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The Natural Environmental Valuation (NEV) Modelling Suite: A Summary Technical Report

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Introduction

The purpose of this report is to provide a summary of the technical workings of the Natural Environment Valuation (NEV) modelling suite identifying its assumptions, and its strengths and weaknesses with regards to its core purpose of simulating the multiple outcomes of land use policy.

NEV is an integrated natural science to socio-economic behaviour model of land-use in Great Britain. Combining environmental science, econometric and process modelling, the NEV modelling suite captures ecosystem benefits of food, timber, greenhouse gas sequestration, outdoor recreation, river water quality and quantity, flooding, biodiversity, pollination and environmental non-use.

The NEV modelling suite is a spatially and temporally explicit tool such that it records where and when ecosystem service benefits and losses are accrued. A number of interacting spatial scales are considered, including a grid of $2km^2$ (400 hectare) cells, recreational parks and paths, as well as hydrological subcatchments and basins connected by a river network. In terms of the temporal scale, it is important to note that the NEV modelling suite predicts ecosystem service flows and values into the future, with the majority of values available at the annual scale between 2020 and 2060.

The key modules and module interactions in the NEV modelling suite are illustrated in Figure 1. The modelling suite is split into three tiers: (i) land covers & land uses, (ii) environmental processes, and (iii) ecosystem service valuation.

Tier (i) contains a set of models that predict the land use choices of land managers, particularly those of farmers and foresters. Those decisions are determined both by the characteristics of the land and the climate but also by policies and market conditions. In turn, land use outcomes act as inputs to the environmental processes in tier (ii). This tier contains a range of natural science models of river hydrology, above- and below-ground carbon fluxes, and biodiversity, as well as economic models of recreation activity, pollination services, flooding, and environmental non-use. Finally, in many cases these environmental processes can be monetised, through the ecosystem services valuation models in tier (iii). Food and timber have market values. Greenhouse gas control and recreational value have monetised values which can be included (with market values) in a societal value. Water quantity and quality changes can be monetised as a reduction in flood damage and water treatment costs respectively. An increase in wild pollinator species can be monetised as a reduction in commercial pollination service costs to horticultural farmers. Finally, a range of environmental non-use values are considered where people benefit from the environment even if they do not interact with it, and these include wildflowers meadows, clean rivers and upland habitats.

Whilst the NEV modelling suite covers a broad range of environmental processes and ecosystem services, it is important to note that is it not a comprehensive tool. There are many environmental processes and values missing, for example air quality, bathing water quality, and overnight recreation. Some of these missing elements are highlighted by the orange boxes in Figure 1.

A technical summary of each of the individual models is given in the following sections. Each technical summary describes the model’s purpose, spatial and temporal scale, underpinning data, mechanisms, equations and outputs. The models are grouped by the three tiers. Models concerned with land use decisions are covered in Section A. Models concerned with environmental and economic processes connecting land uses with ecosystem services are covered in Sections B and C. Models concerned with economic valuation of ecosystem services, are considered separately in Section D. The NEV summary report is concluded with a discussion of missing ecosystem service flows and values and an assessment of the model suite’s strengths and weaknesses.

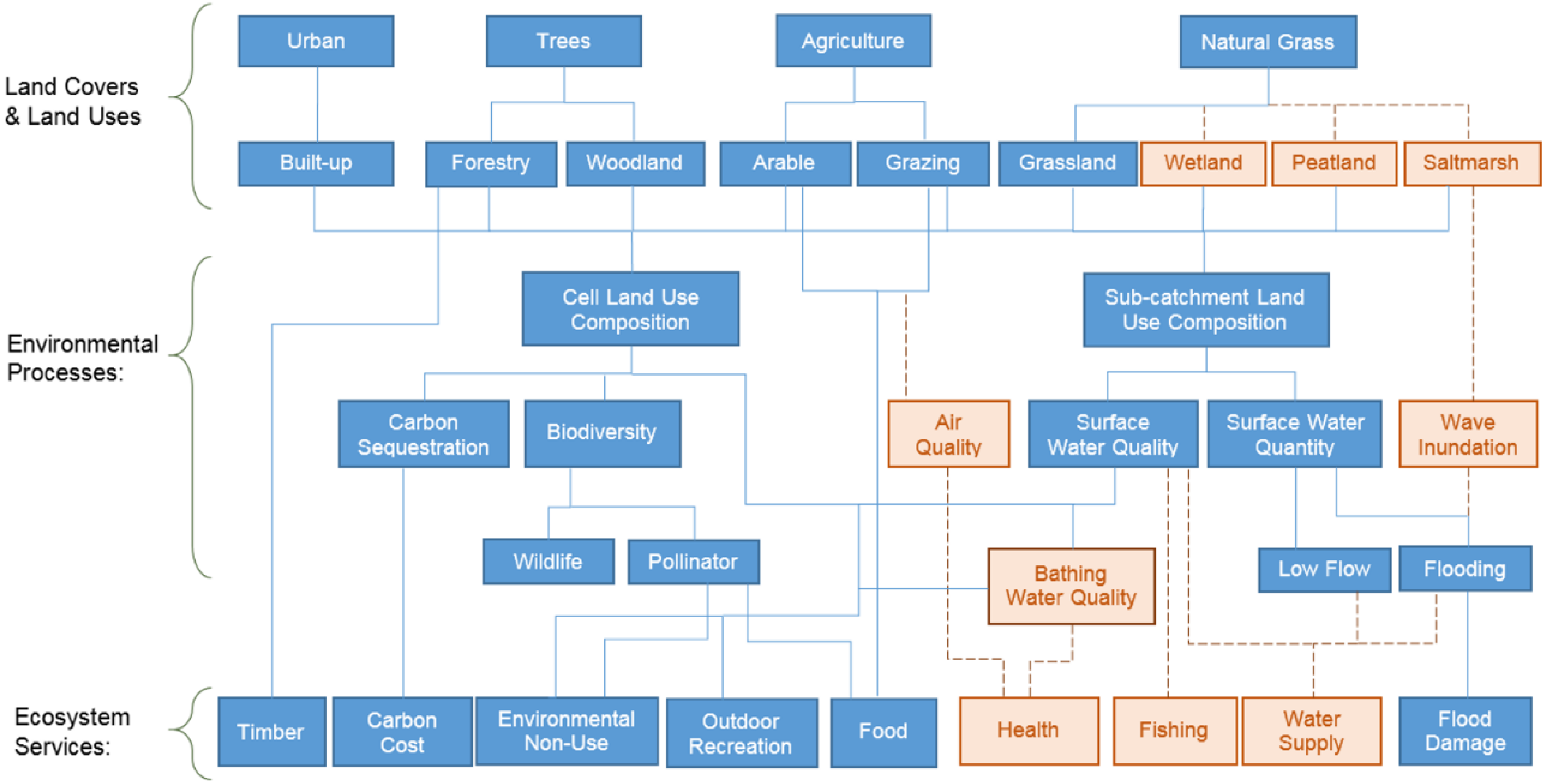

Figure 1: Structure of the NEV modelling suite, outlining its three tiers going from land covers & land uses, through environmental processes, and finally ecosystem services.

A. Land Use Decision Models

In the NEV modelling suite, many of the models – including the land use decision models – work at a 2km^2 grid cell resolution. This grid, which we refer to throughout this document as the NEV 2km^2 grid, is derived from a range of data sources including the 2007 Land Cover Map (Morton et al, 2011), 2010 June Agricultural Census (Defra, 2013) and the National Inventory for Woodland and Trees (Forestry Commission, 2002).[1] A snapshot of the full grid is shown in Figure 2. The NEV grid contains 57,230 cells across Great Britain, of which 32,784 are in England.

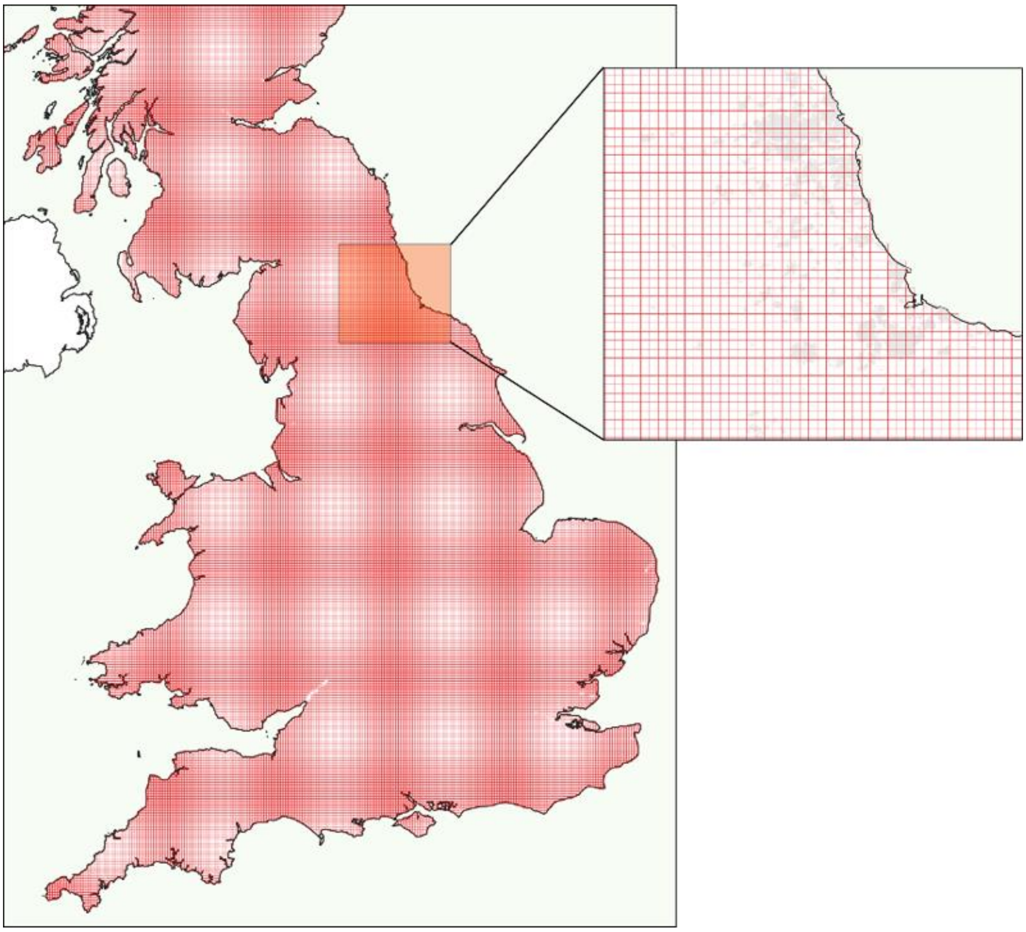

Figure 2: The NEV 2km^2 grid.

Each 2km^2 grid cell contains 400 hectares and these are split into five 'high level' land covers: agriculture, woodland, semi-natural grassland, urban and water. For simplicity, we assume that there is a single farmer managing the hectares of agriculture in each cell, and a single forester managing the hectares of woodland in each cell. The areas of semi-natural grassland, urban and water are not considered to be managed, but like agriculture and woodland, do feed into many of the models in the NEV modelling suite. Furthermore, it is possible to change the hectares of the five land covers in the cell, and the NEV model will predict the response in ecosystem flows and values. The decisions of the farmer and forester in each cell are predicted by the farm management and forestry management models in the NEV modelling suite respectively, and these will now be described in Sections A.1 and A.2.

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[1] The creation of the NEV 2km^2 grid is described in full in Annex 1 of Bateman et al (2014).

A.1. Farm management model

Purpose

The farm management model in the NEV modelling suite predicts farm planting and stocking decisions in response to land characteristics, climate and market conditions. The model is estimated primarily using data from the June Agricultural Census (1976-present, Defra), and the Farm Business Survey (2007-2015, Defra). Many other data sources have been used to determine farmer decision making, including:

- Predictions of temperature and rainfall in the growing season (April-September) from the 2009 UK Climate Projections (UKCP09, Met Office).
- Soil characteristics from the Harmonized World Soil Database (FAO, 2009).
- Crop and livestock prices from the John Nix Pocketbook (Redman, 2018).
- Altitude and slope from the Integrated Hydrological Digital Terrain Model (Morris and Flavin, 1990; Morris and Flavin, 1994).
- Land designations including country, national parks, greenbelts, environmentally sensitive areas, and nitrate vulnerable zones.
- Distance to nearest urban centres and processing factories.

Each grid cell in the NEV 2km^2 grid is assumed to have a single farm manager making decisions over their hectares of agricultural land. In the NEV modelling suite, the land use decisions of each of these farm managers is predicted on an annual basis between 2020 and 2060.

Mechanism

The farm management model in the NEV modelling suite takes a structural and hierarchical form, as shown in Figure 3. Starting from the total hectares of agriculture within each 2km^2 grid cell, the model proceeds by predicting how the farmer would manage that land by dividing it into various crop and grassland types as well as different types of livestock. The key assumption of the econometric model is that the farm manager's decision is profit maximising based on their knowledge of land characteristics, climate and agricultural prices.

The initial stage is to divide the total hectares of agriculture into two broad land use categories: arable and grazing. A quasi-maximum likelihood logit regression model is used to this end. Given the total hectares of agricultural in each cell, the shares of arable and grazing land within the cell can be converted into hectares.

The second stages divide the hectares of arable and grazing land respectively into individual crop and farm grassland types. Firstly, the arable land is divided into four individual crops – wheat, barley, oil seed rape and root crops – with the leftover being allocated to an 'other' category which includes horticulture, maize, other crops and cereals, and bare fallow land. The barley category includes spring and winter barley separately, and the root crop category includes potatoes and sugar beet. Secondly, the grazing land is divided into three individual grassland types – temporary grassland, permanent grassland and rough grazing. Both of these models employ the multivariate Tobit regression specification of Fezzi and Bateman (2011).

The third stage is to predict livestock densities of dairy cattle, beef cattle and sheep. A quasi-maximum likelihood Poisson model is used to this end. The model does not distinguish between the different grassland types from the second stage, rather multiplying the predicted livestock densities by the total hectares of grazing land to estimate the number of heads of different livestock types.

All models employ a range of covariates including crop and livestock prices, slope, elevation, land designation, distance to market and processing factories, soil characteristics and climate. The exact specification of the models can be found in Fezzi et al (2019).

The final stage is to convert the predicted hectares of the individual crop types, grassland types and the livestock types into an estimate of the profitability of the farm. This economic valuation process is described later in Section D1.1.

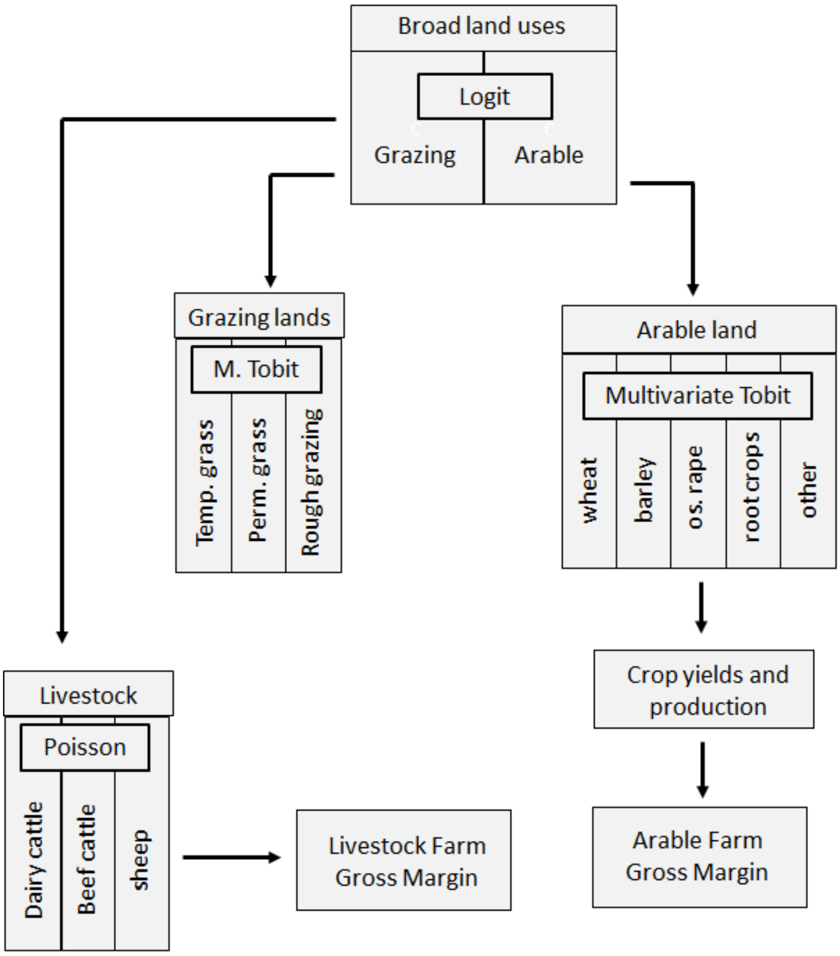

Figure 3: Structure of the NEV farm management model.

<u>Outputs</u>

The outputs of the NEV farm management model are the predicted hectares of various agricultural land types, and the predicted number of heads of different livestock types. This information is available for each of the cells in the NEV 2km^2 grid, which are treated as independent farm managers, and on an annual basis in the years 2020-2060. The agricultural land types considered are the total farmland, arable, grazing, wheat, barley (winter and spring), oil seed rape, root crops (potatoes and sugar beet), other crops, temporary grassland, permanent grassland and rough grazing. The livestock classes are dairy cattle, beef cattle and sheep.

Information on the profitability of the individual crop and livestock types, as well as the profitability of the arable and grazing areas and the farmland as a whole, is also available. As previously mentioned, more detail on the economic valuation of the farm business will be presented in Section D1.1.

A.2. Forestry management model

Purpose

The forestry management model in the NEV modelling suite predicts forestry planting decisions and resulting timber output and profitability in response to characteristics, climate and market conditions. The forest management model is based on a range of data and models including:

- National Inventory for Woodland and Trees (Forestry Commission, 2002).
- Predictions of temperature and rainfall in the growing season (April-September) from the 2009 UK Climate Projections (UKCP09, Met Office).
- Soil characteristics from the Harmonized World Soil Database (FAO, 2009).
- Altitude and slope from the Integrated Hydrological Digital Terrain Model (Morris and Flavin, 1990; Morris and Flavin, 1994).
- CARBINE model (Thompson and Matthews, 1989).
- Ecological Site Classification model (Forestry Commission, 2013).
- Forest Investment Appraisal Package (Forestry Commission, 2013).

Each grid cell in the NEV 2km^2 grid is assumed to have a single forest manager making decisions over their hectares of managed woodland. In the NEV modelling suite, the land use decisions of each of these forest managers is predicted on an annual basis between 2020 and 2060, although these may incorporate tree rotations further into the future.

Mechanism

The forestry management model is applied to areas of managed woodland within each 2km^2 grid cell, identified from Forestry Commission data. If land cover changes to woodland within a cell, then that woodland is assumed to be managed, and the forestry management model is applied. Within each managed woodland area, the decisions the forest managers is considered over deciduous (here assumed to be Pedunculate Oak) and coniferous (here assumed to be Sitka Spruce) woodland.

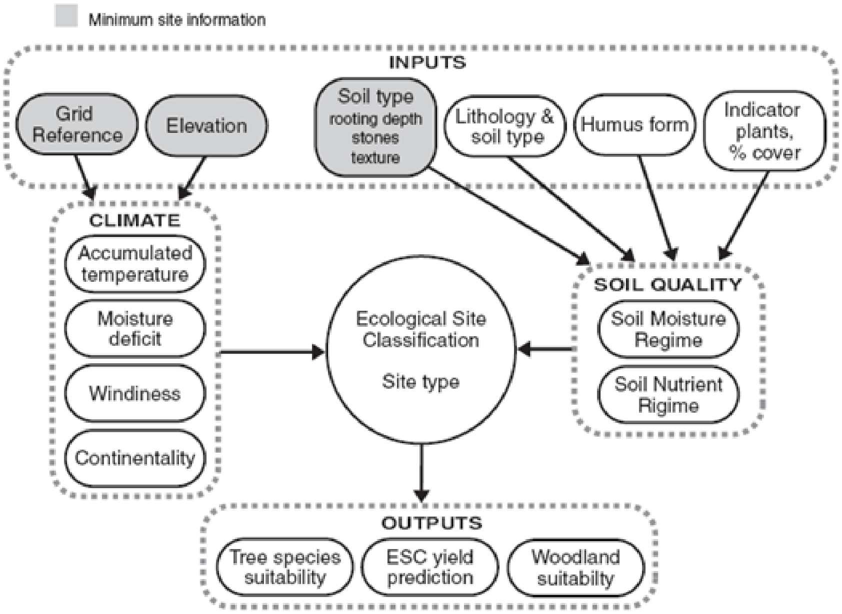

Figure 4: Structure of the Ecological Site Classification model, developed by Pyatt et al (2001). Diagram source: Matthews (2011).

The forestry management model relies heavily on the concept of yield classes and Ecological Site Classification (ESC), both of which provide an estimate of the suitability of land and climate conditions for tree growth. The ESC model (Pyatt et al, 2001), a schematic of which is shown in Figure 4, provides an estimate of expected forest growth and tree suitability as a function of climate, soil and land characteristics. The ESC is a continuous variable which assumes value zero where soil and climatic factors are unsuitable for planting, such as in urban areas, and a positive value otherwise. The yield class is simply the ESC rounded to the nearest even number, used conventionally in forestry studies.

In the NEV modelling suite, the forestry management model is a two stage process. Firstly, the CARBINE model (Thompson and Matthews, 1989) is used to predict timber volume on an annual basis over the rotation period of a given tree species, yield class and management regime. As previously stated, we focus on Pedunculate Oak and Sitka Spruce species as proxies for deciduous and coniferous trees as a whole. For all analyses we implement the 'thinning and felling' management regime. As an example, Figure 5 shows the volume of timber per year produced from Pedunculate Oak and Sitka Spruce years with differing yield classes.

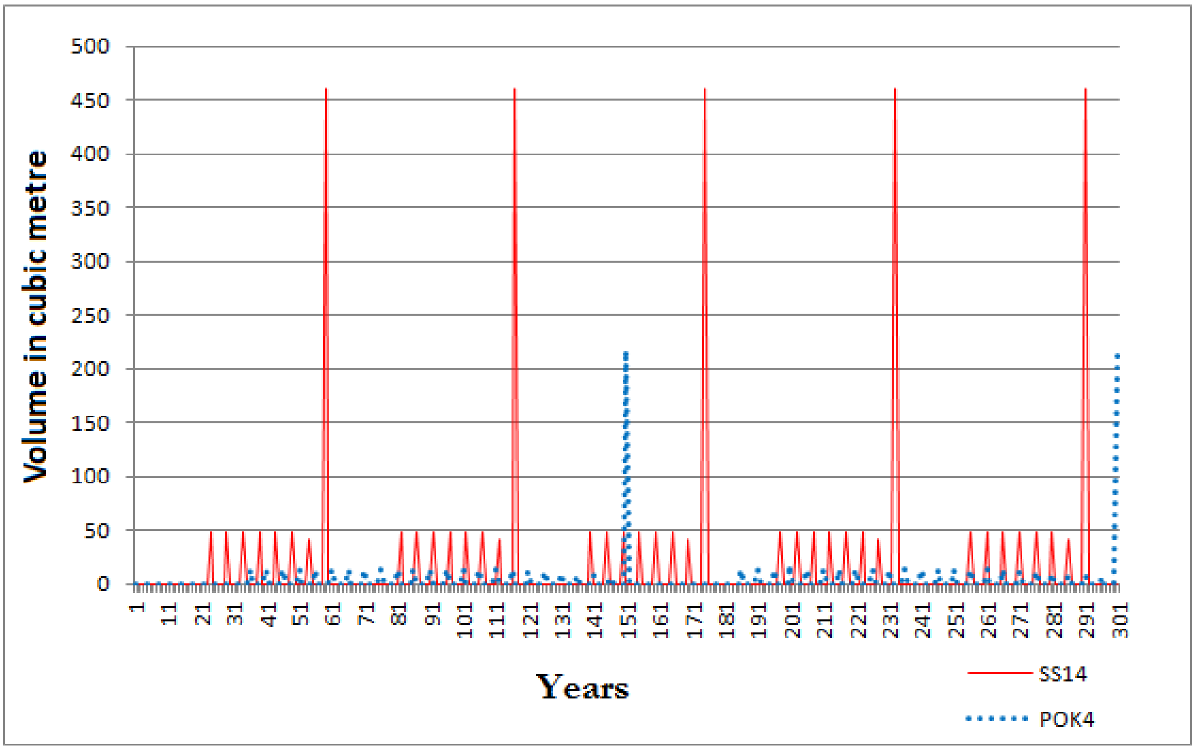

Figure 5: The volume of timber per year from Sitka Spruce trees with yield class 14 over five rotations (SS14, red) and Pedunculate Oak trees with yield class 4 over two rotations (POK4, blue).

The second stage of the model predicts how forest growth may change over time with the influence of climate change. A semi-parametric regression model is used to this end, with the yield class of Pedunculate Oak and Sitka Spruce predicted as a function of temperature and rainfall, elevation, slope and soil characteristics (particularly pH, carbon and water content). The exact specification of the models can be found in Binner et al (2019a). Using this model in conjunction with the CARBINE model, for each cell in the NEV 2km^2 grid the forestry management model predicts timber output into the future with the influence of climate change.

The final stage is to convert the predicted timber output of the tree species into an estimate of the profitability of the forest. This economic valuation process is described later in Section D1.2.

Outputs

The outputs of the NEV forestry management model are predictions of the volume of timber in each $2km^2$ grid cell per year from 2020 given a continuous planting rotation of the hectares of managed woodland in the cell. In fact, four planting scenarios are considered given the available hectares of managed woodland: (i) 100% deciduous woodland, (ii) 100% coniferous woodland, (iii) a 60%/40% deciduous/coniferous mix, and (iv) the current mix of deciduous/coniferous woodland in the cell, known from Forestry Commission data.

Information on the profitability of the forest under these four planting scenarios is also available. As previously mentioned, more detail on the economic valuation of the farm business will be presented in Section D1.2.

B1. Carbon System Models

In the NEV modelling suite, the emission and sequestration of greenhouse gases from the environment are considered from three sources: (i) emissions from agriculture, (ii) sequestration from above ground forestry, and (iii) below ground soil sequestration or emission arising from land use change. The models for these three processes are now described in Sections B1.1, B1.2 and B1.3 respectively. Sequestration and emission of greenhouse gases are expressed as positive and negative quantities respectively, in order to reflect the benefit and cost to society in line with the other environmental outcomes in the NEV modelling suite.

B1.1. Agricultural emissions

Purpose

The agricultural emissions model in the NEV modelling suite predicts the greenhouse gas emissions from different agricultural activities, given the decisions made by the farm manager. The model is based on a range of data and models including:

- Output from the NEV farm management model (described in Section A.1), namely the predicted hectares of agricultural land uses including individual crops and grasslands, as well as the predicted heads of livestock.
- Predictions of temperature and rainfall in the growing season (April-September) from the 2009 UK Climate Projections (UKCP09, Met Office).
- Soil characteristics from the Harmonized World Soil Database (FAO, 2009).
- The Cool Farm Tool (CFT, 2013).

Like the NEV farm management model, the agricultural emissions model operates on the NEV 2km^2 grid across Great Britain, and predictions are available on an annual basis between 2020 and 2060.

Mechanism

Agriculture is a substantial emitter of GHGs through for example, machinery use, mineral and organic fertiliser use, ruminant livestock, as well as effects of both biomass and soil carbon stocks. The agricultural emissions model in the NEV modelling suite predicts the greenhouse gas emissions from these sources given the land use decisions made by the farm manager.

The NEV agricultural emissions model is based on a tailored version of the Cool Farm Tool, which is a model of intermediate complexity sitting between simple emissions factor approaches and more complex process-based models. It requires information on seven agricultural land uses (cereals, oil seed rape, root crops, other crops, temporary grassland, permanent grassland and rough grazing) and three livestock classes (dairy cattle, beef cattle and sheep), predictions of which are obtained from the NEV farm management model. Detailed soil characteristics are also required, and information of the texture, organic material, moisture, drainage and pH level have been obtained from the Harmonized World Soil Database. Finally, projections of climate change are necessary for projections in the future.

The key greenhouse gases and pollutants considered are nitrous oxide (N_2O), ammonia (NH_3) and methane (NH_4). Nitrous oxide and ammonia emissions arise due to the mineralisation of nitrogen in organic matter (in the soil or for example in animal manures), and through the use of synthetic nitrogen fertilisers. Major sources of methane are from ruminant livestock (a function of dry matter intake) and manure management. Given the agricultural practice, soil and climate data, the Cool Farm Tool predicts the emissions of these pollutants under a specific management scheme.

Assumptions on the management regime of land use and livestock are given in Table 1 and Table 2 respectively, and include fertiliser application, livestock emission factors and general land management. More information on the model specification and assumptions can be found in Binner et al (2019b).

Land use	Fertiliser	Fertiliser (organic)	Management
Oilseed rape	N = 191 kg ha^{-1} P_2O_5 = 58 kg ha^{-1} K_2O = 65 kg ha^{-1} CaO = 4400 kg ha^{-1}	N = 172 kg ha^{-1} P_2O_5 = 52 kg ha^{-1} K_2O = 58.5 kg ha^{-1} CaO = 3960 kg ha^{-1}	Ploughing Discing Fertiliser spraying Harvesting
Cereals	N = 146 kg ha^{-1} P_2O_5 = 54 kg ha^{-1} K_2O = 64 kg ha^{-1} CaO = 4000 kg ha^{-1}	N = 131 kg ha^{-1} P_2O_5 = 48.6 kg ha^{-1} K_2O = 57.6 kg ha^{-1} CaO = 3600 kg ha^{-1}	Ploughing Harrowing Gain drilling Roller harrowing Fertiliser spraying Harvesting Baling
Root crops	N = 129 kg ha^{-1} P_2O_5 = 95 kg ha^{-1} K_2O = 165 kg ha^{-1}	N = 116 kg ha^{-1} P_2O_5 = 85.5 kg ha^{-1} K_2O = 148.5 kg ha^{-1}	Ploughing Field Cultivating/ridging Rotary hoeing/bed Tilling Planting Tine harrowing/seed handling & transport Fertiliser spraying Potato harvesting
Grassland with grazing	-	-	-
Permanent grazing	N = 85 kg ha^{-1} P_2O_5 = 21 kg ha^{-1} K_2O = 25 kg ha^{-1} CaO = 4300 kg ha^{-1}	N = 76.5 kg ha^{-1} P_2O_5 = 18.9 kg ha^{-1} K_2O = 22.5 kg ha^{-1} CaO = 3870 kg ha^{-1}	Ploughing Fertiliser Spraying Harvesting
Temporary grazing	N = 118 kg ha^{-1} P_2O_5 = 27 kg ha^{-1} K_2O = 41 kg ha^{-1} CaO = 4600 kg ha^{-1}	N = 106 kg ha^{-1} P_2O_5 = 24 kg ha^{-1} K_2O = 36.9 kg ha^{-1} CaO = 4140 kg ha^{-1}	Ploughing Fertiliser Spraying Harvesting

Table 1: Assumptions of fertiliser use and general management of agriculture in the NEV agricultural emissions model. Source: St. Clair et al (2008), Haverkort and Hillier (2011) and Defra (2011).

Emissions	**Dairy cows (600 kg)**	**Beef cows (300kg)**	**Sheep (65 kg)**
CH_4 from fermentation *(kg CH_4 head^{-1} yr^{-1})*	117	57	8
CH_4 from manure due to annual temperature (T=13°C) *(kg CH_4 head^{-1} yr^{-1})*	27	8	0.19
N excretion rate *(kg N (1000 kg animal mass)$^{-1}$ day^{-1})*	0.48	0.33	0.85
N_2O from manure *(factor)*	0.02	0.02	0.01

Table 2: Assumptions of livestock emission factors used in the NEV agricultural emissions model. Source: IPCC (2006).

Finally, predictions of the greenhouse gases from land use and livestock are converted into tonnes of carbon dioxide equivalent (tCO2e) so as to be compared across agricultural practices. Emissions from different agricultural practices are also summed to give an estimate of the total emissions from agriculture. The economic cost to society of the agricultural emissions is also available, with details of the calculation covered in Section D1.3.

Outputs

The outputs of the NEV agricultural emissions model are the predicted greenhouse gas emissions from various agricultural land use types and livestock in tonnes of carbon dioxide equivalent. This information is available for each of the cells in the NEV 2km^2 grid, which are treated as independent farm managers, and on an annual basis in the years 2020-2060. The agricultural land types considered are the total farmland, arable, grazing, cereals, oil seed rape, root crops, other crops, temporary grassland, permanent grassland and rough grazing. The livestock classes are dairy cattle, beef cattle and sheep.

Information on the economic cost of agricultural emissions is also available and more detail will be presented in Section D1.3.

B1.2. Forest timber sequestration

Purpose

The forestry timber sequestration model in the NEV modelling suite predicts permanent equivalent capture of carbon in above ground biomass and in wood product from harvested timber, given the decisions made by the forest manager. The forest timber sequestration model is based on a range of data and models including:

- Output from the NEV forestry management model (described in Section A.2), namely the predicted growth of Pedunculate Oak and Sitka Spruce trees of different yield classes into the future with climate change.
- National Inventory for Woodland and Trees (Forestry Commission, 2002).
- Predictions of temperature and rainfall in the growing season (April-September) from the 2009 UK Climate Projections (UKCP09, Met Office).
- Soil characteristics from the Harmonized World Soil Database (FAO, 2009).

- Altitude and slope from the Integrated Hydrological Digital Terrain Model (Morris and Flavin, 1990; Morris and Flavin, 1994).
- CARBINE model (Thompson and Matthews, 1989).
- Ecological Site Classification model (Forestry Commission, 2013).

Like the NEV forestry management model, the forest timber sequestration model operates on the NEV 2km^2 grid across Great Britain, and predictions are available on an annual basis from 2020 incorporating tree rotations into the future.

Mechanism

The forest timber sequestration model takes on a similar form and structure to the NEV forestry management model, in that it is applied to areas of managed or new (via land cover change) woodland within each 2km^2 grid cell. The same two-stage process is used, with the CARBINE model (Thompson and Matthews, 1989) being used in conjunction with data on soil and land characteristics, as well as a model predicting how the yield class of representative tree species may change with climate (see Section A.2 for more details). Once again, Pedunculate Oak and Sitka Spruce species are used as proxies for deciduous and coniferous trees as a whole.

As well as timber volume, the CARBINE model also provides output for the above ground greenhouse gas sequestration in tree products for a range of tree species, yield classes and management regimes. In accordance with the forestry management model, for all analyses we implement the ‘thinning and felling’ management regime. Three above ground sources of greenhouse gas sequestration are considered: (i) livewood, (ii) deadwood, including litter, and (iii) harvested wood products. For simplicity, in the NEV forest sequestration model we accumulate sequestration across the three sources. For example, the livewood component of above ground sequestration is shown for Pedunculate Oak trees in Figure 6 and for Sitka Spruce trees in Figure 7 over multiple rotations. Estimates of below ground sequestration are also available from the CARBINE model but these are considered separately in Section B1.3. The economic benefit to society of forest timber sequestration is also available, with details of the calculation covered in Section D1.3.

Outputs

The outputs of the NEV forest timber sequestration model are predicted quantities of above ground greenhouse gas sequestration each in 2km^2 grid on an annual basis from 2020 given a continuous planting rotation of the hectares of managed woodland in the cell. Like the NEV forestry management model, four planting scenarios are considered: (i) 100% deciduous woodland, (ii) 100% coniferous woodland, (iii) a 60%/40% deciduous/coniferous mix, and (iv) the current mix of deciduous/coniferous woodland in the cell.

Information on the economic benefit of forest timber sequestration is also available and more detail will be presented in Section D1.3.

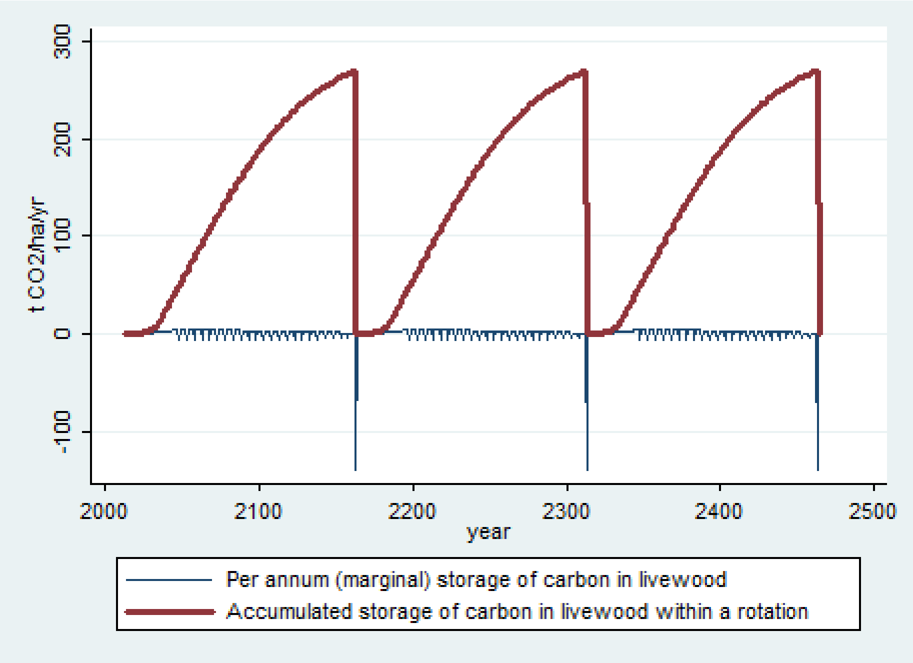

Figure 6: Above ground greenhouse gas sequestration from livewood per annum (blue) and cumulative (red) for Pedunculate Oak trees with yield class 4 over three rotations.

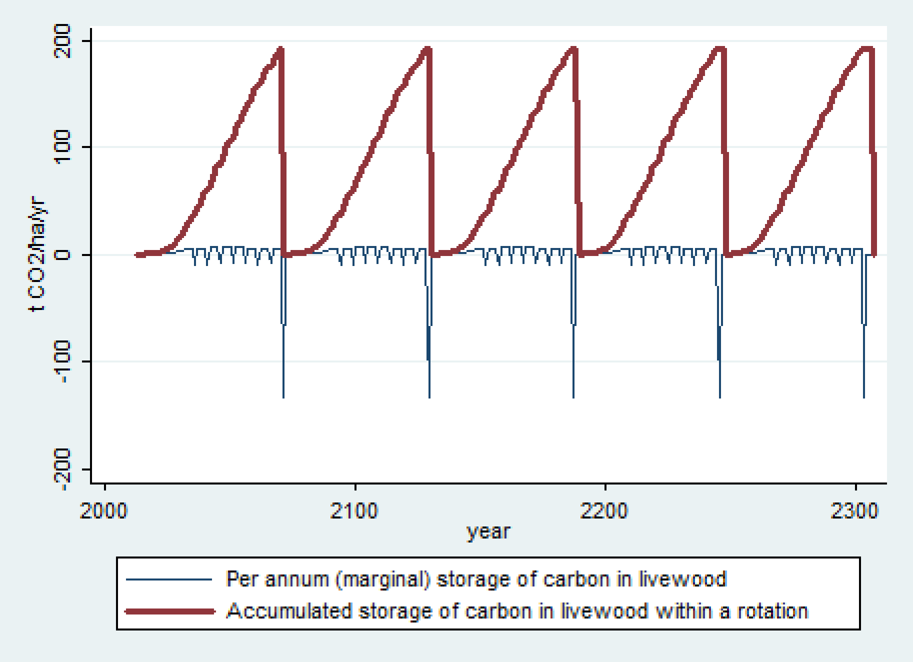

Figure 7: Above ground greenhouse gas sequestration from livewood per annum (blue) and cumulative (red) for Sitka Spruce trees with yield class 14 over five rotations.

B1.3. Soil sequestration

Purpose

The soil sequestration model in the NEV modelling suite predicts changes in greenhouse sequestration in different soils resulting from land uses from agriculture or semi-natural grassland to woodland. The soil sequestration model is based on a range of data and models including:

- Output from the NEV forestry management model (described in Section A.2), namely the predicted growth of Pedunculate Oak and Sitka Spruce trees of different yield classes into the future with climate change.
- National Inventory for Woodland and Trees (Forestry Commission, 2002).
- Predictions of temperature and rainfall in the growing season (April-September) from the 2009 UK Climate Projections (UKCP09, Met Office).
- Soil characteristics from the Harmonized World Soil Database (FAO, 2009).
- Altitude and slope from the Integrated Hydrological Digital Terrain Model (Morris and Flavin, 1990; Morris and Flavin, 1994).
- CARBINE model (Thompson and Matthews, 1989).
- Ecological Site Classification model (Forestry Commission, 2013).

Like the NEV forestry management model, the soil sequestration model operates on the NEV 2km^2 grid across Great Britain, and predictions are available on an annual basis from 2020 incorporating tree rotations into the future.

Mechanism

The soil sequestration model is applied only in cases where there is a land use change from agriculture or semi-natural grassland to woodland. In cases where there is no land use change, the soil carbon is assumed to be in equilibrium and the NEV soil sequestration model returns a value of zero. When a conversion to woodland has taken place, the soil sequestration model takes on a similar form and structure to the NEV forest timber sequestration model (see Section B1.2 for more details). The same two-stage process is used, with the CARBINE model (Thompson and Matthews, 1989) being used in conjunction with data on soil and land characteristics, as well as a model predicting how the yield class of representative tree species may change with climate (see Section A.2 for more details). Once again, Pedunculate Oak and Sitka Spruce species are used as proxies for deciduous and coniferous trees as a whole.

As well as timber volume and above ground greenhouse gas sequestration, the CARBINE model also provides output for the below ground greenhouse gas sequestration for a range of tree species, yield classes and management regimes. Key to any forecasts of the soil carbon is the ability to take into account the land-use, and particularly soil type, prior to afforestation. This is differentiated according to whether prior soil use was either classified as disturbed or undisturbed. Figure 8 shows the tonnes of carbon dioxide equivalent sequestered per hectare per year for yield class 4 Pedunculate Oak trees planted on both disturbed and undisturbed organic (peat) and clay soils. In the NEV soil sequestration module, this information is available for arable and non-arable organic, loam, clay and sand soil types.

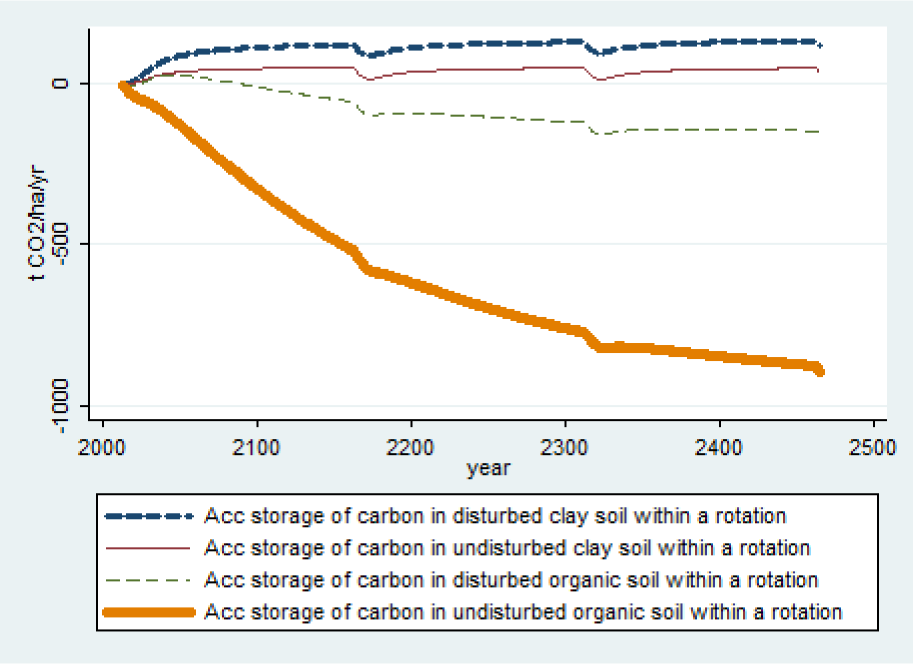

Figure 8: Accumulated below ground storage of greenhouse gases for Pedunculate Oak trees with yield class 4 in disturbed clay (blue), undisturbed clay (red), disturbed organic (green) and undisturbed organic (orange) soils.

The economic benefit to society of soil sequestration is also available, with details of the calculation covered in Section D1.3.

Outputs

The outputs of the NEV soil sequestration model are predicted quantities of below ground greenhouse gas sequestration each in 2km^2 grid on an annual basis from 2020 given a continuous planting rotation of the hectares of managed woodland in the cell. Like the NEV forestry management model, four planting scenarios are considered: (i) 100% deciduous woodland, (ii) 100% coniferous woodland, (iii) a 60%/40% deciduous/coniferous mix, and (iv) the current mix of deciduous/coniferous woodland in the cell. As previously stated, the NEV soil sequestration model is only applied in cases of land use change from agriculture or semi-natural grassland to woodland, return a value of zero otherwise.

Information on the economic benefit of soil sequestration is also available and more detail will be presented in Section D1.3.

B2. Hydrological System Models

The NEV modelling suite includes three hydrological system models: (i) a water flow model, (ii) a water quality model, and (iii) a flood risk model. These individual models are described respectively in Sections B2.1, B2.2 and B2.3 shortly, before a short comment on their spatial scale. Naturally the hydrological system models do not operate on the NEV 2km^2 grid but rather a river network segregated by a series of catchments and subcatchments. During the development of the hydrological system models, two main spatial units of subcatchments and catchments have arisen and these will be described briefly now.

At the heart of all NEV hydrological system models is the Soil & Water Assessment Tool (SWAT, Arnold et al, 2012). The SWAT model can be used to quantify the impact of land use change on hydrological processes at water shed scale. Given data on elevation, soil, land use and climate, the SWAT model delineates a system of modelled subcatchments and catchments which can be calibrated to fit real world water flow and quality data. Using data from the National River Flow Archive (CEH, 2020) and the Water Quality Archive (EA, 2020b) the SWAT model was calibrated for 253 catchments and 6,444 subcatchments across Great Britain. More details on this process can be found in Liuzzo et al (2019). The SWAT subcatchments are shown in Figure 9. The SWAT model was then run under a future climate projection to predict flow, nitrate concentrations and phosphate concentrations for all subcatchments at a daily scale between 2020 and 2060.

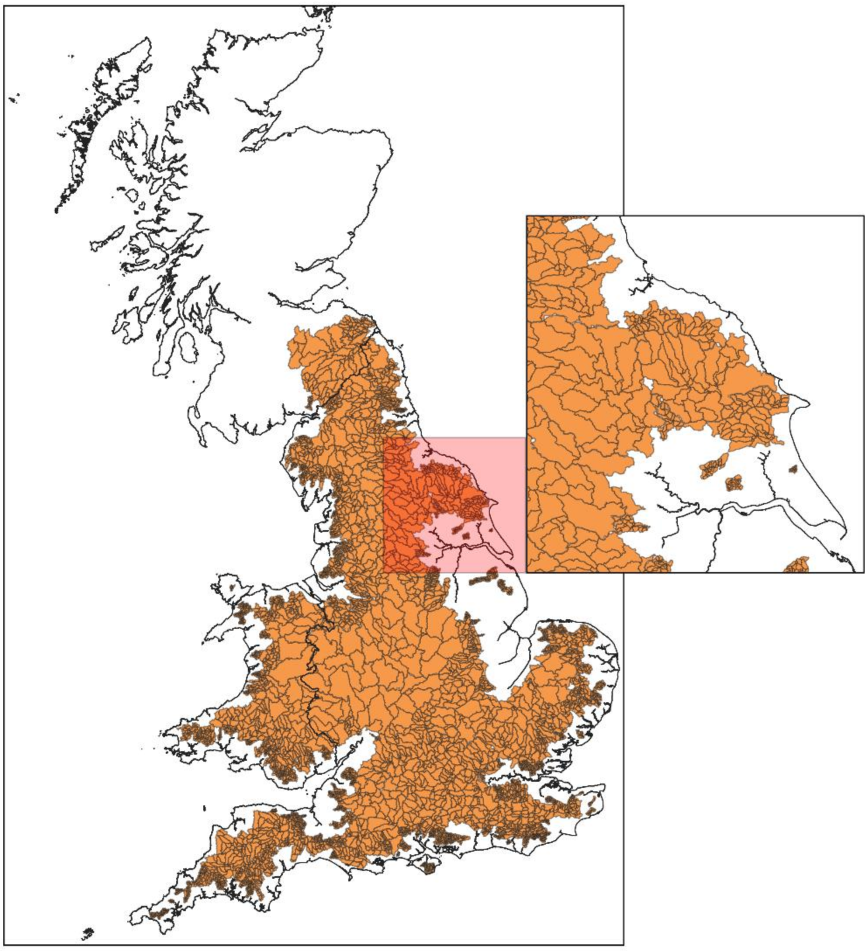

Figure 9: Subcatchments derived from the Soil & Water Assessment Tool (SWAT) used in the NEV hydrological system models.

When used at the Great Britain scale, the SWAT models become infeasible to run due to time constraints. The hydrological system models implemented in the NEV modelling suite are actually fast running versions of the calibrated SWAT models, known as statistical emulators (O'Hagan, 2006). The core set of SWAT emulators predict the response in downstream water flow and quality after a land use change in the catchment. These emulators operate on the system of SWAT modelled catchments in Figure 9. Details on the water quality component of these emulators are given in Section B2.2 and more detail can be found in Owen et al (2019a).

One drawback of the system of modelled SWAT catchments is that (i) they do not extend to the coastline and (ii) coverage of most of Scotland is missing. This is due to resolution of the National River Flow Archive the models were calibrated on. For this reason a second system of subcatchments and catchments were derived with full coverage across Great Britain. These are shown in Figure 10 and are derived from the Water Framework Directive (WFD, Environment Agency, 2020a) and will be referred to as WFD subcatchments throughout this report.

Figure 10: Subcatchments derived from the Water Framework Directive (WFD) used in the NEV hydrological system models.

Obtaining water flow and quality measures at the WFD catchments requires the creation of a second emulator of the SWAT models, essentially "transferring" their behaviour to the new catchment system. Currently in the NEV modelling suite, only the response of water flow and flood risk to land use change is available for the WFD subcatchments, with the addition of water quality a direction for future work. The water flow and flood risk models are described in Sections B2.2 and B2.3 respectively.

Finally, two key concepts relevant to both the water flow and water quality models are briefly discussed. First is the classification of subcatchments into two categories. For the purposes of the NEV hydrological system models we distinguish between two types of subcatchment: first order subcatchments, which have no subcatchments upstream; and second order subcatchments, which take input from upstream subcatchments (which could be first or second order themselves). An example SWAT catchment is shown in Figure 11, with first and second order subcatchments shown in yellow and pink respectively.

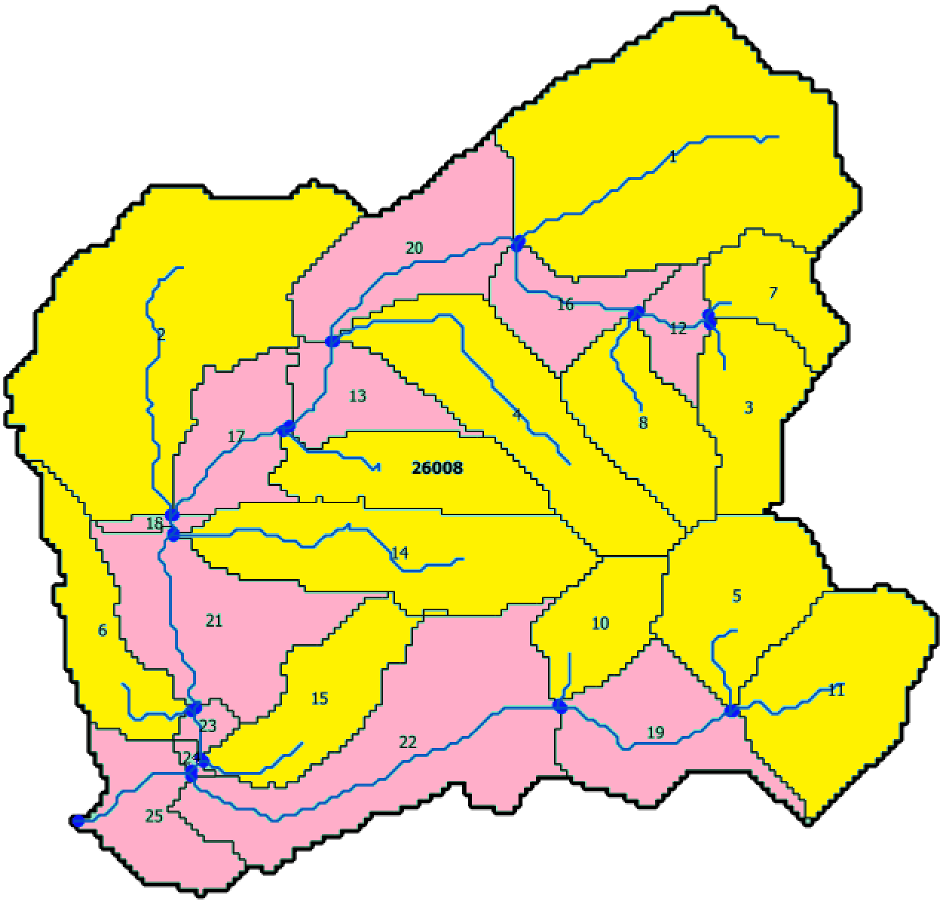

Figure 11: An example of a SWAT catchment (number 26008, Mires Beck in East Riding of Yorkshire), divided into 25 subcatchments. First and second order subcatchments are shown in yellow and pink respectively. The river network is shown as a blue line, with outlet points of each subcatchment shown as blue circles.

Second is the separation of hydrological outcomes available in each subcatchment into three components. For each subcatchment, the SWAT model provides two measures of a hydrological outcome: the "in" component and "out" component. In terms of Figure 11, we think of the "out" variables being measured at the outlet points of each subcatchments (shown as blue circles) and the "in" variables as being measured at the point at which the river enters the subcatchment, or if it is a first order subcatchment, the source of the river. As the SWAT simulation runs from the top of the catchment to the bottom, it is not the case that the "out" variables from upstream subcatchments combine together to form the "in" variables in downstream subcatchments. In fact, we have identified an additional "land use" component, which we define as the "in" component minus the “out” components from next upstream subcatchments. For example, the “land use” component of subcatchment 13 in Figure 11 would be the “in” component of subcatchment 13 minus the “out” components of subcatchments 4 and 20. For first order subcatchments, the “land use” component is equivalent to the “in” component since there are no upstream subcatchments.

Due to the separation of these components, the water flow and water quality models each have two sub-models: (i) the land use emulator and (ii) the instream emulator. The land use emulator predicts the “land use” component of a hydrological outcome as a function of subcatchment characteristics, primarily land use. The instream emulator predicts the “out” component of a hydrological outcome as a function of its “in” component. Using these two sub-processes, the water flow and water quality models can accurately mimic the behaviour of the SWAT model as it moves downstream through a catchment. More information on the specific forms of the land use and instream emulators will be given in Sections B2.1 and B2.2.

B2.1. Water flow model

Purpose

The water flow model in the NEV modelling suite predicts the daily hydrograph of river flow as it responds to land use changes through the catchment. The model is based on a range of data and models including:

- The Soil & Water Assessment Tool (SWAT, Arnold et al, 2012).
- River flow data from the National River Flow Archive (CEH, 2020).
- Land use classification from CORINE Land Cover (Copernicus Land Monitoring Service, 2012).
- Predictions of land use on the NEV 2km^2 grid given by the NEV land use decision models (see Section A).
- Predictions of temperature and rainfall from the 2009 UK Climate Projections (UKCP09, Met Office).
- Soil characteristics from the Harmonized World Soil Database (FAO, 2009).
- Elevation and slope from Ordinance Survey Terrain 50 (OS, 2017).

The NEV water flow model operates on the system of derived WFD subcatchments (Figure 10), taking predictions of land use on the NEV 2km^2 grid from the NEV land use decision models (Section A). Predictions of the daily hydrograph are available between 2020 and 2060 at each subcatchment outlet point and respond to land use change throughout the catchment. Summary statistics of the predicted daily hydrograph are also available.

Mechanism

Recall from Section B2 that the NEV water flow model is based on the SWAT model, which has been calibrated across much of England, Wales and Scotland. In fact, the water flow model is a statistical emulator in that it provides an approximation to the SWAT model in a fraction of the time. In order to obtain better coverage of Great Britain, the NEV water flow model has been applied to the system of WFD catchments shown in Figure 10. Following the discussions in Section B2, each of the WFD subcatchments have been classified as either first or second order, and water flow (more specifically, daily streamflow) in each of the subcatchments is assumed to have a “land use”, “in” and “out” component. Moreover, the NEV water flow model consists of a land use and instream emulator to accurate mimic the behaviour of the SWAT model.

In order to estimate the land use and instream emulators, a large database was created using data from the original SWAT experiments. More specifically, each SWAT subcatchment was run under a climate scenario (including data on temperature, precipitation, relative humidity, solar radiation, wind speed) 66 different land use configurations, with a range of hydrological outcomes stored at daily resolution between 2020 and 2060. SWAT also stores a range of subcatchment characteristics, including subcatchment area and latitude as well as channel length and slope, and these were also stored in the database. More information on the SWAT experiments is given in Owen et al (2019a). A subset of one million observations from this database was used to estimate the land use and instream emulators.

The land use emulator of the water flow model predicts the "land use" component of daily streamflow as a function of climate and subcatchment characteristics (including land use). Specifically, a generalized additive model (Wood, 2017) was used to relate the logarithm of daily streamflow to smooth functions of precipitation and maximum temperature, plus linear functions of (log) subcatchment area and 13 land uses. For the smooth precipitation terms, a log plus one transformation was taken and lags of up to five days prior were included separately. The 13 land uses relate to SWAT classifications and include water, urban, rangeland, woodland, pasture, general agriculture, wheat, barley, canola, potatoes, sugar beet, corn and oats. In order to correspond with the NEV land use decision model categories, we assume: (i) rangeland is semi-natural grassland, (ii) pasture is temporary grassland, permanent grassland and rough grazing, (iii) general agriculture is horticulture, other crops and other farm uses, (iv) canola is oil seed rape, (v) corn is maize and (vi) oats are other cereals.

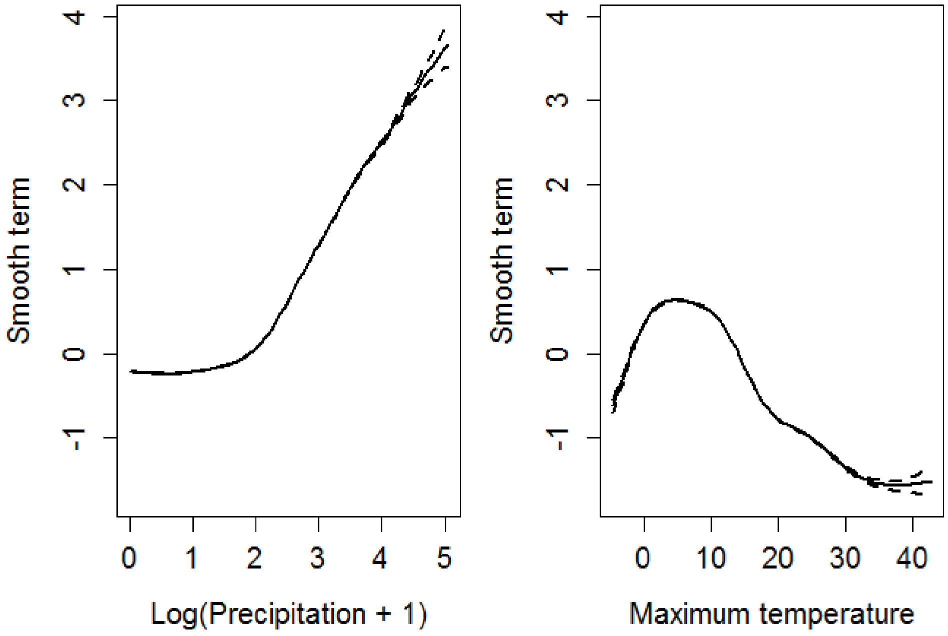

Figure 12: Smooth terms for precipitation (left) and maximum temperature (right) used in the land use emulator of daily streamflow in the NEV water flow model.

The instream emulator of the water flow model predicts the "out" component of daily streamflow as a function of the "in" component of daily streamflow. Specifically, a simple linear regression between the "in" and "out" components of daily streamflow was used, with a log plus one transformation being applied to both variables. The estimated regression fit is shown in Figure 13.

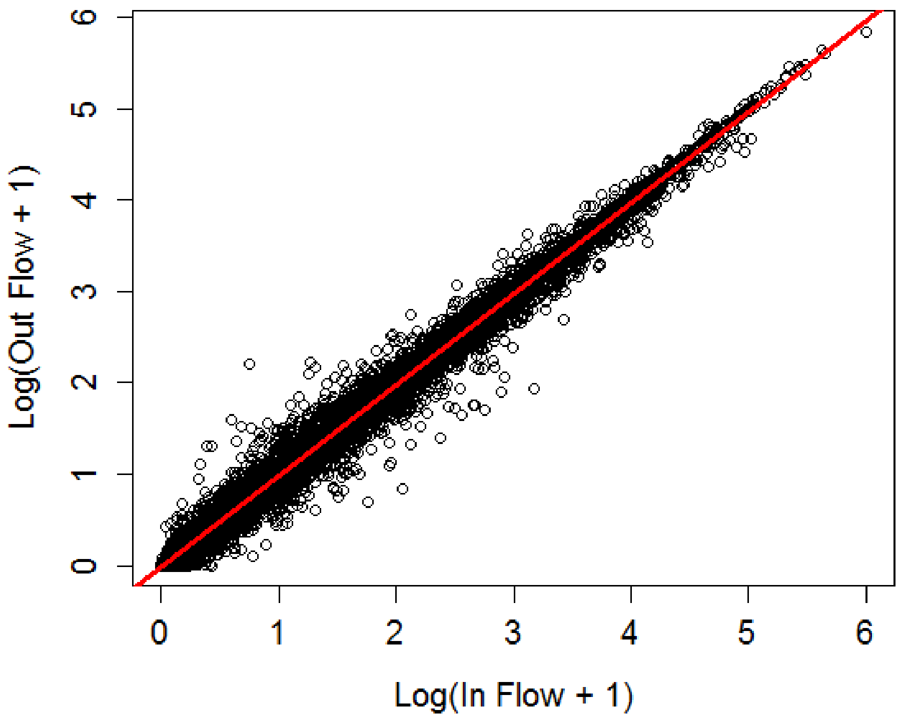

Figure 13: Regression of the "in" and "out" components of daily streamflow, used as the instream emulator in the NEV water flow model.

Using the land use and instream emulators, the NEV water flow model is able to predict the daily streamflow at the outlet of each WFD subcatchment as it responds to land use change through the catchment.

Outputs

The outputs of the NEV water flow model are predictions of the hydrograph of daily streamflow between 2020 and 2060 for each WFD subcatchment across Great Britain. Summary statistics are also calculated for each hydrograph, including the mean, median and volume of flow, as well as the 5th and 95th percentiles of flow which are used as approximations to low flow and peak flow respectively.

The NEV water flow model responds to land use change by linking with the NEV land use decision models (Section A). Land use change in the catchment has an impact on daily streamflow in directly affected subcatchments (containing the land use change) and indirectly affected subcatchments (downstream subcatchments).

In the NEV modelling suite, the outputs of the water flow model are not directly valued in an economic sense (Sections D1 and D2). However, reductions in peak flow are assumed to have an effect on flood risk and subsequently the costs to properties from flood damage. The NEV flood risk model and flood damage valuation are described in Sections B2.3 and D1.5 respectively.

B2.2. Water quality model

Purpose

The water quality model in the NEV modelling suite predicts the daily concentrations of nitrates and phosphates as they respond to land use changes through the catchment. The model is based on a range of data and models including:

- The Soil & Water Assessment Tool (SWAT, Arnold et al, 2012).
- Water quality data from the Water Quality Archive (Environment Agency, 2020b).
- Land use classification from CORINE Land Cover (Copernicus Land Monitoring Service, 2012).
- Predictions of land use on the NEV 2km^2 grid given by the NEV land use decision models (see Section A).
- Predictions of temperature and rainfall from the 2009 UK Climate Projections (UKCP09, Met Office).
- Soil characteristics from the Harmonized World Soil Database (FAO, 2009).
- Elevation and slope from Ordinance Survey Terrain 50 (OS, 2017).

The NEV water quality model operates on the system of SWAT subcatchments (Figure 9), taking predictions of land use on the NEV 2km^2 grid from the NEV land use decision models (Section A). Predictions of daily nitrate and phosphate concentrations are available between 2020 and 2060 at each subcatchment outlet point and respond to land use changes through the catchment. Summary statistics of the predicted daily nitrate and phosphate concentrations, as well as the likelihood of changing WFD ecological status, are also available.

Mechanism

Recall from Section B2 that the NEV water quality model is based on the SWAT model, which has been calibrated across much of England, Wales and Scotland. Like the NEV water flow model, the water quality model is a statistical emulator in that it provides an approximation to the SWAT model in a fraction of the time. The water quality model operates on the system of SWAT subcatchments shown in Figure 10. Following the discussions in Section B2, each of the SWAT subcatchments have been classified as either first or second order, and nitrate and phosphate concentrations in each of the subcatchments are assumed to have “land use”, “in” and “out” components. The NEV water quality model consists of a land use and instream emulator to accurately mimic the behaviour of the SWAT model. The water quality measures considered are organic nitrogen, organic phosphorus, nitrate, ammonium, nitrite, mineral phosphorus and dissolved oxygen.

In order to estimate the land use and instream emulators for each water quality measure, the SWAT experiments discussed in Section B2.1 are used, describing how hydrological outcomes in each subcatchment respond to land use change. In contrast to the water flow model – which employs a single land use and instream emulator across all subcatchments – the water quality model consists of separate land use and instream emulators for each subcatchment. The emulators are the same in structure across subcatchments but have different coefficients to accurately represent the water quality processes in each subcatchment.

The land use emulator of the water quality model predicts the “land use” components of nitrate and phosphate concentrations as a function of land use in the subcatchment. Since the land use emulators are constructed on a per-subcatchment basis, any subcatchment characteristics such as soil, elevation, slope and climate are absorbed into the coefficients of the emulator. The land use emulators are constructed as follows. Firstly, the daily time series of nitrate and phosphate concentrations are reduced in dimension using principal component analysis (Joliffe, 2011). The principal components of this decomposition are then linked to 13 land use types in the subcatchment using a regression model (see Section B2.1 for a description of the land use types). As the land use classes are proportions in the subcatchment summing to one (so-called mixture experiments) a quadratic Scheffé mixture model was used for this purpose. More information can be found in Owen et al (2019a).

The instream emulator of the water quality model predicts the “out” components of nitrate and phosphate concentrations as a function of the “in” components. A similar form is used to that of the instream emulator of the water flow model presented in Section B2.1. For each water quality measure, simple linear regression is used to link the “in” and “out” components. However, to obtain better predictive performance, lagged “in” components are also added as well as “in” components of daily streamflow and other water quality measures. Once again, more information can be found in Owen et al (2019a).

Using the land use and instream emulators, the NEV water quality model is able to predict the daily concentrations of nitrogen (organic, nitrate, ammonium, nitrite), phosphorus (organic, mineral) and dissolved oxygen concentrations at the outlet of each SWAT subcatchment as they respond to land use change through the catchment.

In addition to the predicted water quality concentrations, the NEV water quality model estimates the likelihood of switching WFD ecological status under a land use change (Environment Agency, 2020a). Firstly, the predicted concentrations of total nitrate (organic, nitrate, ammonium and nitrite) and phosphate (organic and mineral) are converted into a categorical variable using the General Quality Assessment (GQA) categories. The thresholds used for this conversion are presented in Table 3.

GQA Nitrate Concentration Categories	**GQA Phosphate Concentration Categories**
Grade 1 : <5 mg NO_3/l	Grade 1: <0.02 mg P/l
Grade 2: >5 to 10 mg NO_3/l	Grade 2: >0.02 to 0.06 mg P/l
Grade 3: >10 to 20 mg NO_3/l	Grade 3: >0.06 to 0.1 mg P/l
Grade 4: >20 to 30 mg NO_3/l	Grade 4: >0.1 to 0.2 mg P/l
Grade 5: >30 to 40 mg NO_3/l	Grade 5: >0.2 to 1.0 mg P/l
Grade 6: >40 mg NO_3/l	Grade 6: >1.0 mg P/l

Table 3: Table showing the conversion of nitrate and phosphate concentrations to General Quality Assessment (GQA) categories.

Secondly, the WFD classifications are regressed against the worst performing nutrient category: that is to say, our regressor captures the concentration category of whichever of nitrates or phosphates is found to be in the highest concentration in a WFD river water body. We call that regressor the nutrient category. Since the data only provides an ordinal categorisation of ecological status, we employ an ordered probit model (Greene, 2003) to perform the statistical analysis. The results of that analysis are reported in Table 4. This model is used to predict the probability that a river body, currently in some particular WFD ecological status class, will switch to some other class as a result of a change in nutrient category.

Parameter	**Coeff** **(*t*-stat)**	***p*-value**
Category Boundaries:		
Low boundary, κ_1	-2.0524 (-26.899)	<0.001
Middle boundary, κ_2	-1.1041 (-16.179)	<0.001
Upper boundary, κ_3	0.561 (8.625)	<0.001
Nutrient Category:		
Category 1	0	baseline
Category 2	-0.0396 (-0.518)	0.3022
Category 3	-0.3225 (-4.096)	<0.001
Category 4	-0.5695 (-7.868)	<0.001
Category 5	-0.5489 (-7.568)	<0.001
Category 6	-0.5159 (-6.827)	<0.001
N	5,282	
Log Likelihood	-5,365.4	

Table 4: Estimated parameters of the ordered probit model used to predict changes in WFD classification as a function of nutrient category in the NEV modelling suite.

Outputs

The outputs of the NEV water quality model are predictions of daily nitrogen (organic, nitrate, ammonium, nitrite), phosphorus (organic, mineral) and dissolved oxygen concentrations between 2020 and 2060 for each SWAT subcatchment across Great Britain. The mean concentration of each of the water quality measure is also calculated at decadal scale in the 2020s, 2030s, 2040s and 2050s.

The NEV water quality model responds to land use change by linking with the NEV land use decision models (Section A). Land use change in the catchment has an impact on daily concentrations of nitrates and phosphates in directly affected subcatchments (containing the land use change) and indirectly affected subcatchments (downstream subcatchments).

In the NEV modelling suite, the outputs of the water quality model are not directly valued in an economic sense (Sections D1 and D2). However, changes in nitrate and phosphate concentrations are assumed to impact the costs of water treatment facilities, and improvements in WFD ecological status are assumed to have a non-use value. The water treatment and non-use valuations are presented in Sections D1.4 and D2.2 respectively.

B2.3. Flood risk model

Purpose

The flood risk model in the NEV modelling suite predicts changes in the risk of flooding to downstream properties as a result of change in land use through the catchment. The primary input of the flood risk model is the output of the NEV water flow model (Section 2.1), that is, hydrographs of daily streamflow between 2020 and 2060 for the system of WFD subcatchments. Given a land use change in a catchment, hydrographs in all affected subcatchments are affected and can be compared to the baseline to calculate the change in flood risk. The outputs of the flood risk model is the predicted change in probability of the 1 in 10, 1 in 30, 1 in 100 and 1 in 1000 year flood events after the land use intervention. In Section **Error! Reference source not found.**.5, the predicted hanges in probability are combined with an economic appraisal of flood damage costs to produce low, medium and high estimates of the reduction in damage costs in pounds per year.

Mechanism

The NEV flood risk model is designed to take output from the NEV flow model under a land use change and predict the change in probability of the 1 in 10, 1 in 30, 1 in 100 and 1 in 1000 year flood events. In order to go from a prediction of flow under a land use change to a prediction of the change in flood risk, there are several intermediate steps which will be described in this section.

Firstly, the land use changes possible in the NEV modelling suite – that is, high level natural flood management interventions such as woodland planting – are not likely to affect the likelihood of flooding in all locations across the country. Due to this reason, the area of study is restricted to only locations with potential for natural flood management intervention. Using the Working With Natural Processes datasets (WWNP, Environment Agency, 2017), each NEV 2km^2 grid cell was classified as having potential for natural flood management or not using a binary variable. Furthermore, for those cells with potential, the maximum hectares available for natural flood management was calculated and used to constrain the model.

Secondly, we must calculate the frequency at which flood events occur in each WFD subcatchment under the baseline land use conditions. For this, the NEV water flow model was run using inputs from the NEV land use decision models to obtain hydrographs of daily streamflow for each subcatchment between 2020 and 2060. To calculate flood event frequency for each hydrograph we use peak over threshold analysis using guidelines from the National River Flow Archive (CEH, 2020). This process involves setting a threshold of flow such that a certain number of flood events per year are retained. To do this we must assume that flow events (daily flows above the threshold) correspond to flood events. A flood event is when we observe flow(s) above the threshold, and multiple flow events may be grouped into a single flood event if they occur close to one another (this is known as the event parameter, we set this to seven so that high flow events within a week or either are considered the same flood event). In the NEV modelling suite, the threshold is set to retain five flood events per year over the 40 year period.

Finally, a land use change in the catchment results in changes to the hydrograph of daily streamflow in affected subcatchments. These hydrographs can be compared to the baseline peak over threshold analysis to calculate the change in likelihood of different flood events. More specifically, we can calculate the frequency of flood events in the land use change scenario by applying the threshold from the baseline case. A common way to do this is to fit an Extreme Value Distribution (such as the Pareto distribution) to the flood events above the threshold in both the baseline and scenario and compare the distributions. In the NEV modelling suite, we take a simpler approach by comparing the number of flood events per year under the baseline and scenario to inform the change in probability of a level of flooding. The probability of a level of flooding under a land use change is estimated using Equation (B2.3.1):

$$p_s = \frac{n_s}{n_b} p_b, \qquad \text{(B2.3.1)}$$

Where: (i) p_s and p_b are the probabilities of a particular level of flooding under the land use scenario and baseline respectively, and (ii) n_s and n_b are the number of flood events per year under the land use scenario and baseline respectively. The change in likelihood of the level of flooding is given by $p_b - p_s$, with positive values indicating a reduction in flood risk. For example, imagine that woodland planting has resulted in the number of flood events per year to decrease from 5 to 4. The probability of the 1 in 30 flood event, which by definition is 1/30 under the baseline, is predicted to decrease to (4/5) * 1/30 ~= 1/38. In other words, this level of flooding is now expected approximately once every 38 years. In the NEV modelling suite, four levels of flooding are considered to align with the Risk of Flooding from Rivers and Seas dataset (Environment Agency, 2019): the 1 in 10, 1 in 30, 1 in 100 and 1 in 1000 year floods.

Outputs

The outputs of the NEV flood risk model are predictions of the change in likelihood of the 1 in 10, 1 in 30, 1 in 100 and 1 in 1000 year floods. This information is available for all subcatchments affected by a land use change in the catchment (from the NEV land use decision models) and is estimated using predictions of flow between 2020 and 2060 (from the NEV water flow model). The change in flood risk is valued economically by linking to the number of properties at risk of flooding and the change in flood damage costs. This valuation is presented in Section D1.5.

B3. Biodiversity Models

The NEV modelling suite includes two biodiversity modules whose aim is to predict the species diversity and their response to climate and land use changes. The first model targets wild insects that provide pollination services, and the second module is focussed on a list of 100 species of conservation priority in the UK. Details on the two models are presented in Sections B3.1 and B3.2 respectively.

B3.1. Pollinator diversity model

Purpose

The NEV pollinator diversity model predicts the diversity of 472 pollinator species as they respond to climatic and land cover change. The model is based on a range of data and models including:

- A species modelling framework developed by UCL (Pearson et al, 2004).
- Species presence data from Rasmont et al (2015) and range maps from the Global Biodiversity Information Facility (GBIF, 2017) and the International Union for Conservation of Nature (IUCN, 2019).
- Bioclimatic variables from WorldClim (2019).
- Land use data from the NEV land use decision models (Section A).

The NEV pollinator diversity model operates on the NEV 2km^2 scale in combination with the NEV land use decision models (Section A). Predictions of the diversity of 472 pollinator species and total species richness are available at decadal scale for the 2020s, 2030s, 2040s and 2050s.

Mechanism

The pollination diversity model included in the NEV modelling suite is provided by UCL and based on the hierarchical modelling approach of Pearson et al (2004). It predicts the presence or absence of 472 pollinator species on a per-cell basis depending on two factors: (i) if the climate in the cell is suitable for the species, and (ii) if the land use in the cell is suitable for the species.

In the first stage, a climatic suitability surface is calculated for each pollinator species at the European scale, predicting the presence or absence of the species based on climate alone. This is generated using a climatic envelope model, relating the presence of each species to 19 bioclimatic variables (WorldClim, 2019) using logistic regression. Climatic suitability for each species is calculated for two Representative Concentration Pathways, RCP6.0 and RCP8.5 (Van Vuuren, 2011). Estimating the climatic suitability surface at European scale allows for possible introduction of species into Great Britain under climate change.

In the second stage, a land use suitability surface is calculated for each pollinator species at the Great Britain scale, predicting probability of occurrence of the species based on land use alone. This is computed using a species distribution model, linking the presence of each species to 25 land use types using logistic regression. The land use types relate directly to the output of the NEV land use decision models. The predicted probability of occurrence of each species is converted to presence/absence using a threshold calculated on a per-species basis.

Finally, the predictions from the species distribution model for each species are masked by the climatic suitability surface (at Great Britain scale). In this way, areas where species presence was predicted under land use conditions alone ruled out (converted to absences) as the climate is not suitable for the species.

Outputs

The outputs of the NEV pollinator species diversity model are the predicted presence or absence of the 472 pollinator species for each of the NEV 2km^2 grid cells available at decadal scale in the 2020s, 2030s, 2040s and 2050s. The species richness, that is the number of species predicted to be present out of 472, is also calculated in each cell as a metric of biodiversity across the 472 pollinator species. This is calculated by summing the predicted presence/absence across the 472 species on a per-cell basis.

In the NEV modelling suite, the pollinator species output is not directly valued in an economic sense (Sections D1 and D2). However, change in the pollinator species richness is assumed to affect two ecosystem services, which can be valued: (i) the horticultural crop industry, in particular the costs horticultural farmers pay for commercial pollination services, and (ii) the value people get from seeing wild insect pollinators and wild flower meadows in the natural environment. The value of pollinator species to the horticultural industry and wild flower meadows are described in Sections D1.6 and D2.1 respectively.

B3.2. Priority species diversity model

Purpose

The NEV priority species diversity model predicts the diversity of 100 priority species as they respond to climatic and land cover change. The model is based on a range of data and models including:

- A species modelling framework developed by the JNCC (Wright et al, 2019).
- Species presence data from the National Biodiversity Network (NBN Atlas, 2019).
- Bioclimatic variables from WorldClim (2019).
- Soil characteristics from the Harmonized World Soil Database (FAO, 2009).
- Land use data from the NEV land use decision models (Section A).

The NEV priority species model operates on the NEV 2km^2 scale in combination with the NEV land use decision models (Section A). Predictions of the diversity of 100 priority species and total species richness are available at decadal scale for the 2020s, 2030s, 2040s and 2050s.

Mechanism

The NEV priority species model aims to capture taxonomic diversity across a range of broad habitat types for a series of 100 selected species of priority conservation in the UK, which have been selected from the Biodiversity Action Plan (JNCC, 2007). Criteria for the species inclusion were: (i) availability of species data in the past 20 years, (ii) wide spatial distribution across the UK, (iii) high resolution of the spatial records (2km to 100m precision), and (iv) (partial preference for) charismatic animals for audience engagement. The final species list is represented by the following taxonomic groups (number of species included):

- Terrestrial mammals (14)
- Birds (17)
- Vascular plants (38)
- Invertebrates (25, of which 10 are butterflies)
- Lichens (5)
- Herptile (1)

Species presence data were downloaded from National Biodiversity Network (NBN Atlas, 2019).

The NEV priority species model is based on a species distribution modelling framework developed by the JNCC (Wright et al, 2019). The diversity (measured using probability of occurrence) of each species is predicted as a function of climate, topography, land use and soil characteristics using an ensemble of seven popular modelling strategies: Bioclim, boosted regression trees, general linear model, generalised additive model, kernel support vector machine, Maxent, and random forest. The modelling framework takes an iterative approach, with the best model selected according to the Receiver Operating Characteristic curve over 100 repetitions with different subsets of the data. The final model for each species is an average of the predictions of probability of occurrence from the 100 best models. More information on the JNCC modelling framework can be found in Wright et al (2019).

When used at the Great Britain scale for all 100 species, the JNCC modelling framework becomes infeasible to run due to time constraints. The NEV priority species model implemented in the NEV modelling suite is actually a fast running version of the JNCC framework, known as a statistical emulators (O'Hagan, 2006). A single emulator for each species is used to approximate the JNCC modelling framework, and this is a quadratic regression model of the species probability of occurrence against the bioclimatic, topographic, land use and soil variables. More information on the formulation of the emulator is given in Owen et al (2019b).

Outputs

The outputs of the NEV priority species model are the predicted probability of occurrence of the 100 priority species for each of the NEV 2km^2 grid cells available at decadal scale in the 2020s, 2030s, 2040s and 2050s. The species richness, that is the number of species predicted to be present out of 100, is also calculated in each cell as a metric of biodiversity across the 100 priority species. This is calculated by summing the predicted probability of occurrence across the 100 species on a per-cell basis.

In the NEV modelling suite, the priority species output is not valued in an economic sense (Sections D1 and D2). Rather, the species diversity can be used to constrain the model, for example, land use change is not permitted in grid cells where the priority species richness would decline.

C. Recreational Demand Model

Purpose

The recreational demand model in the NEV modelling suite predicts changes in day-trip recreational activity as a result of changes in land use. It is based on a range of models and data including:

- The Outdoor Recreation Valuation tool (ORVal, Day and Smith, 2016; Day and Smith, 2018).
- The ORVal greenspace map (Day and Smith, 2016; Day and Smith, 2018).
- Data on recreational activity from the Monitor of Engagement with the Natural Environment survey (MENE, Natural England, 2018).
- Predictions of land use on the NEV 2km^2 grid given by the NEV land use decision models (see Section A).

The NEV recreational demand model operates on the NEV 2km^2 scale in combination with the NEV land use decision models (Section A) by aggregating information from the ORVal greenspace map. Predictions of the number of visits to greenspace areas in each of the 2km^2 grid cells are available on an annual basis between 2020 and 2060.

Mechanism

The NEV recreational demand model is based on the Outdoor Recreation Valuation tool (ORVal, Day and Smith, 2016; Day and Smith, 2018), a statistical model that can be used to predict the number of visits that are made by adult residents of England to different greenspaces. The model adjusts its predictions according to a number of factors, most particularly the socioeconomic characteristics of people, the day of the week, the month of the year, the attributes of a greenspace and the availability and qualities of alternative greenspaces.

The model is estimated from data collected in the Monitor of Engagement with the Natural Environment (MENE) survey. The MENE survey provides information on the recreational behaviour of a large, representative sample of adults (over 16 years of age) resident in England. Over the course of a week, each respondent records when they visited greenspaces and for one randomly-selected visit the exact location of that visit.

The fundamental assumption of the model is that the choices observed in the MENE data are somehow welfare-maximising. By ‘welfare’ we are referring to the sense of well-being or utility that an individual feels from their experiences. So when an individual is observed to have taken a trip to enjoy greenspace, we assume that the welfare of taking a trip at that time exceeds the welfare of doing something entirely different (say watching the TV or going shopping). Likewise when an individual is observed to have chosen a visit to one particular recreational site, we assume that the welfare derived from that visit exceeds the welfare that would be enjoyed from visiting an alternative site. The model seeks to use that information to build a function which describes the welfare an individual gets from making different recreational choices. Indeed, it is this welfare function that is used in the NEV modelling suite to estimate the welfare values generated by different landcovers experienced at open access greenspaces.

The NEV recreational demand model works in conjunction with the ORVal greenspace map, a detailed spatial dataset compiled through the combination and manipulation of a large number of primary data sources that describes the location and characteristics of accessible greenspace across England. Construction of the ORVal greenspace map is provided in Day and Smith (2016).

The ORVal greenspace map identifies some 129,575 greenspace sites in England & Wales that could form the focus of a recreational trip. Those greenspace sites come in three basic forms;

- Parks which consist of areas of accessible greenspace within well-defined boundaries over which visitors usually have freedom to wander at will.
- Paths which consist of accessible, walkable routes that pass through the landscape, often traversing a variety of different greenspaces and tending to restrict visitors to defined routes of passage.
- Beaches.

Each recreation site is described by various aspects of its physical characteristics; particularly the site’s dimensions, landcovers, designations and points of interest.

The NEV recreational demand model can be used to estimate and predict visits to greenspaces. In particular, the model allows us to predict how likely it is that an individual will take a trip to a particular greenspace on a particular day. That likelihood differs according to the socioeconomic characteristics of the person, the attributes and proximity of the greenspace and the attributes and proximity of alternative recreational greenspaces.

To generate estimates of the annual number of visits to a particular greenspace we draw on data from the 2011 UK census and on population estimates for 2016. For each of the more than 32,844 Lower Super Output Areas (LSOAs) in England, that data allows us to estimate the number of adults in each of socioeconomic group (where those groups are social grades AB, C1, C2, and DE). Visitation predictions for a particular greenspace are reached through the following set of calculations:

- For each socioeconomic group in an LSOA, we use the model to calculate the probability of taking a trip to the focus greenspace on a particular day at a particular time of year.
- Adding those probabilities up for each individual from each socioeconomic group in an LSOA provides an estimate of the expected number of visits from that LSOA to that greenspace on that day.
- Given visitation varies across months and days of the week, we reach an annual visitation figure from an LSOA by summing expected visitation numbers calculated for each different day of the year.
- Finally we repeat those calculations for each of the 32,844 LSOAs in and sum the results to arrive at a final prediction of the annual number of visits to a particular greenspace.

Estimating visitation rates for a new recreation site simply entails performing those calculations for the new site. Likewise, In order to estimate changes in visitation that arise from altering the attributes of a particular greenspace, we compare visitation levels estimated before and after the change in attributes.

In addition to predictions of annual visitation, the ORVal recreation demand model also returns predictions of how those visits are divided up across the two different modes ‘by car’ or ‘on foot’.

Finally, the recreation visits and values presented in the NEV modelling suite tool are based on aggregating those quantities for each greenspace to the NEV 2km^2 grid. More information can be found in Day et al (2019a).

Outputs

The outputs of the NEV recreational demand model are the predicted visits to different recreational greenspace areas (parks, paths and beaches) from people in different socioeconomic classes (AB, C1, C2, and DE) and using transport methods (by car and on foot). Predictions are available on an annual basis between 2020 and 2060 for each cell in the NEV 2km^2 grid. The recreational demand model also predicts changes in visitation figures as a result of land use change in combination with the NEV land use decision models (Section A).

Information on the welfare value of greenspace areas is also available. More detail on the economic valuation of recreational activity is presented in Section D1.7.

D. Economic Valuation

As suggested by its name, NEV not only models changes in physical flows through environmental systems but also estimates the value of the changes in ecosystem services that arise as a consequence. In that sense, NEV is a tool firmly grounded in the natural capital paradigm. While we shall not provide a detailed exposition of the natural capital paradigm here, it is worth noting a few key elements of the approach.

First, the natural capital paradigm draws a clear distinction between environmental processes and the goods and services that flow from those processes and are enjoyed by humans. These latter are often referred to as ecosystem services, though economists tend to favour the more precise descriptor; final environmental goods and services. What distinguishes an ecosystem service, therefore, is that it is an output of the environment that is experienced by humans in some way that changes their levels of well-being. This distinction is clearly maintained in the NEV modelling suite. Some illustrative examples include;

- NEV models the environmental processes that lead to changes in surface water quality but those only deliver value where they impact on humans. In this case, one of those impacts will be to reduce processing costs for the water industry at locations where they abstract water for public water supply. Improvements to river water quality in other locations will not deliver this ecosystem service flow.
- NEV models changes in the species richness of wild pollinators associated with changing patterns of land use. One ecosystem service resulting from those changes arises in agriculture through increasing yields from crops that are insect-pollinated (or decreasing reliance on commercial pollinators). Accordingly, values are only realised when wild-pollinators increase in areas previously in deficit that are close to mainly horticultural farms that produce insect-pollinated crops.
- NEV models the relationship between landcovers in the countryside and recreational use of the outdoors. The value that the environment delivers through this route depends on how close the land experiencing change is to where people live and whether that land is accessible for recreation. Changes in landcovers in accessible or very remote locations will not deliver this ecosystem service.

Second, value in the Natural Capital approach is a measure of the change in well-being experienced by people. In particular, it refers to the concept of ‘economic value’ a money measure of that change in well-being. Imagine an individual experiencing an improved flow of ecosystem services. In that case, the money measure is defined as the maximum amount of money that individual would be willing to give up in order to secure the benefits that they would enjoy from that improvement. That measure is simply termed Willingness to Pay or just WTP. Alternatively, if an individual were to experience a loss in ecosystem services then the monetary measure is given by the minimum amount of money they would be willing to accept in compensation for those losses. That measure is termed Willingness to Accept or just WTA. These measures of economic value are useful in project appraisal because they can be added across individuals to assess the total economic value of changes in ecosystem services. Moreover those total values can be directly incorporated into a wider cost benefit analysis judging the overall merits of a project or policy.

The NEV modelling suite remains faithful to this definition of economic value using measures of WTP and WTA estimated through numerous different methods of non-market valuation. In this section, we review range of ecosystems services for which NEV provides value estimates and described the methods used in estimation of those values.

One final general comment to make about economic valuation in NEV concerns time. Changes in environmental systems may play out over time in ways that mean that the flows of economic values may be experienced over many future periods. One example would be the costs and benefits arriving from the establishment of woodland. While the upfront establishment cost of planting the woodland would be experienced now, the benefits, for example in the form of timber products, may only be realised several decades in the future. To make those costs and benefits experienced at different times comparable, NEV adopts standard practices of discounting. Costs and benefits experienced in the future are down-weighted with the level of down-weighting increasing with greater distance in time. Following guidelines provided by H.M. Treasury Greenbook NEV uses a discount rate of 3.5%.

D1. Economic Valuation Methods: Market, Avoided Damages & Revealed Preference

In general, methods for the economic valuation of ecosystem services can be divided into two groups;

- Methods that use real world observations as a guide to the economic value individuals attribute to changes in flows of ecosystem services
- Methods that use structured questionnaires in order to ask individuals directly how greatly they value changes in flows of ecosystem services.

In this section we review values used in NEV that are based on observed behaviour.

Perhaps the simplest valuation method used in NEV is that based on changes in profitability of commercial firms. In economics, a firm is an organisation dedicated to producing some good or service. In most cases, the purpose of that activity is to make profits, profits that are shared between the individuals who have an ownership stake in the firm. So every extra pound of profit made by a firm, is an extra pound of money received by a household somewhere in the economy. The economic value of a pound is rather easy to estimate; the maximum an individual would be willing to pay in order to receive one extra pound, is just one pound. In other words, the economic value of an intervention which changes a firm’s profits can be measured simply as that change in profits. The tricky bit is finding out how a firm’s profits are impacted by an intervention that changes the level of ecosystem services that they enjoy. In NEV we use this change in profitability approach to estimate economic values for;

- *Loss of Agricultural Land*: Changes in farm profits that arise when farmland is reverted to other land uses.
- *Gain in Woodland*: Profits (or losses) that are realised from the production of timber on land committed to growing trees
- *Change in Wild Pollinators*: Changes in the profits of horticultural farms growing crops that can benefit from increases in wild pollinator species richness
- *Change in River Water Quality*: Changes in the profits of water companies who enjoy reductions in water treatment costs as a consequence of improvements in water quality.

A second set of valuation techniques used in NEV focus on ecosystem services that arise from reducing the risks of future damages. The assumption here is that the cost of those damages is a reasonable approximation to the compensation individuals would deem equivalent to the loss in well-being experienced from those damages (their willingness to accept). Economic values based on avoided damages are used for the valuation of;

- *Changes in Carbon Sequestration*: Changes in emissions of carbon or its sequestration in soils and plants contribute to changes in the damages caused by future climate change. The value of the damages avoided when carbon is sequestered are captured in the social cost of carbon estimated used in NEV.
- *Changes in Flood Risk*: NEV models the relationship between landcover and the frequency of fluvial flood events of different severities. The value of reducing those flood risks is captured by the changes in the expected damage costs associated with floods.

A final valuation technique used in NEV is termed revealed-preference valuation. These methods use some observable aspect of individuals' behaviour in order to indirectly deduce how greatly they value an ecosystem service. NEV used a revealed preference method to estimate changes in the value individuals enjoy from recreation as a result of changes in landcovers at outdoor recreation sites. In brief, the method examines the costs in money and time that individuals invest in trips to the outdoors and, through methods of statistical analysis, uses those costs to work out how greatly individuals value access to outdoor recreation sites with different environments.

D1.1. Food valuation

In this section, we describe how we calculate the profits from farm production using the outputs of the farm management model described in Section A.1. Recall that the output of the farm management model include the hectares of crops (wheat, winter barley, spring barley, oil seed rape, potatoes, sugar beet and other crops) and livestock (dairy cattle, beef cattle and sheep).

As is standard practice in agricultural economics, we estimate farm profitability using farm gross margins, defined as the difference between revenues and variable costs. This is a good measure of farm self-sufficiency but does not take into account fixed costs such as labour and machinery. Our definition of farm gross margin also does not include decoupled subsidies such as the single farm payment (now called the basic payment scheme).

In the NEV modelling suite, the farm gross margin of crops and livestock are calculated in different ways. For crops, we first calculate the revenue of each crop by multiplying the predicted hectares of the crop within the cell by its price and yield taken from data. The values for price and yield used in the NEV modelling suite are taken from the John Nix Pocketbook and are displayed in Table 5. The yields and prices are assumed to be fixed over time and space, and the values for the other crop category are assumed to take the values of wheat. To convert from crop revenue to crop farm gross margin, for simplicity we multiply by 0.45. This assumption is based on the fact that the ratio of farm gross margin to crop revenue is remarkably stable over time, staying between 42-45% over the last 10 years (Defra, 2018a).

Crop	Yield (tonnes/hectare)	Price (£/tonnes)
Wheat	8.19	110
Winter barley	6.74	102
Spring barley	5.57	110
Oil seed rape	3.53	228
Potatoes	37.1	128
Sugar beet	60.7	29
Other	8.19	110

Table 5: Crop yields and prices used in the NEV modelling suite, taken from the 2018 John Nix pocketbook.

For livestock, a different approach is taken. Historical data from the John Nix pocketbook is used to determine a relationship between farm gross margin per head of livestock and price. For dairy, the following relationship is estimated: farm gross margin/head of dairy cattle = 183 + 20 * milk price (in pence/litre). A similar relationship was not found for beef cattle and sheep, so farm gross margins from the John Nix pocketbook are taken: farm gross margin/head of beef cattle = £70 and farm gross margin/head of sheep = £9.

The total profitability of the farm is given by the sum of the farm gross margins for individual crops (wheat, winter barley, spring barley, oil seed rape, potatoes, sugar beet and other) and livestock (dairy cattle, beef cattle and sheep). The NEV modelling suite outputs the gross margin of the individual crops and livestock, as well as the total farm, on an annual basis between 2020 and 2060. Annual profits in this period are also expressed in Net Present Value (NPV) and equivalent annuity terms using a constant social discount rate of 3.5%.

D1.2. Timber valuation

In this section, we describe how we calculate the profits from forestry using the outputs of the forestry management model described in Section A.2. Recall that the output of the forestry management model are predictions of the volume of timber in each 2km^2 grid cell per year for four planting scenarios.

To calculate the economic profitability of forests, the predicted timber volume is combined with the Forest Investment Appraisal Package (Forestry Commission, 2013). This linkage brings in timber prices (Lavers and Moore, 1983) to allow analysis of revenues and comparison with management costs (for activities such as mounding, planting, staking, insurance, drainage, weeding, spraying etc.,) under a variety of silvicultural systems. The timber prices for Pedunculate Oak and Sitka Spruce used in the forest management model are shown in Figure 14.

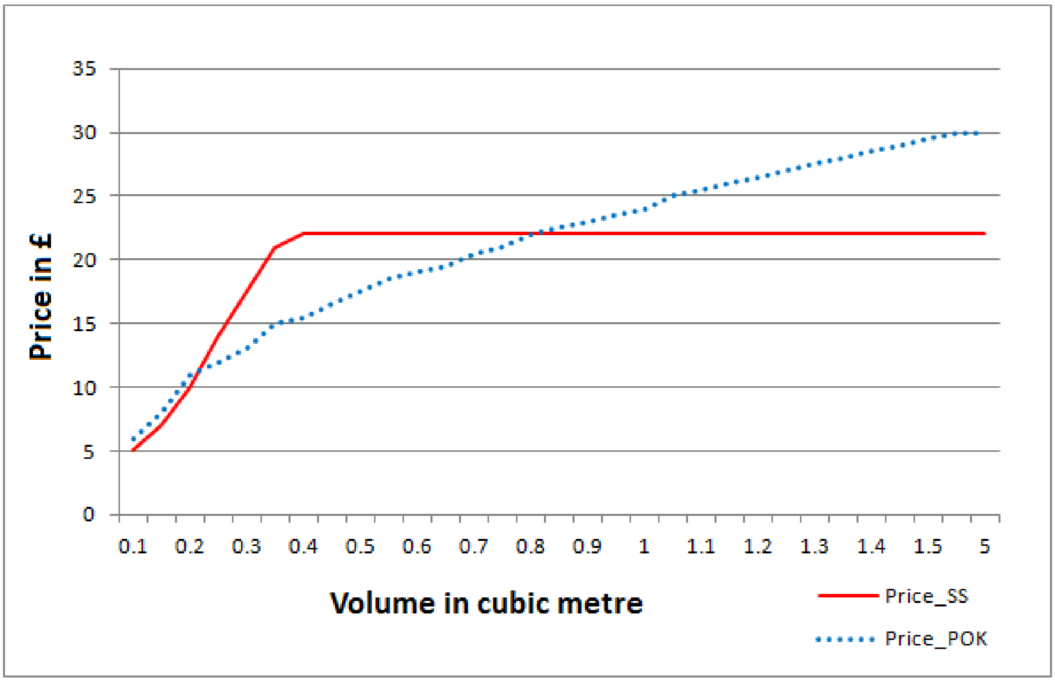

Figure 14: Price per volume of timber (cubic metres) for Sitka Spruce (red) and Pedunculate Oak (blue).

Timber profits are calculated as the difference between revenues (timber volume multiplied by timber price) and costs. Relevant management costs include both variable costs and exclude fixed costs, which are expected to be significant only in the early years of land use conversion. Given the time delays between costs and revenues, as well as the differing rotation periods of the tree species, profits are calculated in NPV and annuity equivalent terms using a constant social discount rate of 3.5%. In the NEV modelling suite, these measures of profitability are calculated for the four different planting scenarios described in Section A.2.

D1.3. Carbon valuation

In this section, we describe how greenhouse gas emissions and sequestration from agriculture, forestry and soil resulting from change in land cover and land use are translated into changes in social value. Recall that quantities of greenhouse gas sequestration are generated from the agricultural emissions (Section B1.1), forest timber sequestration (Section B1.2) and soil sequestration (Section B1.3) models. For the agricultural emissions model, quantities from different agricultural land uses and livestock are given as flows per year between 2020 and 2060. For both the forest timber and soil sequestration models, quantities from four different woodland planting scenarios are given as flows per year from 2020, assuming a continual planting rotation. Sequestration and emission of greenhouse gases are given as positive and negative quantities respectively to correspond with a benefit and cost to society, in expressed in tonnes of carbon dioxide equivalent for comparison.

Following standard practice in environmental economics, we value the quantity of carbon sequestered or emitted using the social cost of carbon (Tol, 2013). The social cost of carbon, given in pounds per tonne of carbon dioxide equivalent, is plotted in Figure 15.

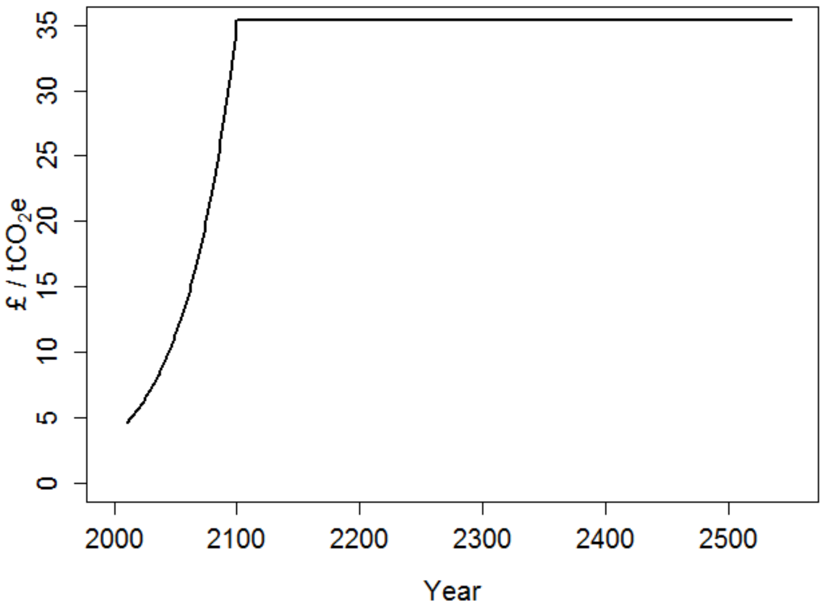

Figure 15: Social cost of carbon (£/tCO_2e) between 2010 and 2551. Source: Tol (2013)

To calculate the economic value of carbon sequestration, the quantity of carbon sequestrated is multiplied by the social cost of carbon in the relevant year and converted into NPV and annuity equivalent terms using a constant social discount rate of 3.5%. The period over which the discounting applies differs between the agricultural, forestry and soil quantities. For the agricultural emissions, the annual quantities of greenhouse gas sequestration are discounted between 2020 and 2060. For forestry sequestration, we discount over one rotation of tree planting. Finally, for soil sequestration, we discount over two rotations of tree planting to account for the longer term fluctuations in carbon storage.

D1.4. Water treatment valuation

In this section, we describe how the outputs of the NEV water quality model are used to estimate changes in water treatment costs as a consequence of changes in nutrient concentrations. Recall that the outputs of the water quality model are predictions of nitrate (organic, nitrate, ammonium and nitrite) and phosphate (organic and mineral) concentrations at daily resolution between 2020 and 2060. For simplicity in the valuation of water treatment costs, we make use of decadal averages of the total nitrate and phosphate concentrations in the 2020s, 2030s, 2040s and 2050s.

In order to relate changes in water quality to changes in water treatment costs, we must estimate a number of quantities: (i) the locations in which water abstraction takes place across the country, (ii) how much water is abstracted at those locations, and (iii) the treatment costs of abstracted water.

We will address the first two quantities first, that is, where and how much water abstraction is taking place spatially across the country. For this purpose, we obtained data under licence from the Environment Agency (2012) containing information on all live water abstraction licences in England and Wales. This dataset includes the point locations of water abstractions as well as the maximum annual and daily quantities of abstraction permitted under the licence. In the NEV modelling suite, the maximum annual abstraction for public water supply (in cubic metres) has been processed and aggregated to the NEV 2km^2 grid and SWAT subcatchment scale.

Secondly, the costs of treating abstracted water for public consumption must be estimated. For this purpose, case studies from the United States Environmental Protection Agency (EPA, 2015) were used. A drawback of this approach is that the case studies refer to wastewater treatment rather than treatment of abstracted water, so the assumption is made that the procedures for removing nitrates and phosphates are similar across the two processes. By taking the median value across 12 case studies in the United States, the cost per milligram per litre change in total nitrate per cubic metre of water abstracted is estimated to be £0.0006. In the NEV modelling suite, this is assumed to also hold true for changes in total phosphate.

With that information in place, the valuation of water treatment costs works as follows. Firstly, a land use change is made for one or more NEV 2km^2 grid cells using the NEV land use decision models. This change is then aggregated to all affected SWAT subcatchments, and the NEV water quality model is used to predict changes in nitrate and phosphate concentrations downstream. Changes in total nitrate and phosphate concentrations are then translated to changes in water treatment costs at all downstream subcatchments which have water abstraction using the costs estimated above. In the NEV modelling suite, it is possible for a land use change on a single 2km^2 grid cell to affect water quality in several downstream subcatchments and in turn, the water treatment costs of several abstraction points.

D1.5. Flood damage valuation

In this section, we describe how the outputs of the NEV flood risk model are used to estimate changes in expected damage costs as a consequence of changes in flood risks. Recall that the outputs of the flood risk model are predictions of the change in likelihood of the 1 in 10, 1 in 30, 1 in 100 and 1 in 1000 year floods for subcatchments which have been affected by land use change. In order to translate from changes in flood risk to changes in expected damage costs to properties, two quantities must first be calculated: (i) the number of residential and non-residential properties at risk of flooding in each subcatchment, and (ii) the economic cost to those properties from different magnitudes of flooding.

Step (i) requires a spatial dataset for Great Britain showing areas affected by different magnitudes of flooding. Due to data availability, we must use different data sources for England/Wales and Scotland. For England and Wales we use the Risk of Flooding from Rivers and Seas dataset (Environment Agency, 2019), which gives the number of residential and non-residential properties at risk from four different levels of flooding at postcode resolution. The four risk levels are high (at risk from 1 in 10 year flood), medium (at risk from 1 in 30 year flood), low (at risk from 1 in 100 year flood) and very low (at risk from 1 in 1000 year flood). For Scotland we use the Mapping Flood Disadvantage in Scotland report (Kazmierczak et al, 2015), which gives the number of residential and non-residential properties at risk from two levels of flooding on spatial units known as "data zones" (compact areas of 500-1000 residents containing household with similar social characteristics). The two risk levels are medium (at risk from 1 in 30 year flood) and low (at risk from 1 in 200 year flood). Using these two datasets, we estimate the number of residential and non-residential properties in each subcatchment at risk from different levels of flooding by aggregating the information at the postcode (England & Wales) and data zone (Scotland) level to the WFD subcatchments.

Step (ii) requires an appraisal of the damage costs associated with different levels of flooding. For this purpose we use the 'Multi-Coloured Manual' (Penning-Rowsell et al, 2013). In applying damage costs across Great Britain, a number of assumptions must be made. For all damage costs we assume residential homes and non-residential properties are of average size and age, and have received flood warning. The damage costs used for residential and non-residential properties for very low, low, medium and high flood depths are shown in Table 6. To scale up non-residential properties (which are expressed as £/m^2), we assume a plot size of 200m^2 which is the average size of A1 retail units given by the City of London Corporation[2]. Finally, coastal subcatchments are given a damage cost of zero since the NEV water flow model is only able to predict river flooding.

Flood depth	Residential cost (£/household)	Non-residential cost (£/m^2)
Very low	34,455	636
Low	37,808	964
Medium	42,846	1,265
High	50,138	1,509

Table 6: The residential cost (£/household) and non-residential cost (£/m^2) of four flood levels used in the NEV modelling suite. Derived from the Multi-Coloured Manual (Penning-Rowsell et al, 2013).

Steps (i) and (ii) provide an estimate of the total damage cost for the 1 in 10, 1 in 30, 1 in 100 and 1 in 1000 year floods for both residential and non-residential properties in each WFD subcatchment. Denote these d_{10}, d_{30}, d_{100} and d_{1000} respectively for each subcatchment. These quantities were sense-checked against the economic cost of the 2015/2016 winter floods (Environment Agency, 2018) using the Historic Flood Map (Environment Agency, 2020c).

Combining the damage costs with the change in likelihood of the 1 in 10, 1 in 30, 1 in 100 and 1 in 1000 year floods (provided by the NEV flood risk model) allows the estimation of the reduction in expected damage costs as a result of land use change. Figure 16 demonstrates how the reduction in expected damage costs is calculated in the NEV modelling suite. In principle, the expected damage

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[2] https://www.struttandparker.com/knowledge-and-research/does-size-matter-changing-shape-retail

cost under the baseline or a scenario is given by the area underneath the probability-damage cost curve. However, predictions of only four points along this curve are given by the NEV flood risk model. The expected damage cost under the baseline and scenario is approximated as the rectangular areas below the four predicted points. Note that this assumes that there are no damage costs for flood events more likely than the 1 in 10 year flood. Using this approximation, the reduction in expected damage costs as a consequence of a land use change is given by the area of the coloured rectangular areas shown in Figure 16. Due to the uncertainty in natural flood management interventions affecting the likelihood of rare flood events, a low, medium and high estimate of the reduction in expected damage costs is given. The low estimate assumes that the land use change affects the likelihood of the 1 in 10 and 1 in 30 year floods and is calculated by summing the green areas in Figure 16. The medium estimate assumes that the 1 in 100 year event is also affected, so is given by the summation of the green and orange areas. Finally, the high estimate assumes that the 1 in 1000 year event is also affected and is computed by adding the red, orange and green areas.

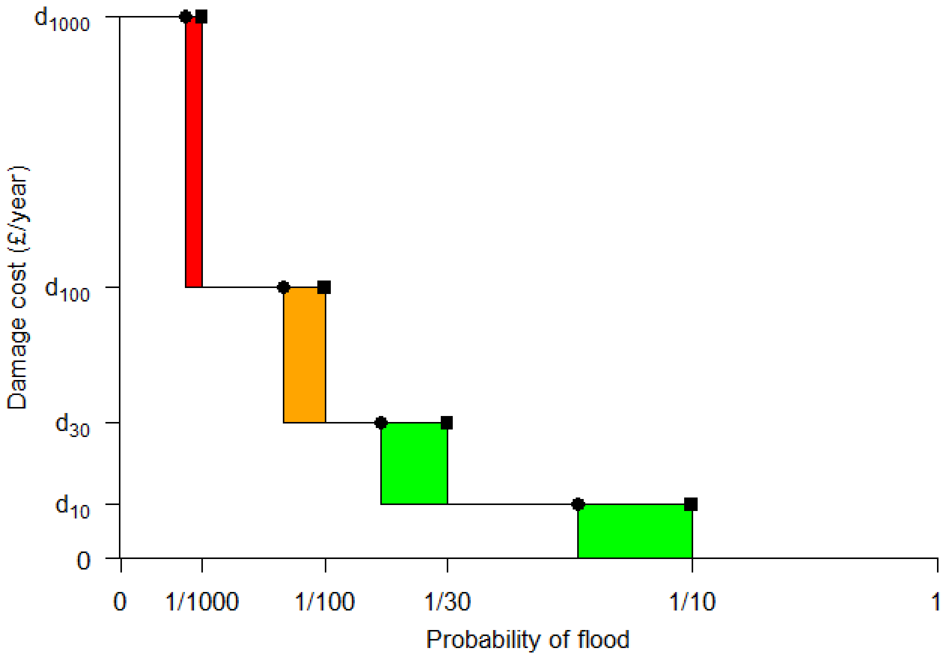

Figure 16: The calculation of the reduction in expected flood damage costs as a result of land use change used in the NEV modelling suite. Four predictions are available under the baseline (squares) and a land use change (circles). The expected damage cost is given by the summation of the coloured areas. Three quantities are returned: (i) low, considering the 1 in 10 and 1 in 30 year flood reductions (green), (ii) medium, the low estimate also considering the 1 in 100 year flood reduction (orange), and (iii) high, the medium estimate also considering the 1 in 1000 year reduction (red).

D1.6. Pollination service valuation

In the NEV modelling suite, we value the contribution of wild insect pollination to the horticultural sector using the outputs of the NEV pollinator species diversity model (Section B3.1). Specifically, we focus on crops within the horticultural sector which rely primarily on insect pollination, whether that be through commercial beehives (i.e. honeybees) or wild insect pollinator species. The aim is to estimate the change in value of pollination services from wild insects given a land use change (and hence a change in the number of pollinator species), and the impact that land use decisions might have on the provision of wild insect pollination services for the horticultural sector.

We make the assumption that the horticultural farmer incurs a cost of bringing in commercial pollination in cases where wild insect pollination does not account for all pollination services, in order to maximise their yield and value. The change in value of insect pollinated horticultural crops as a result of an increase or decrease in wild insect pollination can be estimated on a per-cell basis using Equation (D1.6.1):

$$V_c^i = V^i(p_s^i - p_b^i), \qquad \text{(D1.6.1)}$$

Where: (i) V_c^i is the change in value of insect pollinated horticultural crops as a result of a change wild insect pollination levels in cell i, (ii) V^i is the estimated market value of insect pollinated horticultural crops under full pollination services in cell i, (iii) p_s^i is the proportion of pollination services provided by wild insects under a land use change in cell i, and (iv) p_b^i is the proportion of pollination services provided by wild insects in the baseline in cell i.

In order to use Equation (D1.6.1), we must estimate two quantities:

- The market value of insect pollinated horticultural crops under full pollination services for all cells, i.e. $V^i, i = 1, \ldots, n$, where n is the number of cells of interest.
- The diversity of wild insect pollinator species required for full pollination services (i.e. no need for commercial pollination).

Firstly, the market value V^i of insect pollinated horticultural crops under full pollination services in cell i is estimated using Equation (D1.6.2):

$$V^i = h^i \times p \times GM, \qquad \text{(D1.6.2)}$$

Where h^i is the hectares of horticultural land in cell i, p is the proportion of horticultural land containing crops which depend on pollination by insects (either wild or commercial) and GM is the value of insect pollinated horticultural crops, expressed as a gross margin (£ ha^{-1}). The hectares of horticultural land in each cell in known from the NEV farm management model (Section A.1). The proportion of horticultural land containing crops pollinated by insects is estimated to be $p = 0.245$ using Horticultural Statistics (Defra, 2018b) and Klein et al (2007, Appendix 1 & Appendix 2). The gross margin (*GM*) of insect pollinated horticulture is calculated to be the average of the gross margins of individual insect pollinated horticultural crops weighted by the hectares devoted to each of these crops across GB. The gross margin (£ ha^{-1}) of each individual crop was obtained from the John Nix Pocketbook (Redman, 2018), Cross et al (2019) (plums), Wermund et al (2011) (cherries), and the Crop Production Guide (CALU, 2007) (courgettes). The hectare weighed average gross margin of insect pollinated horticulture was estimated to be $GM = 3{,}607$ (£ ha^{-1}). Both the estimated proportion and gross margin are assumed not to vary spatially across Great Britain.

Secondly, the diversity of wild insect pollinator species required for full pollination services is estimated from Winfree et al (2018). The authors estimate the minimum set of bee species that could meet various pollination thresholds (25, 50, and 75% of the observed mean) to be 20, 55, and 79 respectively. Since we require the number of wild insect pollinator species required to meet 100% of horticultural pollination services, we perform a simple linear regression of the three data points from Winfree et al (2018) with the assumption that 0 species are required to meet 0% of pollination services. The fitted regression line predicts the number of species required to meet 100% of pollination services is 105 species.

In order to predict the change in value from wild insect pollinated horticulture using Equation (D1.6.1), the NEV pollinator species diversity model is used. This allows the calculation of the proportion of pollination services provided by wild insects under the baseline and a land use change by comparing the number of species present in the cell with the number of species required for 100% pollination service.

The result is the change in value of insect pollinated horticultural crops from a change in pollinator species richness which has resulted from a land use change. This information is available for all cells in the NEV 2km^2 grid and at a decadal scale for the 2020s, 2030s, 2040s and 2050s. The change in value across the four decades is also calculated in NPV and annuity equivalent terms using a constant social discount rate of 3.5%.

D1.7. Recreation valuation

In this section, we describe how the NEV recreational demand model is used to predict changes in values generated from recreation activity as a result of land use change. As well as predicting visits to greenspace areas, the recreational demand model can be used to estimate welfare values for greenspaces. The calculation of welfare values is enabled by the fact that the recreation demand model provides an estimate of the recreation welfare function. That function identifies how much welfare an individual enjoys as a result of beneficial attributes of a greenspace (e.g. the extent of woodland, the presence of a children's playground). Likewise, it identifies how much welfare is lost from each extra pound of cost incurred in travelling to a greenspace. The latter amount is crucial in calculating welfare values. It tells us the amount of welfare a person considers is equivalent to having one extra pound. In other words, it provides an exchange rate that we can use to convert estimates of changes in welfare into equivalent amounts of money.

Welfare values for an existing site are estimated by calculating how much each individual's welfare would fall if they were no longer able to access that site and then converting that welfare quantity into an equivalent monetary amount. Those welfare values can then be aggregated over the adult population of England and Wales for an entire year using the same sequence of steps used to aggregate estimates of visitation (see Section C).

Land use changes from the NEV land use decision models (Section A) lead to changes in recreational welfare values. The NEV modelling suite allows for three different assumptions regarding how land use change impacts recreation:

- Alter Current Paths: Here we assume that there is no change in the set of accessible greenspaces. Further, we assume that there is no change to the land covers of existing parks or beaches in the cell being altered. Accordingly, with this option the only recreational impact occurs through changing the land covers through which current paths pass. The recreation model calculates how those changes in land cover impact on the recreational value and visits to those existing paths.

- Provide New Paths: Here we assume that land cover changes resulting in new woodland or new semi-natural grass are made accessible to the public through new path access. No changes are experience on existing paths and parks. The length of the new paths is calculated as the circumference of a circle equal in size to the area of new natural grassland and woodland and the land covers accessed by that path are in proportion to the relative size of the new semi-natural grassland and woodland.

- Provide New Parks: similar to the ‘new paths’ option here we assume that land cover changes resulting in new woodland or new semi-natural grass are made accessible to the public as new parks.

In the ORVal recreation demand model making these calculations for many new recreation or changed recreational sites is highly computer intensive. Accordingly, within the NEV modelling suite we use a fast running approximation. The central bottle neck in the calculations is that the model needs to calculate travel costs from each new/changed site to each of the 32,488 LSOAs across England. Of course most of those LSOAs are so far from the new/changed site, that their residents experience no change in recreational value. For that reason, in a pre-processing step, we work through each of the 2km^2 cells in England placing a new 50 ha site made up of an equal share of woodland and grassland at the centre of the cell. We then calculate the additional welfare value generated by that new site for the residents of every LSOA. That allows us to identify the 50 LSOAs that experience the most welfare gain from changes either because of their proximity to the new site, the size of their populations, the socioeconomic characteristics of those populations or some combination of all those elements. In testing we found that in nearly all cases the vast majority of the welfare gain was experienced with those 50 most-impacted LSOAs.

To increase the speed of NEV recreational demand model, therefore, we only carry out calculations of recreational visit and value changes for the 50 most-impacted LSOAs for each cell experiencing land cover change. Moreover, further time savings are achieved by storing the travel costs from each cell to its 50 most-impacted LSOAs along with other quantities for each of those LSOAs used in the visit and value estimates that can be pre-calculated for each LSOA. Restricting attention to the 50 most-impacted LSOAs and pre-calculating travel costs and other elements of the calculations results in huge speed-ups in the estimation of changing recreational visits and values.

Finally, when changes are made across numerous cells creating or changing a number of sites assume, the NEV recreational demand model assumes that those changes happen simultaneously. In other words, the residents of the set of most-impacted LSOAs are assumed to experience all of those changes. Accordingly, our calculations returns an aggregate welfare value for the residents of an LSOA for that set of changes across sites that are located in potentially numerous 2km^2 cells. In that case, the values are allocated back to the cells in proportion to the share of visits to those change cells from that LSOA.

D2. Economic Valuation Methods: Stated Preference

While there are many circumstances in which we can use information from real world observations in order to value ecosystem service value flows, there are some value flows that are not amenable to such an approach.

One such value flow is described by economists as non-use value. In the context of land use change, non-use value would be the flow of benefits an individual might derive simply by knowing that environmental quality has been improved in some location even if they don't expect to benefit from that quality change in any direct way (for example, by visiting a location enjoying an improvement for the purposes of recreation). Since non-use values leave no observable mark in individuals' behaviour or the profits of firms, the only way with which to estimate those values is to ask people to estimate them directly. Methods of valuation using this questioning approach are known as stated preference methods of non-market valuation.

In the NEV model, we envisage at least three routes through which individuals might enjoy non-use values;

- *Changes in terrestrial habitats*: Non-use values may be held for land use changes that result in the establishment of natural (or more natural) habitats.
- *Changes in fluvial habitats*: Non-use values may be held for changes in rivers that improve the ecological quality of fluvial habitats returning them to natural (or more natural) states.
- *Changes in biodiversity*: Non-use values may be held for changes in environments that create habitats that support a more diverse and more abundant biological community.

It is potentially the case that the non-use values that individuals hold for improvements in habitats are driven in part by their preferences for biodiversity. Accordingly, including non-use values for both habitat improvements and biodiversity improvements may constitute double-counting. It is also true that estimating independent non-use values for biodiversity is very challenging. Those challenges involve establishing some way in which the multi-dimensional nature of biodiversity can be convincingly and reasonably be conveyed to individuals. Should we focus on the question of the number of different species or their abundance? How do we convey the range of different types of species? How do we convey their importance in terms of roles in the functioning of the ecosystem? It's fair to say that practitioners of non-market valuation are stills struggling with these issues. Accordingly, while NEV is able to model changes in measures of species richness, we largely do not attempt to attribute a value directly to those changes.

One exception concerns wild flowers. Here the difficulties of conveying differences in diversity are relatively less complex since most individuals' are reasonably well acquainted with difference in such diversity and in a stated preference study those differences can by succinctly conveyed through photos and text. The diversity of wild flowers is driven in part by the diversity of pollinators. As such, NEV's pollinator species models provide a route through which changes in landcover can be related to changes in wild flowers. And here the final step to values can be made using a stated preference study by Breeze et al. (2015) that estimates UK residents' preferences for the diversity of wild flowers.

While conveying information on changes in habitats is somewhat easier than the more nebulous concept of biodiversity, there are still relatively few stated preference studies on habitat change in the UK. NEV makes use of two such studies in estimating non-use values for changes in terrestrial habitats (Hanley et al., 2007) and fluvial habitats (Day et al., 2019b).

In comparison to value estimates based on observed behaviour, one criticism of stated preference methods is that they are hypothetical; that is to say, they are based on amounts that individuals say they would pay for an environmental improvement, not on amounts actually paid. Indeed, evidence exists that suggests individuals tend to overstate their values for ecosystem services when answering stated preference surveys (Murphy et al., 2005). How to proceed? Ignoring values for ecosystem services coming from stated preference studies is tantamount to assuming those value flows are worthless. On the other hand, using the face value of the estimates from stated preference studies risks over-stating their worth. In NEV we take evidence from the Murphy et al. (2005) paper that reviewed research comparing actual payments to hypothetical payments and estimated that on average actual payments are only 38% of hypothetical payments. Accordingly, NEV allows for the possibility of calibrating stated preference values by this factor to correct for hypothetical bias.

D2.1. Pollinator valuation

In the NEV modelling suite, we estimate the value of wild insect pollinators in maintaining wildflower diversity using the outputs of the NEV pollinator species diversity model (Section B3.1). The change in value of wildflower diversity resulting from a change in the presence of wild pollinators is estimated using Equation D2.1.1:

$$V_c^i = V(p_s^i - p_b^i) \tag{D2.1.1}$$

Where: (i) V_c^i is the change in value of wildflower diversity as a result of an increase or decrease in wild insect pollination levels in cell i, (ii) V is the estimated average willingness to pay for individuals to maintain 100% of the wildflower pollination services from wild insects, (iii) p_s^i is the proportion of pollination services provided by wild insects under a land use change in cell i, and (iv) p_b^i is the proportion of pollination services provided by wild insects in the baseline in cell i.

In order to use Equation (D2.1.1), we must estimate two quantities:

- V, the average value that individuals in the UK give to the maintenance of full pollination services for wild plants.
- The diversity of wild insect pollinator species required for full pollination services (i.e. no need for commercial pollination). Details of this are omitted here since they have already been discussed in Section D1.6.

The average individual willingness to pay for maintaining full pollination services of wildflowers, V, is taken from a choice experiment from Breeze et al (2015). According to this study, an estimate of the willingness to pay to maintain 1% of wildflower diversity in the UK is equal to £1.63 or £0.84 per person, depending on the method selected to cope with respondents ignoring some of the attributes used in the estimation process. In the NEV modelling suite, we take the conservative estimate of £0.84.

Before we can convert to an estimate of willingness to pay for 100% of pollination services, we must calculate the proportion of wildflowers pollinated by wild pollinators. Breeze et al (2015) also state that approximately 78% of the flowering plants in temperate areas are pollinated by insects. Assuming that 50% of these rely exclusively on insect pollination, we can derive that $(78\% * 0.5) = 39\%$ of temperate flowering plants entirely depend on insects to be pollinated. It follows that, if we were to remove all pollinator insects, we would observe a decline of 39% in overall wildflower diversity or, if we were to remove 1% of pollinators, we would incur in a 0.39% total reduction in wildflower diversity.

The willingness to pay to maintain 1% of wildflower pollination services from insects in the UK is thus estimated to be $(0.84 * 0.39) = £0.33$. By converting to 100% pollination services, we estimate V to be $(0.84 * 0.39 * 100) = £32.76$ per person. When we apply pollinator valuation in the NEV modelling suite, this figure is scaled up by the population in the NEV 2km^2 grid cell. More specifically, we scale up by 14% of the population in the cell, using evidence from Breeze et al (2015) who found 14% of questionnaires were returned.

Regarding the calculation of p_b^i and p_s^i, the proportion of pollination services provided by wild insects under the baseline and a land use change respectively, we refer back to the discussions in Section D1.6. The NEV pollinator diversity model (Section B3.1) is used in conjunction with data from a study by Winfree et al (2018).

The result is the change in value of wildflower diversity as a result of a land use change. This information is available for all cells in the NEV 2km^2 grid and at a decadal scale for the 2020s, 2030s, 2040s and 2050s. The change in value across the four decades is also calculated in NPV and annuity equivalent terms using a constant social discount rate of 3.5%.

D2.2. Non-use values of water quality

As described in Section B2.2 the NEV model suite estimates the probability that changes in land uses will lead to changes in the WFD ecological status classification of a water body. The study by Day et al. (2019) allows us to translate those changes in ecological status into estimates of non-use value.

Day et al. (2019) draw on a mid-size study of residents of northern England. Using novel map-based elicitation methods the study gathers information on respondents' use of river locations for recreation and, through a stated preference exercise, the value they attach to changes in river ecological status across the region. A typical question from that survey is shown in Figure 17 where a respondent living at the location marked as 'home' is asked to identify which of the two options they prefer where the options differ in terms of an annual cost (payable through their water bill) and with regards to the ecological status of rivers (as indicated by the different coloured water stretches).[2]

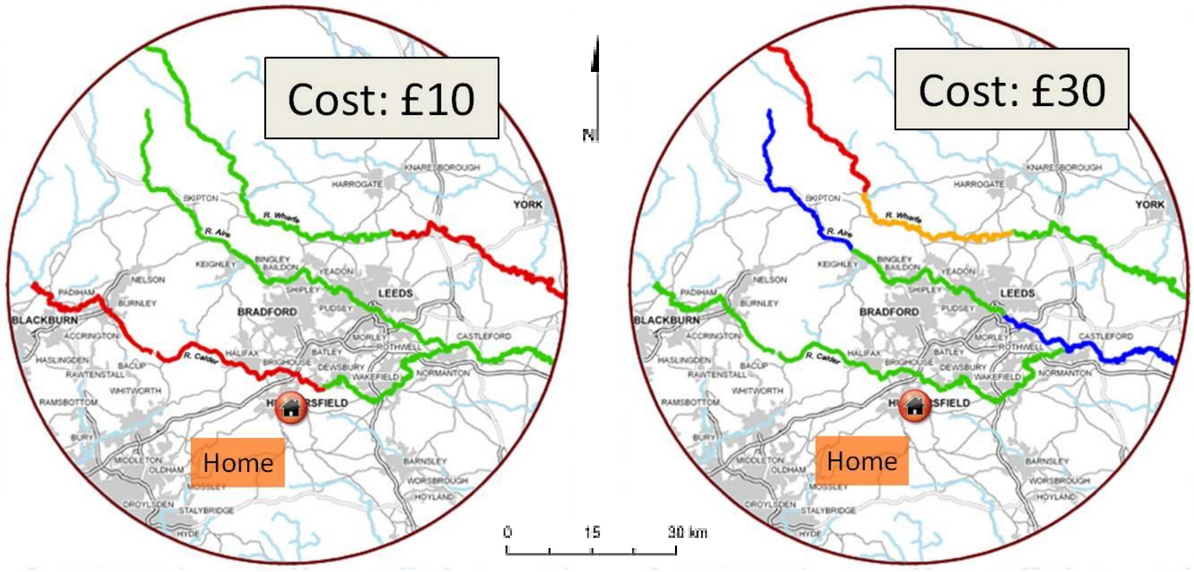

Figure 17: Typical stated preference task from the study by Day et al (2019).

The Day et al. (2019) study is ground-breaking in two ways. First it combines information from respondents' observed use of river locations for recreation and from their responses to the stated preference questions to tease out a non-use value for improvements in river ecological status. Second, the map-based elicitation procedures allow the study to estimate the rate at which non-use value decays with distance. More specifically, the Day et al. (2019) paper provides a value per year of changing the ecological status of a 3km stretch of river across the different ecological status categories. Roughly speaking that value amounts to between £1 and £2 per category change per year for a river located next to an individual's home. Those values decline with distance at a rate roughly equal to the inverse of distance.

The non-use water quality values are implemented in NEV by first identifying each 2km^2 cell through which a main river (defined by the OS main rivers dataset) flows and calculating the length of river in that 'river cell'. For each river cell the current WFD ecological status is recorded and the value of changes to each improving and worsening ecological status level are made. Note that those river cell values are the raw values before distance decay and are scaled to account for the different lengths of river in each river cell.

Calculation of non-use values for water quality is undertaken at the level of Lower Super Output Area (LSOA), a geographical division of the UK used for statistical analysis containing around 1500 individuals. We take the population of each LSOA (using ONS demographic estimates for 2016) and identify the distance from the population-weighted centroid of that cell to each river cell. In order to maintain tractability we associate each cell with only its closest 500 river cells assuming that, as a result of distance decay, ignoring more distant river cells will result in minimal bias in the value estimates. With that information the non-use value realised in an LSOA from changes in water quality across river cells can be calculated. Simply put, when the ecological status of a set of river cells changes, we first select LSOAs impacted by those changes (in other words, LSOAs for whom a river cell experiencing quality change is in their list of closest 500 river cells). For each of those LSOAs, the change in non-use value is the value of the quality change experienced at each river cell deflated by distance decay and then summed across all households in the LSOA.

D2.3. Non-use values of land cover in the uplands

In the NEV modelling suite, we estimate the non-use values associated with changes in land cover in upland areas, specifically the landscapes of Less Favoured Areas (LFAs) and Severely Disadvantaged Areas (SDAs). The non-use value of the land cover change in the uplands is estimated on a per-cell basis using Equation (D2.3.1):

$$V_{nu}^{i} = \sum_{q=1}^{m} V_{q}^{i}(l_{qs}^{i} - l_{qb}^{i}) \qquad \text{(D2.3.1)}$$

Where: (i) V_{nu}^{i} is the non-use value of land cover change in the uplands in cell i, (ii) m is the number of possible land cover changes indexed by q, (iii) V_{q}^{i} represents the non-use value per hectare of a change to land cover q in cell i, (iv) l_{qb}^{i} and l_{qs}^{t} represent the amount of land cover q in cell i under the baseline and a land cover change scenario respectively, given by the NEV land use decision models (Section A). The land covers considered here are creation of semi-natural grassland and woodland.

The non-use values of specific land cover changes in the uplands, V_{q}^{i}, are taken from a study by Hanley et al (2007). The authors elicited regional differences in willingness to pay for different landscape features and habitats in SDAs using a series of choice experiments. As well as looking at four regions containing SDAs, an additional choice experiment was conducted in the South East to estimate non-resident values. Participants in the choice experiments were asked to state their preferences for different levels of landscape attributes, which were then used to calculate the amounts of compensating surpluses for a series of policy alternatives and their predicted outcomes in terms of change in the levels of the specified environmental attributes. In more detail, focus was given to three policy scenarios impacting the levels of (i) heather moorland and bog, (ii) rough grassland, (iii) mixed and broadleaved woodland, (iv) field boundaries and (v) cultural heritage. A tax price attribute for the policy scenarios expressed as an increase from the national and local level of taxation was also included to elicit welfare measures resulting from the proposed policy change options.

To estimate non-use values of land cover change in the uplands, we use results from the South-East region in Hanley et al. (2007). As there are no SDAs in the South East, we make the assumption that the non-resident values elicited in the experiment are as close as possible to non-use values, even if they are likely to include some use value from recreation. Furthermore, the NEV semi-natural grassland and woodland land covers are assumed to take the values of the ‘heather, moorland and bog’ and ‘mixed and broadleaved woodland’ categories from Hanley et al (2007).

The results from the choice experiment in the South-East found a marginal willingness to pay for a 1% increase in the areas classified as ‘heather moorland and bog’ and ‘woodland’ of £0.53 and £0.54 per household per year respectively. Using SDAs outlines (Defra, 2010) and the 2015 Land Cover Map (CEH, 2017), the total area of as ‘heather moorland and bog’ and ‘woodland’ was estimated to be 409,152 ha and 299,443 ha respectively. From this information, the willingness to pay for a per hectare increase in ‘heather, moorland and bog’ and ‘woodland’ was estimated to be £0.0001295 and £0.0001803 respectively. Scaling by the number of households in England (22.9 million, ONS 2016), we estimate the total willingness to pay per year for an increase in in ‘heather, moorland and bog’ and ‘woodland’ to be equal to £2,966.38 per ha and £4,129.67 per ha respectively.

The result is the non-use value of associated with land cover changes to semi-natural grassland or woodland in SDAs. This information is available for all cells in the NEV 2km^2 grid (a value of zero is attributed to cells outside the SDAs) and at a decadal scale for the 2020s, 2030s, 2040s and 2050s. The values across the four decades is also calculated in NPV and annuity equivalent terms using a constant social discount rate of 3.5%.

D3. Unmodelled ecosystem services and values

As has been demonstrated in this report, the NEV modelling suite is a comprehensive modelling tool covering a wide range of environmental processes and ecosystem services which respond to land use change, climate change and policy drivers. Even so, there are several ecosystem services and values which are not included. The list is extensive but a few key ticket items will be discussed here, including air quality, non-river flooding and water quality, overnight recreation, valuation of wildlife and additional land uses.

D3.1. Air quality

The NEV agricultural emissions model provides estimates of the levels of emissions of different air pollutants from agriculture (Section B1.1). Moreover, the costs of agricultural greenhouse gas emissions are valued using the social cost of carbon (Section B1.3). While the costs of greenhouse gas emissions are already accounted for in the simulations, those relating to the health effects of nitrogen oxides and methane emissions are not.

D3.2. Non-river flooding

Flood Guidance[3] states that the UK is affected by six key types of flooding: (i) river flooding, (ii) coastal flooding, (iii) surface water flooding, (iv) groundwater flooding, (v) sewer flooding, and (vi) reservoir flooding. In the NEV modelling suite, the water flow model (Section B2.1), flood risk model (Section B2.3) and subsequent flood damage valuation (Section D1.5) only address the impacts of land use change on river or fluvial flooding.

These uncaptured types of flooding are known to affect large parts of the country and may result in substantial damage costs. For example, as of 2018 in England there are an estimated 2.6 million properties at risk from river and sea flooding, 3.2 million properties at risk from surface water flooding and up to 290,000 properties at risk from groundwater flooding (Defra, 2018c). As an example of damage costs, the 2004 Boscastle flood, caused by flash floods, had an estimated damage cost of £15 million.

D3.3. Non-river water quality

Similar to the previous comments on non-river flooding values, in the NEV modelling suite the water quality model only considers pollution (specifically nitrate and phosphate concentrations) within rivers. Additional sources of water pollution that could be included are groundwater pollution and the bathing quality of lakes and beaches.

D3.4. Overnight recreation

The predictions of the NEV recreational demand model (Section C) are limited to modelling value generated by short trips of less than one day duration. We know that every year some 50 million overnight 'holiday' trips are made to locations in England and that some 55% of those are focused on coastal or countryside locations. While holiday trips to engage with the outdoors are less frequent than the 2.5 billion 'day trips' we suspect that the value of each of those trips may be very significant and that they may focus on a markedly different set of locations. In particular, accounting for the value generated by holiday visits may attribute significant additional benefits to the maintenance and enhancement of natural environments in, for example, National Parks, AONBs and heritage coastlines.

D3.5. Valuation of wildlife

Wildlife and biodiversity is represented in the NEV modelling suite via the pollinator diversity model (Section B3.1) and the priority species diversity model (Section B3.2). The outputs from the pollinator diversity model are valued by their contribution to the horticultural sector (Section D1.6) as well as maintaining wildflower habitats (Section D2.1). However, the outputs from the priority species diversity model are not valued in an economic sense, due to the lack of research in this area. Rather, the species diversity can be used to constrain the model, for example, land use change is not permitted in grid cells where the priority species richness would decline.

D3.6. Additional land uses

Recall that in the NEV modelling suite each land unit is divided into five high level land cover categories: agriculture, woodland, semi-natural grassland, urban and water. The NEV land use decision models allow a further dissemination of agricultural land (Section A.1) and woodland (Section A.2). The carbon system models (Section B1), hydrological system models (Section B2),

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[3] https://www.floodguidance.co.uk/what-is-resilience/types-flooding/

biodiversity models (Section B3) and recreation demand model (Section C) all respond to the changes in these land covers and uses. However, there are additional services that could be included given a more detailed description of land use in the cell. For example, no direct ecosystem services or costs are assume to flow from the urban land use category. The semi-natural grassland category is also relatively broad due to data availability. A finer classification of land including features such as peatland, heathland, moorland, saltmarshes, wetland and sand dunes would allow an appraisal of ecosystem services these areas provide such as flood alleviation, carbon storage and recreation.

Strengths & Weaknesses

To conclude, we give a brief summary of the strengths and weaknesses of the NEV modelling suite. Beginning with the strengths, as has been demonstrated the NEV modelling suite is a comprehensive modelling tool which can assess the impact of land use, climate and policy change on a wide range of processes in the natural environment. These include implications for farm and forestry production, greenhouse gas sequestration, hydrological systems, wildlife, recreation and environmental non-use. One of the key strengths of the NEV modelling suite however is that these environmental outcomes are, wherever possible, converted to ecosystem services using state-of-the-art economic valuation models. Such ecosystem services include the profitability of food and timber, the benefit of greenhouse gas sequestration, cost of water treatment and flood damages, pollination services, recreational welfare and environmental non-use. The NEV model outputs ecosystem service values in a common monetary unit for use in cost benefit analyses.

The NEV modelling suite is a system of interlinking models which interact with each other and respond to several factors including land use change, climate change and policy drivers such as the prices of crops, livestock and timber. In fact, land use change is endogenous with changes in climate and policy, with farm and forest managers responding to fluctuations in conditions around them. Those changes in land use then drive the behaviour of a series of environmental processes, which themselves are then translated into benefits to society.

Finally, the NEV modelling suite is a spatially and temporally specific tool such that it provides detail on when and where environmental flows and values are realised. Operating on a fine scale resolution of 2km^2 grid cells, recreational areas, subcatchments and river networks, variability in characteristics of the land impact on decision making and the resulting environmental benefits. In terms of temporal scale, outputs of the NEV modelling suite predictions into the future and are available at decadal, annual and sometimes daily resolution between 2020 and 2060.

Moving to the weaknesses of the NEV modelling suite, in order to construct such a system of interlinking models working at fine resolution across Great Britain, it was necessary to simplify the behaviour of some processes. For this purpose we employed statistical emulators, which provide fast running approximations to models, and fast coding techniques. These procedures try to balance the trade-off between the level of sophistication in the modelling and the speed of running the suite.

While the NEV modelling suite is spatially and temporally explicit, we do not affect for spatial and temporal interactions, in that for the majority of models the spatial units are considered independent of one another and one year does not influence the next. Again, there is a trade-off to be had between the predictive performance of the models, which could be improved with the inclusion of spatial and temporal interactions, and the run time of the suite of tools.

The spatial resolution of the NEV modelling suite, whilst relatively fine scale, prohibits the study of fine scale land management activities. The majority of models respond to the proportions of land cover within the spatial units rather than their specific location within them. Due to this reason, the NEV modelling suite is restricted to fairly extreme changes in land cover.

Finally, as stated in Section D3, while the NEV modelling suite is a comprehensive set of tools there are several ecosystem services and values missing. As a consequence, predictions from the model are likely to be a lower bound on the benefits of the natural environment.

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