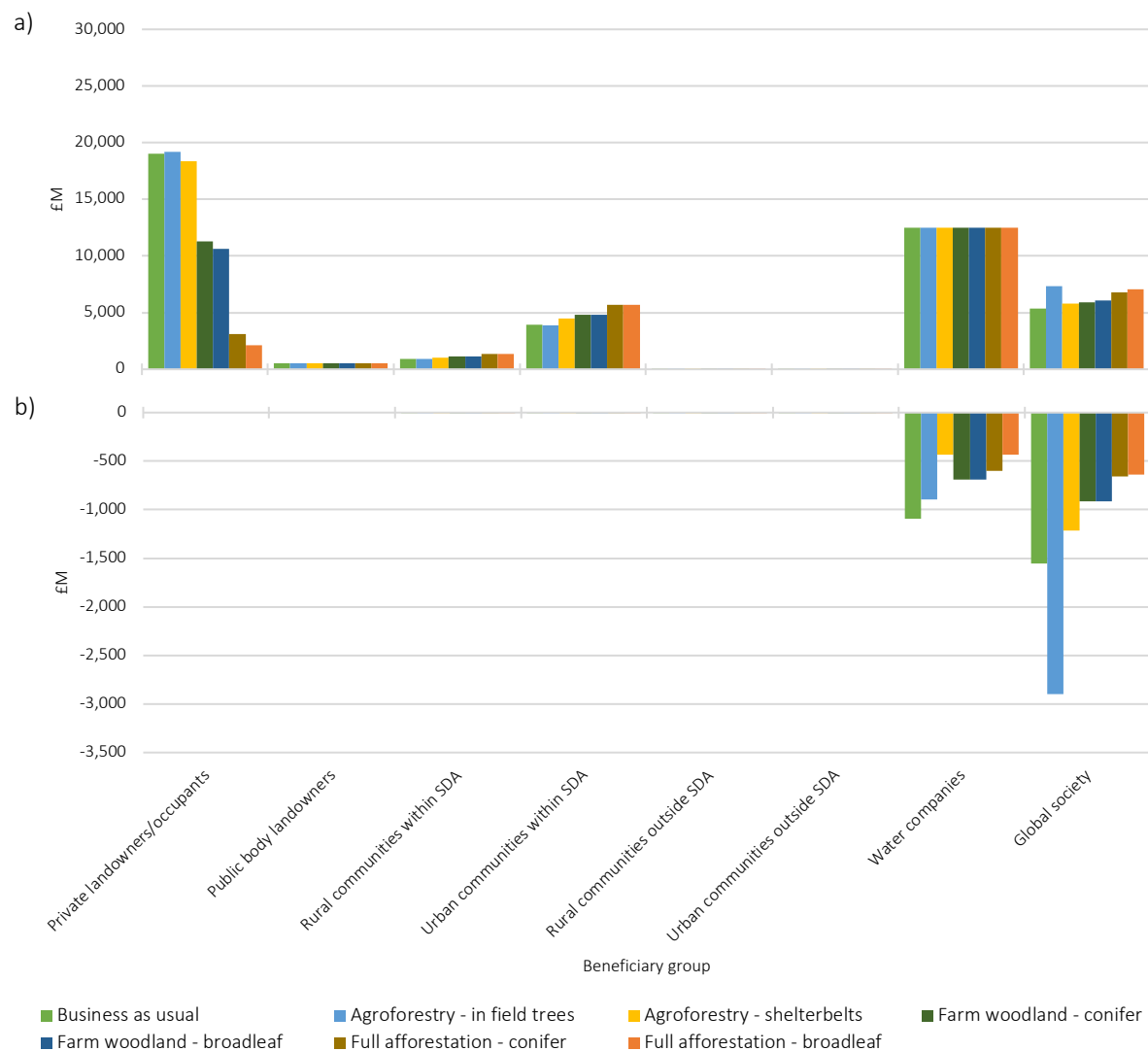


Figure 10: Disaggregation of the economic value of a) ecosystem service benefits and b) dis-service costs from the Welsh uplands into beneficiary specific bundles. For each of the land use options the economic value of a) ecosystem service benefits and b) dis-service costs are disaggregated into the bundles of benefits and costs received by each of the relevant beneficiary groups. The economic values are disaggregated by the relative population size of the beneficiary group. The economic values are the present value of the future flows of benefits and costs and are based on 2018 market and shadow prices and calculated over 120 years at a discount rate of 3%.

4. Discussion

Given the limited evidence surrounding the impacts of increasing of tree and woodland cover on agricultural land on ESs and EDS, our study has made further steps to contributing towards the evidence base required to rationalise future land use changes (involving expansion of tree cover) in the Welsh uplands and agricultural landscapes generally. This study represents one of the first studies utilising a holistic assessment of changes to ES benefits and EDS costs resulting from expanding tree cover in upland agricultural systems. We produced spatially explicit estimates of EV of ES benefits and EDS costs based on country-specific data of biophysical and economic variables where they were available (e.g., estimates of timber production yields based on Welsh climate data) and spatial determinants of ES and EDS demand. By using spatially explicit methods we demonstrate that changes to ESs and EDSs values are uneven across the study area and they affect beneficiaries in significantly different ways. We hope to demonstrate that this is more informative than other assessments of ESs from tree based land use change in Wales (Bateman, 1996; Cosby *et al.*, 2019) and from forestry land use in the UK generally (Dittrich *et al.*, 2019; Eftec, 2010; Europe Economics, 2017; Saraev *et al.*, 2017; Willis *et al.*, 2003) which simply provide aggregated values. This study provides evidence based hypothetical ES and EDS values for different land sparing and sharing strategies potentially suitable for increasing tree cover in upland agricultural systems. Whilst these values are constrained by the scale at which the assessment was undertaken, we still hope they provide an initial set of ES values and framework for informing land use change decisions in Welsh upland agricultural systems (and agricultural systems more generally) to address climate challenges and demand for public benefits.

4.1 Which strategies are most suitable for improving ecosystem service provision in the Welsh uplands?

Contrary to similar work in Wales our economic valuation shows that land-sparing strategies (FA-CO and FA-BR options) where trees replace agricultural production (similar to those modelled in Bateman (1996) and Cosby *et al.* (2019)) result in substantial reductions to the total basket of ES benefits but they do lead to significant increases in the EV of public ES benefits and decreases in EDS costs. This is principally because private, agriculturally based provisioning services from the Welsh uplands are significantly reduced under land sparing strategies for increasing tree cover. In contrast, our results suggest that land-sharing strategies where trees are intimately integrated within agricultural production (AF-IF and AF-SH options) can lead to substantial increases in the total basket of ES benefits and increases in public ES benefits. Our results suggest that land-sharing strategies where tree are coarsely integrated alongside agricultural production (FW-CO and FW-BR options) lead to smaller decreases in the total basket of ES benefits than land sparing strategies, but the significant decreases in the private ES benefits under these

strategies are not compensated by large increases in public ES benefits like the land sparing strategies. Ostensibly, our results suggest that the AF-IF option could lead to the biggest increase in the EV of ESs and potentially represents the best land use strategy for improving the provision of ESs in the Welsh uplands through increasing tree cover on grassland and arable land. However, exploring our results further suggests that the AF-IF option may not be a universally optimal strategy across all Wales' uplands.

4.1.1 Land-sharing and adoption of the agroforestry – in field trees option

The AF-IF option performs best in terms of ES benefits but the worst in terms of EDS costs. The AF-IF option performs the best when implemented on improved and semi-improved grassland in the east of the region where the intensity of agricultural production is higher and the prevalence of seminatural habitats is much lower (as shown in Figure 5). There are however many areas (primarily in the north west as shown in Figure 6) where the AF-IF option makes little or no difference. Widespread adoption of the AF-IF option on *all* grassland and arable land could increase the EV of ES benefits from the Welsh uplands as a whole by £2.62bn but would also increase the EV of EDS costs by £1.10bn. Adopting the AF-IF option could deliver against all eight ES categories, which is the broadest set of benefits of any of the seven land use options. Widespread adoption of the AF-IF option could lead to significant amounts trees (around 226,000,000) being planted alongside continued agricultural activity in the Welsh uplands. Notwithstanding this, the AF-IF option may not be the socially optimal choice because much of the increase in ES benefits (+£2.10bn) are actually associated with private ES benefits (through *timber production* and *livestock shelter and shade*) accruing to a single set of beneficiaries (private landowners and occupants). Furthermore, whilst the AF-IF option does lead to an increase in public ES benefits of +£1.98bn it could also lead to a +£1.35bn increase in public EDS costs.

4.1.2 Land-sharing and adoption of the full afforestation – broadleaf and conifer options

Given the trade-offs associated with the AF-IF option, the FA-CO and FA-BR options perform better in terms of increases in the EV of public ES benefits. These land sparing strategies could lead to a major shift in public benefits from the Welsh uplands; increasing the public ES benefits from the Welsh uplands as a whole from around £5.54bn to £7.33bn (FA-CO option) and £7.60bn (FA-BR option). The FA-CO and FA-BR options may well represent optimal choices for policy makers seeking to address significant climate change priorities and tree planting commitments. Furthermore, this may represent the optimum choice for beneficiary groups such as global society and rural and urban communities in Wales who will benefit from the significant decarbonising effect and flood mitigation benefits of these strategies. While it is important to restore and enhance these regulating functions in upland areas (as flood mitigation benefits flow down into lowland areas), it is important to recognise that doing so by increasing tree cover through

land sparing measures will reduce the capacity of people to derive livelihood benefits from these systems through agricultural production. Increasing tree cover through these strategies could lead to significant losses of some ES categories, notably a major drop in provisioning benefits (-£16.93bn) through reduced meat production. The FA-CO and FA-BR options will likely not represent the most desirable strategies for increasing tree cover for beneficiary groups such as private landowners and occupants because it weights benefits towards regulation and maintenance ESs and would require a significant livelihood shift for farmers. Furthermore, full afforestation of grassland and arable land in uplands with tree cover could lead to significant displacement issues by outsourcing agricultural activity into other heavily intensified areas, potentially increasing EDS costs elsewhere.

4.1.3 Land-sharing and adoption of the agroforestry – shelterbelts option

Considering the inherent trade-offs associated with adoption of the AF-IF, FA-CO and FA-BR options, the best strategy may be one which performs slightly less well but imposes fewer major trade-offs. If the best strategy is now considered to be the one which delivers an increase in ES benefits (both public and private), reduces the EV of EDS costs and retains agricultural production, then adoption of the AF-SH option is potentially a more suitable strategy. The AF-SH option performs best, increasing ES benefits and reducing EDS costs the most, when implemented on improved, semi-improved and unimproved grassland in the east of the region (as shown in Figure 5). Here, the intensity of agricultural production is higher and there is greater benefit from the addition of agricultural production-specific ES benefits (*livestock shelter and shade*). This strategy has the potential to reduce the EV of EDS costs from the Welsh uplands as a whole by £1.17bn and increase the EV of ES benefits by £1.21bn. The AF-SH option could lead to a modest rebalancing of public and private benefits, increasing the level of public ES benefits from the Welsh uplands by £741.74 million (M) through an enhancement of the regulation and maintenance benefits (*carbon sequestration and local flood risk reduction*) compared to the BAU option. The AF-SH option is likely to represent a desirable strategy for the entire spectrum of beneficiary groups because it maintains provisioning ES benefits, enhances regulation and maintenance ES benefits and reduces EDS costs. Moreover, because land-sharing and adoption of the AF-SH option allows retention of livestock and arable production, it is likely to be one of the more attractive options for private landowners and occupants.

4.2 Broader implications of case study findings

Engaging in broad scale thinking and decision making around land use change and restoration of tree cover within agricultural landscapes requires consideration of how ecosystem functions and flows of ESs and EDSs are altered, but also how this affects the livelihoods of and benefits derived by people working

and living in these landscape (Chazdon *et al.*, 2017; Meli *et al.*, 2019). Much of the evidence base around the benefits of tree cover within landscapes in a UK context generally (Eftec, 2010; Europe Economics, 2017; Saraev *et al.*, 2017; Willis *et al.*, 2003) and Wales specifically (Bateman, 1996; Cosby *et al.*, 2019) currently does not show how the benefits accruing to different people within these landscape are affected or who bears the costs of adopting varying strategies to restore tree cover. The approach demonstrated in this case study has added to the debate around restoration of tree cover within primarily agricultural landscape and broader arguments around land-sparing/sharing. Our approach demonstrates the ES benefits from land-sparing strategies for increasing tree cover are uneven across beneficiary groups and the people bearing the costs of adoption (e.g., changes to livelihoods and reductions in bundles of ES benefits) are the same people who will likely be delivering these land use changes on the ground. Our approach also demonstrates that land-sharing strategies for increasing tree cover can perform better than complete conversion to tree cover in the delivery of multiple ES benefits (including public ES benefits) without significantly constraining the livelihoods of primarily farmers and landowners and the benefits they derive from upland landscapes. This is only revealed by splitting provisioning benefits into *food* and *other* categories, disaggregating ES benefits into *public* and *private* benefits and disaggregating total values into bundles of ES benefits/EDS costs for individual beneficiary groups. The analysis presented here is valuable in demonstrating how decision makers may deliver against climate change and tree planting targets while explicitly considering who will benefit and who will bear costs. Consequently, the approach could easily be transferred and modified to fit other contexts surrounding land use change and ecosystem services in agricultural landscapes.

4.3 Highlighted knowledge gaps

We feel this study provides a more balanced view of the potential impacts to ES benefits and EDS costs from large scale increases of tree cover in agricultural landscapes. That said, it is not simply tree canopy cover, species choice and management (e.g., silvicultural system) that will have a significant impact on the EV of ESs and EDSs, but also future climatic and economic changes. Furthermore, our land use options are based on trees being integrated with, or replacing, a mixed grazing livestock system. We did not consider the possibility of switches within agricultural production (e.g., a move from mixed livestock grazing to dairy) within the land use options. We accept that it was beyond the scope of this current study to quantify these further impacts. In order to fully understand the full picture of the effects of large-scale increases of tree cover on ESs and EDSs in the Welsh uplands and further afield, the next step in assessments such as these is to explore alternative agricultural management systems and their interactions with climatic, economic and even food policy changes.

4.4 Caveats of the present study

This study does not give an indication of the likelihood of adoption of these land use options. In addition, our estimates of the impacts on the total basket of ESs and EDSs from the Welsh uplands as a whole are based on widespread adoption of the land use options and transformation in land use assuming all parcels are changed at the same time, without onward economic impacts. We accept this is unlikely in reality, and readers should be cognisant of this when considering the findings. What this study does illustrate however, is the maximum potential for increased tree cover to impact ESs and EDSs (either positively or negatively). This study is also subject to three additional caveats related to the economic valuation of ESs and EDSs. Firstly, the economic valuation of ESs and EDSs is not without flaws, from a methodological standpoint, the EV of ES benefits and EDS costs can vary significantly across the range of valuation methods (Spangenberg and Settele, 2016, 2010), choice of discount rates and is highly sensitive to the biophysical and economic data along with modelling assumptions used. This uncertainty is captured in Table 4; however, it should be noted that different input data, valuation methods or discount rates may lead to different outcomes. Secondly, we restricted our economic valuation to ESs and EDSs for which there is existing pricing and valuation data based on reasonably robust biophysical parameters. Furthermore, as we focused our valuation on use values, the economic values reported in this study are not the full economic value of ESs and EDSs. Thirdly, although appropriate for pragmatic studies such as this with limited existing valuation data, limited resources and temporal constraints, the use of pricing-based methods means that the full welfare impacts (i.e., consumer surpluses) of ESs and EDSs are likely to be underestimated.

5. Conclusions

Improving the delivery of ESs and EDSs from agricultural systems by increasing tree cover requires spatially explicit assessment of alternative land use strategies that is sensitive to a variety of tree canopy coverages and how these changes affect different groups of beneficiaries. In this case study, we developed a simple, low data input, spatially explicit methodology to estimate the impact of land use changes in the Welsh uplands involving increasing tree cover on the EV of ES benefits and EDS costs. Our methodology integrated biophysical data and economic output values with spatially explicit indicators of demand for ESs and EDSs to provide estimates of the EV of ES benefits and EDS costs that represent potential alternative flows of ESs and EDSs. We have moved forward the evidence base surrounding the impacts of tree cover increases on ESs and EDSs generally, and in the Welsh uplands specifically by considering a range of canopy coverages not just a binary switch between trees and agriculture. Our results suggest that increasing tree cover on upland grassland and arable land through a range of land-sparing/sharing strategies can both significantly increase and reduce the EV of ES benefits; it can also

increase and reduce the EV of EDS costs. Our results suggest that land-sparing strategies where trees replace agricultural production is not a panacea for improving ES and EDS provision from the Welsh uplands.

Our results do not imply a single optimum strategy, but suggest that, depending on the antecedent land use, there are three suitable ways forward for improving ES and EDS provision through increasing tree cover on grassland and arable land; these are:

1. Land-sharing and adoption of the AF-IF option for maximising the total basket of ES benefits.
2. Land-sparing and adoption of the FA-CO and FA-BR options for shifting the supply of ES benefits towards a greater public ES benefits and maximising the reduction of EDS costs (but at a significant cost to agricultural production).
3. Land-sharing and adoption of the AF-SH option for increasing ES benefits (both public and private), decreasing EDS costs and maintaining agricultural production.

Overall, our results suggest that agroforestry systems have an important role to play in improving ESs and EDSs as part of increased tree cover on agricultural land in the Welsh uplands. While our results diverge from previous studies, our work represents a systematic evaluation of woodland creation and its impacts on ESs and EDSs that feeds into wider conversations about land use and delivering tree cover within agricultural landscapes.

The spatially explicit information provided by our GIS generated maps permits policy makers and analysts to identify the land use options and locations where tree cover expansion will have a positive effect on ES benefits and reduce EDS costs. In addition, our results and approach allow policy makers to recognise the potential future trajectory of ES benefits and EDS costs from different types of tree cover and 0%, 20%, 50% and 100% afforestation of grassland and arable land in the Welsh uplands. The spatially explicit approach employing the LSSM as a framework for formalising hypothetical land use options covering a range of canopy coverages presents a more balanced view of the relative ES benefits and impacts of transformation and adaption of land use in the Welsh uplands and has broader applicability in debates around land use changes in similar agricultural systems generally. While we acknowledge certain limitations in that this study does not evaluate all conceivable ESs and EDSs, it does represent a significant addition to the evidence base surrounding the impacts of land use change on ESs and EDSs in agricultural systems generally and in the Welsh uplands generally.

Funding sources and Acknowledgements

This paper was funded as part of the Knowledge Economy Skills Scholarships (KESS 2) a pan-Wales higher level skills initiative led by Bangor University on behalf of the higher education sector in Wales. It is part funded by the Welsh Government's European Social Fund (ESF) convergence programme for West Wales

and the Valleys. This paper was funded as part of a collaboration between KESS 2 and Coed Cymru and the authors would like to thank Coed Cymru for their support of the PhD project of which this paper forms part. The authors would like to thank the reviewers for their thoughtful comments and efforts towards improving our manuscript.

References

- Armstrong, E., 2016. The Farming Sector in Wales. National Assembly for Wales.
- Balmford, A., Green, R.E., Scharlemann, J.P.W., 2005. Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Glob. Chang. Biol.* 11, 1594–1605. <https://doi.org/10.1111/j.1365-2486.2005.01035.x>
- Bateman, I., Lovett, A.A., 2000. Estimating and valuing the carbon sequestered in softwood and hardwood trees, timber products and forest soils in Wales. *J. Environ. Manage.* 60, 301–323. <https://doi.org/10.1006/jema.2000.0388>
- Bateman, I.J., 1996. An economic comparison of forest recreation, timber and carbon fixing values with agriculture in Wales: a geographical information systems approach. University of Nottingham.
- Bateman, I.J., Mace, G.M., Fezzi, C., Atkinson, G., Turner, K., Turner, R.K., 2014. Economic analysis for ecosystem service assessment, in: Ninan, K.N. (Ed.), *Valuing Ecosystem Services. Methodological Issues and Case Studies*. Edward Elgar Publishing, Cheltenham, pp. 78–89. <https://doi.org/10.1007/s10640-010-9418-x>
- Blanco, J., Dendoncker, N., Barnaud, C., Sirami, C., 2019. Ecosystem disservices matter: Towards their systematic integration within ecosystem service research and policy. *Ecosyst. Serv.* 36, 100913. <https://doi.org/10.1016/j.ecoser.2019.100913>
- Brainard, J., Bateman, I.J., Lovett, A.A., 2009. The social value of carbon sequestered in Great Britain's woodlands. *Ecol. Econ.* 68, 1257–1267;; <https://doi.org/10.1016/j.ecolecon.2008.08.021>
- Burton, V., Metzger, M.J., Brown, C., Moseley, D., 2018a. Green Gold to Wild Woodlands; understanding stakeholder visions for woodland expansion in Scotland. *Landsc. Ecol.* 1–21. <https://doi.org/10.1007/s10980-018-0674-4>
- Burton, V., Moseley, D., Brown, C., Metzger, M.J., Bellamy, P., 2018b. Reviewing the evidence base for the effects of woodland expansion on biodiversity and ecosystem services in the United Kingdom. *For. Ecol. Manage.* 430, 366–379. <https://doi.org/10.1016/j.foreco.2018.08.003>
- Campagne, C.S., Roche, P.K., Salles, J.-M., 2018. Looking into Pandora's Box: Ecosystem disservices assessment and correlations with ecosystem services. *Ecosyst. Serv.* 30, 126–136. <https://doi.org/10.1016/j.ecoser.2018.02.005>
- Chazdon, R.L., Brancalion, P.H.S., Lamb, D., Laestadius, L., Calmon, M., Kumar, C., 2017. A Policy-Driven Knowledge Agenda for Global Forest and Landscape Restoration. *Conserv. Lett.* 10, 125–132. <https://doi.org/10.1111/conl.12220>
- Cord, A.F., Bartkowski, B., Beckmann, M., Dittrich, A., Hermans-Neumann, K., Kaim, A., Lienhoop, N., Locher-Krause, K., Priess, J., Schröter-Schlaack, C., Schwarz, N., Seppelt, R., Strauch, M., Václavík, T., Volk, M., 2017. Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. *Ecosyst. Serv.* 28, 264–272. <https://doi.org/10.1016/j.ecoser.2017.07.012>
- Cosby, J., Thomas, A., Emmett, B.A., Anthony, S., Bell, C., Carnell, E., Dickie, I., Fitch, A., Gooday, R., Kettel, E., Jones, M., Matthews, R., Petr, M., Siriwardena, G., Steadman, C., Thomas, D., Williams,

777 B., Vieno, M., 2019. Environment and Rural Affairs Monitoring & Modelling Programme - ERAMMP
778 Year 1 Report 12: "Quick Start" Modelling (Phase 1). Report to Welsh Government (Contract
779 C210/2016/2017). Centre for Ecology & Hydrology Project NEC06297.

780 Crous-Duran, J., Graves, A.R., de Jalón, S.G., Kay, S., Tomé, M., Burgess, P.J., Giannitsopoulos, M., Palma,
781 J.H.N., 2020. Quantifying regulating ecosystem services with increased tree densities on European
782 Farmland. *Sustainability* 12, 1–20. <https://doi.org/10.3390/su12166676>

783 Dasgupta, P., 2008. Nature in economics. *Environ. Resour. Econ.* 39, 1–7.
784 <https://doi.org/10.1007/s10640-007-9178-4>

785 de Groot, R., Alkemade, R., Braat, L., Hein, L., Willemen, L., 2010. Challenges in integrating the concept
786 of ecosystem services and values in landscape planning, management and decision making. *Ecol.*
787 *Complex.* 7, 260–272. <https://doi.org/10.1016/j.ecocom.2009.10.006>

788 Decocq, G., Andrieu, E., Brunet, J., Chabrierie, O., De Frenne, P., De Smedt, P., Deconchat, M.,
789 Diekmann, M., Ehrmann, S., Giffard, B., Mifsud, E.G., Hansen, K., Hermy, M., Kolb, A., Lenoir, J.,
790 Liira, J., Moldan, F., Prokofieva, I., Rosenqvist, L., Varela, E., Valdés, A., Verheyen, K., Wulf, M.,
791 2016. Ecosystem Services from Small Forest Patches in Agricultural Landscapes. *Curr. For. Reports*
792 2, 30–44. <https://doi.org/10.1007/s40725-016-0028-x>

793 Dickie, M., 2003. Defensive Behaviour and Damage Cost Methods, in: Champ, P.A., Boyle, K.J., Brown,
794 T.C. (Eds.), *A Primer on Nonmarket Valuation*. Kluwer Academic Publishers, Dordrecht, pp. 395–
795 444.

796 Dittrich, R., Ball, T., Wreford, A., Moran, D., Spray, C.J., 2019. A cost-benefit analysis of afforestation as a
797 climate change adaptation measure to reduce flood risk. *J. Flood Risk Manag.* 12, 1–11.
798 <https://doi.org/10.1111/jfr3.12482>

799 Dixon, J.A., Scura, L.F., Carpenter, R.A., P. B. Sherman, 1997. *Economic Analysis of Environmental*
800 *Impacts*. Earthscan, London.

801 Dunn, R.R., 2010. Global mapping of ecosystem disservices: the unspoken reality that nature sometimes
802 kills us. *Biotropica* 42, 555–557. <https://doi.org/10.1098/rspb.2010.0340.F>

803 Eftec, 2010. The economic contribution of the public forest estate in England.

804 Europe Economics, 2017. *The Economic Benefits of Woodland*.

805 Fairhead, J., Leach, M., Scoones, I., 2012. Green Grabbing: A new appropriation of nature? *J. Peasant*
806 *Stud.* 39, 237–261. <https://doi.org/10.1080/03066150.2012.671770>

807 Ferrini, S., Schaafsma, M., Bateman, I.J., 2015. Ecosystem Services Assessments and Benefit Transfer, in:
808 Johnston, R.J., Rosenberger, R.S., Brouwer, R. (Eds.), *Benefit Transfer of Environmental and*
809 *Resource Values*. Springer, Dordrecht, pp. 307–328. <https://doi.org/10.1007/978-94-017-9930-0>

810 Fischer, J., Brosi, B., Daily, G.C., Ehrlich, P.R., Goldman, R., Goldstein, J., Lindenmayer, D.B., Manning,
811 A.D., Mooney, H.A., Pejchar, L., Ranganathan, J., Tallis, H., 2008. Should agricultural policies
812 encourage land sparing or wildlife-friendly farming? *Front. Ecol. Environ.* 6, 380–385.
813 <https://doi.org/10.1890/070019>

814 Fisher, B., Turner, K., Zylstra, M., Brouwer, R., de Groot, R., Farber, S., Ferraro, P., Green, R., Hadley, D.,
815 Harlow, J., Jefferiss, P., Kirkby, C., Morling, P., Mowatt, S., Naidoo, R., Paavlova, J., Strassburg, B.,
816 Yu, D., Balmford, A., 2008. Ecosystem Services and Economic Theory : Integration for Policy-
817 Relevant Research. *Ecol. Appl.* 18, 2050–2067. <https://doi.org/10.1890/07-1537.1>

818 Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision
819 making. *Ecol. Econ.* 68, 643–653. <https://doi.org/10.1016/j.ecolecon.2008.09.014>

820 Flores, N.E., 2003. Conceptual Framework for Nonmarket Valuation, in: Champ, P.A., Boyle, K.J., Brown,

821 T.C. (Eds.), *A Primer on Nonmarket Valuation*. Kluwer Academic Publishers, Dordrecht, pp. 27–58.

822 Forest Research, 2017a. *Forestry Statistics 2017*. Forest Research, Edinburgh.

823 Forest Research, 2017b. *Forestry Statistics 2017*. Chapter 2: UK Grown Timber. Edinburgh.

824 Forestry Commission Wales, 2009. *Woodlands for Wales*.

825 Freeman, M., 2003. *The measurement of environmental and resource values: theory and methods*.
826 Routledge, Washington DC.

827 Goldenberg, R., Kalantari, Z., Cvetkovic, V., Mörtberg, U., Deal, B., Destouni, G., 2017. Distinction,
828 quantification and mapping of potential and realized supply-demand of flow-dependent
829 ecosystem services. *Sci. Total Environ.* 593–594, 599–609.
830 <https://doi.org/10.1016/j.scitotenv.2017.03.130>

831 Green, R.E., Cornell, S.J., Scharlemann, J.P.W., Balmford, A., 2005. Farming and the fate of wild nature.
832 *Science* (80-.). 307, 550–555. <https://doi.org/10.1126/science.1106049>

833 Haines-Young, R., Potschin, M., 2017. *Common International Classification of Ecosystem Services*
834 (CICES) V5.1 and Guidance on the Application of the Revised Structure.

835 Haines-Young, R., Potschin, M.B., 2010. The links between biodiversity, ecosystem services and human
836 well-being, in: Raffaelli, D., Frid, C. (Eds.), *Ecosystem Ecology: A New Synthesis*, BES Ecological
837 Reviews Series, Ecosystem E. Cambridge.

838 Hardaker, A., Pagella, T., Rayment, M., 2020. Integrated assessment, valuation and mapping of
839 ecosystem services and dis-services from upland land use in Wales. *Ecosyst. Serv.* 43, 101098.
840 <https://doi.org/10.1016/j.ecoser.2020.101098>

841 Häyhä, T., Franzese, P.P., Paletto, A., Fath, B.D., 2015. Assessing, valuing, and mapping ecosystem
842 services in Alpine forests. *Ecosyst. Serv.* 14, 12–23. <https://doi.org/10.1016/j.ecoser.2015.03.001>

843 Hein, L., van Koppen, K., de Groot, R.S., van Ierland, E.C., 2006. Spatial scales, stakeholders and the
844 valuation of ecosystem services. *Ecol. Econ.* 57, 209–228.
845 <https://doi.org/10.1016/j.ecolecon.2005.04.005>

846 Hepburn, C.J., Koundouri, P., 2007. Recent advances in discounting: Implications for forest economics. *J.*
847 *For. Econ.* 13, 169–189.

848 Howarth, R.B., Farber, S., 2002. Accounting for the value of ecosystem services. *Ecol. Econ.* 41, 421–
849 429. [https://doi.org/10.1016/s0921-8009\(02\)00091-5](https://doi.org/10.1016/s0921-8009(02)00091-5)

850 Hubbard, C., Davis, J., Feng, S., Harvey, D., Liddon, A., Moxey, A., Ojo, M., Patton, M., Philippidis, G.,
851 Scott, C., Shrestha, S., Wallace, M., 2018. Brexit: How Will UK Agriculture Fare? *EuroChoices* 17,
852 19–26. <https://doi.org/10.1111/1746-692X.12199>

853 Johnston, R.J., Wainger, L.A., 2015. Benefit Transfer for Ecosystem Service Valuation: An Introduction to
854 Theory and Methods, in: Johnston, R.J., Rosenberger, R.S., Brouwer, R. (Eds.), *Benefit Transfer of*
855 *Environmental and Resource Values*. Springer, Dordrecht, pp. 237–274.
856 <https://doi.org/10.1007/978-94-017-9930-0>

857 Kay, S., Graves, A., Palma, J.H.N., Moreno, G., Rocas-Díaz, J. V., Aviron, S., Chouvardas, D., Crous-Duran,
858 J., Ferreiro-Domínguez, N., García de Jalón, S., Măcicășan, V., Mosquera-Losada, M.R., Pantera, A.,
859 Santiago-Freijanes, J.J., Szerencsits, E., Torralba, M., Burgess, P.J., Herzog, F., 2019. Agroforestry is
860 paying off – Economic evaluation of ecosystem services in European landscapes with and without
861 agroforestry systems. *Ecosyst. Serv.* 36, 100896. <https://doi.org/10.1016/j.ecoser.2019.100896>

862 Lawrence, A., Dandy, N., 2014. Private landowners’ approaches to planting and managing forests in the
863 UK: What’s the evidence? *Land use policy* 36, 351–360.
864 <https://doi.org/10.1016/j.landusepol.2013.09.002>

865 Lawrence, A., Dandy, N., Urquhart, J., 2010. Landowners' attitudes to woodland creation and
866 management in the UK A review of current evidence. Forest Research, Alice Holt, Farnham.

867 Mansfield, L., 2011. Upland Agriculture and the Environment. Badger Press, Bowness on Windermere.

868 Meli, P., Rey-Benayas, J.M., Brancalion, P.H.S., 2019. Balancing land sharing and sparing approaches to
869 promote forest and landscape restoration in agricultural landscapes: Land approaches for forest
870 landscape restoration. *Perspect. Ecol. Conserv.* 17, 201–205.
871 <https://doi.org/10.1016/j.pecon.2019.09.002>

872 Metropolis, N., Ulam, S., 1949. The Monte Carlo Method. *J. Am. Stat. Assoc.* 44, 335–341.
873 <https://doi.org/10.2307/2280232>

874 National Assembly for Wales, 2013. Forestry in Wales.

875 Natural Resources Wales, 2018. Terrestrial Phase 1 Habitat Survey [WWW Document]. URL
876 <http://lle.gov.wales/catalogue/item/TerrestrialPhase1HabitatSurvey/?lang=en> (accessed 9.21.18).

877 Natural Resources Wales, 2016. NRW priority (sensitive) habitats and new planting.

878 Pearce, D., Turner, R.K., 1990. Economics of Natural Resources and the Environment. Pearson, Harlow.

879 Pearce, D.W., 1993. Economic Values and the Natural World. MIT Press, Cambridge MA.

880 Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity
881 conservation: Land sharing and land sparing compared. *Science* (80-.). 333, 1289–1291.
882 <https://doi.org/10.1126/science.1208742>

883 Phalan, B.T., 2018. What have we learned from the land sparing-sharing model? *Sustainability* 10, 1–24.
884 <https://doi.org/10.3390/su10061760>

885 Population Reference Bureau, 2011. 2011 World Population Data Sheet. Washington DC.

886 Reis, S., Liska, T., Steinle, S., Carnell, E., Leaver, D., Roberts, E., Vieno, M., Beck, R., Dragosits, U., 2017.
887 UK Gridded Population 2011 based on Census 2011 and Land Cover Map 2015.

888 Saraev, V., MacCallum, S., Moseley, D., Valatin, G., 2017. Valuation of Welsh Forest Resources. Forest
889 Reseach.

890 Scarpa, R., 2003. The recreation value of woodlands. Centre for Research in Environmental Appraisal &
891 Management.

892 Schaubroeck, T., 2017. A need for equal consideration of ecosystem disservices and services when
893 valuing nature; countering arguments against disservices. *Ecosyst. Serv.* 26, 95–97.
894 <https://doi.org/10.1016/j.ecoser.2017.06.009>

895 Sen, A., Darnell, A., Crowe, A., Bateman, I.J., Munday, P., 2011. Economic Assessment of the
896 Recreational Value of Ecosystems in Great Britain, Report to the Economics Team of the UK
897 National Ecosystem Assessment.

898 Shackleton, C.M., Ruwanza, S., Sinasson Sanni, G.K., Bennett, S., De Lacy, P., Modipa, R., Mtati, N.,
899 Sachikonye, M., Thondhlana, G., 2016. Unpacking Pandora's Box: Understanding and Categorising
900 Ecosystem Disservices for Environmental Management and Human Wellbeing. *Ecosystems* 19,
901 587–600. <https://doi.org/10.1007/s10021-015-9952-z>

902 Sivia, D.S., 1996. Data Analysis. A Bayesian Tutorial. Oxford Science Publication.

903 Spangenberg, J.H., Settele, J., 2016. Value pluralism and economic valuation - defensible if well done.
904 *Ecosyst. Serv.* 18, 100–109. <https://doi.org/10.1016/j.ecoser.2016.02.008>

905 Spangenberg, J.H., Settele, J., 2010. Precisely incorrect? Monetising the value of ecosystem services.
906 *Ecol. Complex.* 7, 327–337. <https://doi.org/10.1016/j.ecocom.2010.04.007>

907 Swanwick, C., 2009. Society's attitudes to and preferences for land and landscape. *Land use policy* 26,
 908 62–75. <https://doi.org/10.1016/j.landusepol.2009.08.025>
 909 UKCCC, 2020. Land use: Policies for a Net Zero UK.
 910 Verhagen, W., Verburg, P.H., Schulp, N., Strürck, J., 2015. Mapping Ecosystem Services, in: Bouma, J.A.,
 911 Beukering, P.J.H. van (Eds.), *Ecosystem Services: From Concept to Proactice*. Cambridge University
 912 Press, Cambridge, pp. 65–87.
 913 Wegner, G., Pascual, U., 2011. Cost-benefit analysis in the context of ecosystem services for human
 914 well-being: A multidisciplinary critique. *Glob. Environ. Chang.* 21, 492–504.
 915 <https://doi.org/10.1016/j.gloenvcha.2010.12.008>
 916 Welsh Government, 2018a. Woodlands for Wales. Welsh Government.
 917 Welsh Government, 2018b. Brexit and our land: Securing the future of Welsh farming.
 918 Willis, K.G., 2002. Benefits and costs of forests to water supply and water quality. Centre for Research in
 919 Environmental Appraisal and Management University of Newcastle.
 920 Willis, K.G., Garrod, G., Scarpa, R., Lovett, A., Bateman, I.J., Hanley, N., Macmillan, D.C., 2003. The Social
 921 and Environmental Benefits of Forests in Great Britain. Centre for Research in Environmental
 922 Appraisal and Management University of Newcastle.
 923 <https://doi.org/10.1080/09640560600601587>
 924 Wong, J., Lawrence, A., Urquhart, J., Feliciano, D., B. Slee, 2015. Forest Land Ownership Change in
 925 United Kingdom. COST Action FP1201 FACESMAP Country Report, European Forest Institute
 926 Central-East and South-East European Regional Office.
 927