
BRITAIN

# Land Use Model

## Contents

# 1 Introduction

Land in the ZCB scenario has to play 3 roles:

- Providing food for the UK population.
- Providing hydrocarbon fuels and energy storage for parts of our energy demand that cannot be met through renewable electricity generation.
- ‘Balancing’ (or annually ‘offsetting’ in the long-term) residual emissions in the scenario using carbon capture – there are some emissions which we cannot ‘get rid of’ in the scenario – some from industrial processes and waste processing, and some from agriculture (largely livestock and fertiliser).

Everything grown on the land is modelled here, apart from food production. This is done separately via the ‘**Food + Diets**’ model, and priority is given to food production on UK cropland, and on some grassland (livestock is much reduced in the scenario to reduce the greenhouse gases from them). Also modelled separately is the energy system – annual ‘**Power Down**’ and ‘**Power Up**’ models, and an **hourly model** of supply and demand for the UK, based on our renewable energy mix. Out of this, comes a demand for some hydrocarbon fuels (which can be made with biomass from energy crops), and some amount of energy that can be stored (build up the store when there is a plentiful supply of energy, and run it down when energy is in short supply). Our method of energy storage is conversion of biomass to synthetic gas and biogas through anaerobic digestion and by the addition of hydrogen (made through electrolysis with excess energy at times of high supply and low demand).

The aim of the land-use model is to satisfy all three demands above. The requirements of the ‘Food + Diets’ model are absolute: they cannot be changed. There is, however, some flexibility in the energy model which means that what the final land-use in the scenario is depends on a process of iteration.

This document supplies the information behind the land-use model of ZCB. It is these parameters which are used to try and satisfy the energy and carbon capture demands on land. What we can decide, is:

- How much land can be used for what (via assigning kilohectares (kha’s) to various land-uses).
- What products from the land go into different processes, and where they can end up ultimately (via fractional assignment of each product to a number of ‘streams’).

# 2 Methods

**Table 1: ZCB Land-use Types, CS Broad Habitat Types and descriptions (NERC, 2008a).**

| ZCB Land Use Types | CS Broad Habitats (CS 2007) | Broad Habitat Description |
|---|---|---|
| **Broadleaf woodland** | Broadleaved, Mixed and Yew Woodland | Vegetation dominated by trees >5m high when mature, with tree cover >20%. Scrub (<5 m) requires cover >30% for inclusion in this Broad Habitat. It includes stands of both native and non-native broadleaved trees and yew. Woodlands dominated by coniferous species but with >20% cover by deciduous species are included in this category. Areas of fen woodland dominated by species such as willow (Salix spp.), alder (Alnus glutinosa) or birch (Betula spp.) are also included. |
| **Coniferous woodland** | Coniferous Woodland | Vegetation dominated by trees >5m high when mature, which forms a canopy having a cover of >20%. „Coniferous Woodland" includes semi-natural stands and plantations and includes both native and nonnative coniferous trees. |
| **Arable + Horticultural Cropland** | Arable and Horticulture | Includes annual crops, perennial crops, woody crops, intensively managed commercial orchards, commercial horticultural land (such as nurseries, commercial vegetable plots and commercial flower growing areas), freshly-ploughed land, annual leys, rotational set-aside and fallow. |
| | Linear Features | Covers a range of linearly arranged landscape features such as hedgerows, lines of trees, walls, stone and earth banks, grass strips and dry ditches |
| **Improved Grassland** | Improved Grassland | Vegetation dominated by a few fastgrowing grasses such as Lolium spp., and also white clover (Trifolium repens), on fertile, neutral soils. Improved Grasslands are typically either managed as pasture or mown regularly for silage production or in non-agricultural contexts for recreation and amenity purposes. |
| **Semi-natural Grassland** | Neutral Grassland | Vegetation dominated by grasses and herbs on a range of neutral soils usually with a pH of between 4.5 and 6.5. It includes enclosed dry hay meadows and pastures, together with a range of grasslands which are periodically inundated with water or permanently moist. |
| | Calcareous Grassland | Vegetation dominated by grasses and herbs on shallow, well-drained soils which are rich in bases (principally calcium carbonate) formed by the weathering of chalk and other types of limestone or baserich rock. Soil pH tends to be high (>6) although it may be as low as 5 |
| | Acid Grassland | Vegetation dominated by grasses and herbs on a range of lime-deficient soils which have been derived from acidic bedrock or from superficial deposits such as sands and gravels. Such soils usually have a low base status, with a pH of <5.5. |

| | | |
|---|---|---|
| | Fen, Marsh, Swamp | Includes fen, flushes, springs, fen meadows, rush pasture and swamp. Fens are peatlands which receive water and nutrients from groundwater and surface run-off, as well as from rainfall. Flushes are associated with lateral water movement, and springs with localised upwelling of water. Marsh is a general term usually used to imply waterlogged soil; it is used more specifically here to refer to fen meadows and rush-pasture communities on mineral soils and shallow peats. Swamps are characterised by tall emergent vegetation. Reedbeds (i.e. swamps dominated by stands of common reed Phragmites australis) are also included in this type. |
| | Bracken | Areas dominated by a continuous canopy cover of bracken (Pteridium aquilinum) at the height of the growing season. It does not include areas with scattered patches of bracken or areas of bracken which are >0.25 ha |
| **Mountain, Heath + Bog** | Dwarf Shrub Heath | Vegetation that has >25% cover of plant species from the heath family (ericoids) or dwarf gorse Ulex minor. It generally occurs on well-drained, nutrient-poor, acid soils. This habitat type does not include dwarf shrub dominated vegetation in which species characteristic of peat-forming vegetation such as cotton-grass Eriophorum spp. and peat-building sphagna are abundant, or that occurs on deep peat (> 0.5 m) |
| | Bog | Covers wetlands that support vegetation that is usually peatforming and which receive mineral nutrients principally from precipitation rather than ground water. This is referred to as ombrotrophic (rain-fed) mire. The Bog Broad Habitat includes ericaceous, herbaceous and mossy swards in areas with a peat depth >0.5m. |
| | Montane | Includes a range of vegetation types that occur exclusively in the montane zone such as prostrate dwarf shrub heath, snow-bed communities, sedge and rush heaths, and moss heaths. The distinction between the sub-montane and montane zone is often blurred and the two usually merge through a band of transitional vegetation. |
| | Inland Rock | Covers both natural and artificial exposed rock surfaces which are >0.25ha, such as inland cliffs, caves, screes and limestone pavements, as well as various forms of excavations and waste tips such as quarries and quarry waste. |
| **Coastal + Fresh Water** | Standing Open Waters | Includes natural systems such as lakes, meres and pools, as well as man-made waters such as reservoirs, canals, ponds and gravel pits. |
| | Rivers and Streams | Covers rivers and streams from bank top to bank top, or where there are no distinctive banks or banks are never overtopped, it includes the extent of the mean annual flood. |
| **Urban Areas** | Built-up Areas and Gardens | Covers urban and rural settlements, farm buildings, caravan parks and other man-made built structures such as industrial estates, retail parks, waste and derelict ground, urban parkland and urban transport infrastructure. It also includes domestic gardens and allotments. This type does not include amenity grassland which should be included in the 'Improved Grassland' category |

**Table 2: Forestry, peatland, agricultural land and priority habitat allocations to CS Broad Habitat (BH) type, and conversion through to land 'available' for use in ZCB scenario (calculated as total area in BH minus 'protected' habitat). 'Productive land' and 'Protected habitat' are taken from different data sources and so totals may not equal those totals in BH types. They are to be used as comparison and further sub-division where necessary for the ZCB scenario. Please see references for definition of each classification.**

| **LCM 2007 Broad Habitat** | Area (kha) | Ref | Of which | | | | Of which | | | | **Land Available for ZCB Scenario** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Productive Land** | Area (kha) | Notes | Ref | **Protected Habitat** | Area (kha) | Notes | Ref | Land Use | Area (kha) |
| | | | | | | | Upland Mixed Ash Wood | 30 | | [13] | | |
| | | | | | | | Wet Woodland | 75 | | [13] | | |
| | | | | | | | Upland Oakwood | 61 | | [13] | | |
| | | | FC/FS Broadleaf Woodland | 113 | [5] [8] | [11] | Lowland Mixed Deciduous | 60 | | [13] | | |
| | | | Non-FC/FS Broadleaf Woodland | 1271 | [5] [8] [9] | [11] | Upland Birchwoods | 31 | | [13] | | |
| **Broadleaf Woodland** | **1385** | **[10]** | | **1384** | | | | **257** | | | **Broadleaf Woodland** | **1128** |
| | | | FC/FS Conifer Woodland | 670 | [5] [8] | [11] | | | | | | |
| | | | Non-FC/FS Conifer Woodland | 839 | [5] [8] [9] | [11] | | | | | | |
| **Coniferous Woodland** | **1508** | **[10]** | | **1509** | | | | | | | **Coniferous Woodland** | **1508** |
| | | | Arable crops (c) | 4333 | [1] | [12] | | | | | | |
| | | | Horticultural crops | 171 | [1] | [12] | | | | | | |
| | | | Uncropped arable land (d)(e) | 608 | [1] | [12] | | | | | | |
| | | | Temporary grass (<5 years old) | 1193 | [1] | [12] | | | | | **Temporary grass** | **1193** |
| **Arable and Horticultural Cropland** | **6306** | **[10]** | | **6305** | | | | | | | **Arable + Horticultural Cropland** | **5113** |
| **Improved grassland** | **6256** | **[10]** | **Grass over 5 years old** | **5965** | **[2]** | [12] | | | | | **Improved grassland** | **6256** |
| | | | | | | | Peatlands (Fens) | 26 | [6] | [14] | | |
| | | | | | | | Lowland Calcareous | 45 | | [13] | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Grass | | | | | |
| | | | | | | | Upland Calcareous Grass | 19 | | [13] | | |
| | | | Sole right rough grazing (f) | 2737 | [3] | [12] | Purple Moor Grass Rush Pasture | 59 | | [13] | | |
| | | | Common rough grazing | 289 | [4] | [12] | Reedbed | 6 | | [13] | | |
| **Semi-natural grassland** | **3289** | **[10]** | | **3026** | **[20]** | [12] | | **155** | | | **Semi-natural grassland** | **3134** |
| | | | | | | | Peatlands (bogs) | 2277 | [6] | [14] | | |
| | | | | | | | Blanket Bog | 1234 | [19] | [13] | | |
| | | | Sole right rough grazing (f) | 1582 | [3] | [12] | Lowland Dwarf Shrub Heath | 93 | | [13] | | |
| | | | Common rough grazing | 949 | [4] | [12] | Upland Dwarf Shrub Heath | 1196 | | [13] | | |
| **Mountain, Heath and Bog** | **3833** | **[10]** | | **2531** | | | | **3566** | **[7]** | | **Mountain, Heath and Bog** | **267** |
| **Coastal + Freshwater** | **692** | **[10]** | | | | | | | | | **Coastal + Freshwater** | **0** |
| **Urban Areas** | **1459** | **[10]** | **All other non-agricultural land** | **291** | | [12] | | | | | **Urban Areas** | **0** |
| TOTAL | 24728 | | | 21011 | | | | 3978 | | | | **18599** |
| | | | Agriculture | 17827 | | | | | | | | |

**Notes**

[1] These are fractionally distributed to cover the entire 'Arable and Horticultural' LCM land class

[2] This doesn't totally cover the LCM land class. For the purpose of this study, the LCM class will be taken to be correct, and all the 'Improved Grassland' is taken to be agricultural land

[3] Sole right rough grazing is distributed (somewhat arbitrarily) between 'Semi-natural grassland' and 'Mountain, Heath and Bog'

[4] Common rough grazing is distributed (somewhat arbitrarily) between 'Semi-natural grassland' and 'Mountain, Heath and Bog'

[5] FC/FS Owned/private owned woodland is distributed fractionally over the woodland (broken down into Conifer and Broadleaf according to the Forestry Commission)

[6] There may be some crossover between 'Peatlands' and other 'Protected Areas' and even land that is grazed (according to 'Productive Land')

[7] 'Peatland (bogs)' and 'Blanket Bogs' are taken to be the same thing and so are not double-counted in the total

**[8] Not all of this woodland is currently productive (harvested for timber), roughly 90% of all forested land in the UK is currently ‘productive’ forestry in one way or another [15]**

[9] Non FC/FS woodland (both conifer and broadleaf) also includes 663kha of woodland on agricultural land

[19] NB This number may be low compared to other sources. About 85% of all peatland is blanket bog.

[20] This land includes urban grassland areas - 'amenity grassland'

**Refs**


[10] NERC (2008a) CS Technical Report No 11/07: Final Report for LCM2007 - the new UK Land Cover Map, D. Morton, C. Rowland, C. Wood, L. Meek, C. Marston, G. Smith, R. Wadsworth, I. C. Simpson, Centre for Ecology & Hydrology, (Natural Environment Research Council), July 2
And
**Natural Environment Research Council, November 2008 Countryside Survey: UK Results from 2007 CHAPTER 2 • The National Picture,**
Information on use of land-types from correspondance with Lisa Norton (CEH): "Norton, Lisa R." <lrn@ceh.ac.uk>
More information on land-types can be found here: http://www.ceh.ac.uk/documents/LCM2007FinalReport.pdf

[11] Forestry Commission (2007) Forestry Facts & Figures, 2007, A summary of statistics about woodland and forestry, Forestry Commission, 2007, **http://www.forestry.gov.uk/pdf/fcfs207.pdf/$FILE/fcfs207.pdf**

[12] DEFRA (2012) June Surveys/Census of Agriculture/SAF land data Scotland. For more details please see the introduction section of this chapter., '07 June 2012; Table 3.1 Agricultural land use (a) **http://www.defra.gov.uk/statistics/foodfarm/cross-cutting/auk/**
**More information: email: farming-statistics@defra.gsi.gov.uk**
**Enquiries: Jenny Tickner on +44 (0)1904 455332**

[13] NERC (2008b) Countryside Survey: UK Results from 2007 CHAPTER 2 • The National Picture, Natural Environment Research Council, November 2008; Table 2.3: Estimated area ('000s ha) of selected Priority Habitats in Great Britain in 1998 and 2007. Estimates for 1998 could not be calculated for all Priority Habitats.

[14] Bain, C.G., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Keenleyside, C., Labadz, J., Lindsay, R., Littlewood, N., Lunt, P., Miller, C.J., Moxey, A., Orr, H., Reed, M., Smith, P., Swales, V., Thompson, D.B.A., Thompson, P.S., Van de Noort, R., Wilson, J.D. & Worrall, F. (2011) IUCN UK Commission of Inquiry on Peatlands. IUCN UK Peatland Programme, Edinburgh.; Table 1 Summary of organic-rich soils extent and bogs and fen UK BAP type extent; adapted with kind permission from JNCC (2011)

[15] Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds). 2009. Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office, Edinburgh.

## 2.1 Current day land classification

Countryside Survey (or Land Cover Map – LCM) Broad Habitat Types were used as the basis for the current land-use classification system (NERC, 2008a). These were combined with data on agricultural land-use from the June Agricultural Survey by Defra (DEFRA, 2012), details on forestry from the Forestry Commissions (FC, 2007), on priority habitats from the Countryside Survey (NERC, 2008b); and on peatlands from the IUCN Inquiry on Peatlands (IUCN, 2011).

The final ZCB land-use type crossover with CS 2007 Broad Habitat Types, and their descriptions are as in Table 1.

Once rough allocation of current agricultural land, forestry and protected habitats into CS Broad Habitat Type, then estimations were made of the proportion of land that would be 'available' under the ZCB scenario (i.e. areas not protected, nor peatland, nor currently urban developments). Table 2 summarises the land use allocations, and the calculations showing 'available land' for the ZCB scenario.

## 2.2 Land Use

A number of potential land-uses in ZCB are described below. The way they are modelled in the scenario is detailed, with justifications for any assumption used.

All values are multiplied by the area of land allocated to them out of the 'land available' to get long-term carbon accumulation in biomass and in Harvested Wood Products (HWP) per year in mega-tonne $CO_2$-equivalent per year ($MtCO_2e$/yr) (as appropriate – see below) for areas allocated in the model as current natural and productive woodland, new broadleaf and coniferous woodland, and short rotation forestry.

Yield values for short rotation coppice, Miscanthus (perennial grassland), rotational grasses and hemp were multiplied by the areas allocated to them (dependent on the quality of land in them) to get total yield of material per year in million oven-dried tonnes per year (Modt/yr).

Tables 3,4 and 5 summarise the information presented here.

**Current 'natural' UK Woodland (~10% of UK woodland according to Read et al. (2009))**

- **Biomass accumulation (Trees + Litter):** None (assume all UK woodland is reaching maturity and thus should not take in much more carbon for much longer).
- **Products:** None (this is not productive forest).
- **Product end-of-life:** None.
- **Long-term Soil Organic Carbon (SOC) accumulation:** None. It is assumed that current woodland in the UK has neared equilibrium carbon stocks in soils.
- **Waste:** None.

**Current 'productive' UK Woodland (~90% of UK woodland according to Read et al. (2009))**

- **Biomass accumulation (Trees + Litter):** None (assume all UK woodland is reaching maturity and thus should not take in much more carbon for much longer).
- **Products:** 90% of both current coniferous and broadleaf forest is assumed to be productive. Each produces timber, and sequesters carbon, at the same rate, over a long time period, as those newly planted forests (below), assuming once a forest is felled, it is replanted. Coniferous and broadleaf forests are treated separately.
- **Product end-of-life:** None.
- **Long-term SOC accumulation:** None. It is assumed that current woodland in the UK has neared equilibrium carbon stocks in soils.
- **Waste:** None.

**New Natural Broadleaf Woodland**

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from the 'mixed native woodland' example in the Carbon

LookupTables (available here: http://www.forestry.gov.uk/forestry/INFD-8jue9t (Forestry Commission, 2013)). Initial changes in soil carbon due to planting remains as in the example provided, but long-term accumulation is removed. The final figure of 912t$CO_2$e/ha in the stock at 100 years is divided by the number of years (100) to get an average accumulation every year equal to 9.12Mt$CO_2$e/ha/yr).

- **Products:** None (this is not productive forest).
- **Product end-of-life:** None.
- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate, but would require data that we currently do not have in the land model (soil type and current carbon content) – see 2.9 Carbon sequestration/emissions that are not counted in the scenario. Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** None.

**New Natural Coniferous Woodland**

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from table 3.2 in Morison et al. (2012). The figure for Sitka Spruce over 90 years (no harvest, no thinning - SS YC12) is taken as 'representative' of a coniferous forest. It is 8.8t$CO_2$e/ha/yr.
- **Products:** None (this is not productive forest).
- **Product end-of-life:** None.
- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate (see above). Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** None.

**New Productive Coniferous Woodland**

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from table 3.13 in Morison et al. (2012). The figure for Sitka Spruce woodland (YC20, 2m spacing, un-thinned, 51 year rotation) is used as 'representative' of a productive coniferous forest. Values for the long-term stock of carbon accumulated in trees and litter (425t$CO_2$e/ha) were divided by 100 years to get a long-term annual accumulation of 2.25t$CO_2$e/ha/yr.
- **Products:** The same 'representative' example from table 3.1.3 was used (SS YC20, 2m spacing, un-thinned, 51 year rotation), and the figure for long-term carbon stock in harvested wood products (HWP) of 147t$CO_2$e/ha was again divided by 100 (years) to get an average annual accumulation of 1.47t$CO_2$e/ha/yr.
- **Product end-of-life:** See '2.7 End of life' below.
- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate (see above). Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** Waste fraction of 0.05 during harvesting is already included in the model of HWP above.

**New Productive Broadleaf Woodland**

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from table 3.13 in Morison et al. (2012). The figure for Oak woodland (YC4, 1.2m spacing, thinned, 95 year rotation) is used as 'representative' of a productive broadleaf forest. Values for the long-term stock of carbon accumulated in trees and litter (249t$CO_2$e/ha) were divided by 100 years to get a long-term annual accumulation of 2.49t$CO_2$e/ha/yr.
- **Products:** The same 'representative' example from table 3.1.3 was used (Oak, YC4, 1.2m spacing, thinned, 95 year rotation), and the figure for long-term carbon stock in harvested wood products (HWP) of 70t$CO_2$e/ha was again divided by 100 (years) to get an average annual accumulation of 0.7t$CO_2$e/ha/yr.
- **Product end-of-life:** See '2.7 End of life' below.

- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate (see above). Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** Waste fraction of 0.05 during harvesting is already included in the model of HWP above.

**Short Rotation Forestry**

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from table 3.13 in Morison et al. (2012). The figure for Poplar (YC12, 26 year rotation) is used as 'representative' of a short rotation forest. Values for the long-term stock of carbon accumulated in trees and litter (326.33t$CO_2$e/ha) were divided by 100 years to get a long-term annual accumulation of 3.26t$CO_2$e/ha/yr.
- **Products:** The same 'representative' example from table 3.1.3 was used (Poplar, YC12, 26 year rotation), and the figure for long-term carbon stock in harvested wood products (HWP) of 132t$CO_2$e/ha was this time divided by one rotation (26 years) to get an average annual accumulation of 5.08t$CO_2$e/ha/yr. This is because there is likely to be more than one rotation over a long period. The accumulation in trees + litter on average should not increase much, but the fast-growth and felling on a short rotation should be repeatedly yield the same amount. This is then converted into odt/yr by dividing by the amount of carbon in $CO_2$ (44/12 = 3.67), and then by 0.5tC/odt (Broadmeadow and Matthews, 2003), so that it may be used as timber in buildings or as biomass for energy or fuel production.
- **Product end-of-life:** None. Since we allocate whether or not this product is used as fuel or as HWP later in the model, we do not include any figure for waste going to landfill from this product stream.
- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate (see above). Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** Waste fraction of 0.05 during harvesting is already included in the model of HWP above.

**Short Rotation Coppice**

- **Biomass accumulation (Trees + Litter):** None (due to very short rotation).
- **Products:** Various yields, depending on land quality/type (see Table 5). Yield increase of 50% expected in the future (Carbon Trust (2004) report between 30% and 100% crop yield improvements).
- **Long-term SOC accumulation:** None. It is assumed that the land planted on will currently be in equilibrium and therefore no long-term accumulation will occur. Short-term effects on SOC from land-use change are dealt with elsewhere.
- **Waste:** We assume a fraction of 0.05 from that produced is wasted.

**Perennial Grass (Miscanthus)**

- **Biomass accumulation (Trees + Litter):** None (due to very short rotation).
- **Products:** Various yields, depending on land quality/type (see Table 5). Yield increase of 50% expected in the future (Carbon Trust (2004) report between 30% and 100% crop yield improvements).
- **Long-term SOC accumulation:** None. It is assumed that the land planted on will currently be in equilibrium and therefore no long-term accumulation will occur. Short-term effects on SOC from land-use change are dealt with elsewhere..
- **Waste:** We assume a fraction of 0.05 from that produced is wasted, and potentially returned to the land to provide nutrients.

**Rotational Grass**

- **Biomass accumulation (Trees + Litter):** None (due to very short rotation).
- **Products:** Various yields, depending on land quality/type (see Table 5). Yield increase of 50% expected in the future (Carbon Trust (2004) report between 30% and 100% crop yield improvements).

- **Long-term SOC accumulation:** None. It is assumed that the land planted on will currently be in equilibrium and therefore no long-term accumulation will occur. Short-term effects on SOC from land-use change are dealt with elsewhere.
- **Waste:** We assume a fraction of 0.05 from that produced is wasted, and potentially returned to the land to provide nutrients.

**Hemp**

- **Biomass accumulation (Trees + Litter):** None (due to very short rotation).
- **Products:** Various yields, depending on land quality/type (see Table 5). Yield increase of 50% expected in the future (Carbon Trust (2004) report between 30% and 100% crop yield improvements).
- **Long-term SOC accumulation:** None. It is assumed that the land planted on will currently be in equilibrium and therefore no long-term accumulation will occur. Short-term effects on SOC from land-use change are dealt with elsewhere.
- **Waste:** We assume a fraction of 0.05 from that produced is wasted.

**Table 3: Long-term biomass (Trees + Litter) carbon accumulation ($tCO_2e/ha/yr$). Original Broad Habitat type is displayed in the first row; potential land-use in the ZCB scenario is in displayed in the first column.**

| | Broadleaf Woodland | Coniferous Woodland | Temporary grass | Arable + Horticultural Cropland | Improved grassland | Semi-natural grassland | Mountain, Heath and Bog | Urban Areas | **Refs** |
|---|---|---|---|---|---|---|---|---|---|
| Natural Coniferous Woodland | 9.11 | 9.11 | 9.11 | 9.11 | 9.11 | 9.11 | 9.11 | 9.11 | Carbon Lookup Tables |
| Natural Broadleaf Woodland | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | Morison et al. (2012) |
| Productive Broadleaf Woodland | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | Morison et al. (2012) |
| Productive Coniferous Woodland | 4.25 | 4.25 | 4.25 | 4.25 | 4.25 | 4.25 | 4.25 | 4.25 | Morison et al. (2012) |
| Short Rotation Forestry | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 | 3.26 | Morison et al. (2012) |

**Table 4: Long-term HWP carbon accumulation ($tCO_2e/ha/yr$) [NB See Table 5 for odt/yr equivalents]. Original Broad Habitat type is displayed in the first row; potential land-use in the ZCB scenario is in displayed in the first column.**

| | Broadleaf Woodland | Coniferous Woodland | Temporary grass | Arable + Horticultural Cropland | Improved grassland | Semi-natural grassland | Mountain, Heath and Bog | Urban Areas | **Refs** |
|---|---|---|---|---|---|---|---|---|---|
| Natural Coniferous Woodland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| Natural Broadleaf Woodland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| Productive Broadleaf Woodland | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | Morison et al. (2012) |
| Productive Coniferous Woodland | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 | Morison et al. (2012) |
| Short Rotation Forestry | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | Morison et al. (2012) |

**Table 5: Current yield (odt/ha/yr) of various energy crops on various land types. Original Broad Habitat type is displayed in the first row; potential land-use in the ZCB scenario is in displayed in the first column.**

| | Temporary grassland | Arable + Horticultural Cropland | Improved grassland | Semi-natural grassland | Mountain, Heath and Bog | **Reference** |
|---|---|---|---|---|---|---|
| Productive Broadleaf Woodland | 0.38 [1.13] | 0.38 [1.13] | 0.38 [1.13] | 0.38 [1.13] | 0.38 [1.13] | = 0.7 / (44/12) / 0.5 (converting $tCO_2e$/ha/yr into odt/ha/yr (Broadmeadow and Matthews, 2003)) [NB For comparison only] ** |
| Productive Coniferous Woodland | 0.8 [1.55] | 0.8 [1.55] | 0.8 [1.55] | 0.8 [1.55] | 0.8 [1.55] | = 1.47 / (44/12) / 0.5 (converting $tCO_2e$/ha/yr into odt/ha/yr (Broadmeadow and Matthews, 2003)) [NB For comparison only] ** |
| Short Rotation Forestry (SRF) | 2.77 | 2.77 | 2.77 | 2.77 | 2.77 | = 5.08 / (44/12) / 0.5 (converting $tCO_2e$/ha/yr into odt/ha/yr (Broadmeadow and Matthews, 2003)) |
| Short Rotation Coppice (SRC) | 12 | 12 | 12 | 8 | 4 | 12odt/ha/yr on 'good quality' land (Sims et al., 2006; Taylor et al., 2005); 9-15 on improved pasture, 5-11 on moderate, rough grazing land, 1-7 on very poor land (Anderson et al., 2005) |
| Miscanthus | 14.5 | 14.5 | 12 | 10 | 10 | 13-16odt/ha/yr on arable (Sims et al., 2006); 9-15odt/ha/yr on Grade 3 or 4 (Lovett et al., 2009); 10odt/ha/yr on grassland (Richter et al., 2007) |
| Rotational Grass | 9.5 | 9.5 | 6.5 | n/a | n/a | 5-14odt/ha/yr on leys (Spedding, 1980); 6-7odt/ha/yr on pasture (Kadziuiene, 2009) |
| Hemp | 6.75 | 6.75 | n/a | n/a | n/a | 5.5-8odt/ha/yr (Weightman and Kindred, 2005; Garstand et al., 2005) |
| ** NB These figures include decay of wood products too and so cannot strictly be taken as yield figures, but may be helpful for comparison. Using 'end-of-life' figures, of 3.6Mt$CO_2e$/yr waste wood + paper in landfill from 2603.7kha of productive forest, provides and additional 0.75odt/ha/yr that is produced on average by forestry in the UK. The value including this figure is shown in [square parentheses] | | | | | | |

## 2.3 Soil Organic Carbon (SOC)

### 2.3.1 Land Use Change (LUC)

Soil Organic Carbon stocks change as land use is changed. Values are taken from research by J. Bellarby of the University of Aberdeen:

> "Values for LUC have been derived from (Bell et al., 2011), who provide estimates of carbon stocks in % for four land uses (cropland, woodland, temporary and permanent grassland). These are based on several UK databases with a total of 24777 soil samples, which were sampled over the whole UK over a range of soil types and management practices. Therefore the variability of UK soils is reflected, so that it was considered the most relevant data to use. The different soil databases also had to be harmonized into the four land use categories used in (Bell et al., 2011). An additional land use category that may be relevant for the ZCB assessment would be bioenergy. However, this land use can be matched to temporary grassland as the ZCB scenarios use permanent bioenergy crops using e.g. short rotation coppice (SRC).
>
> Median values were applied to a depth of 30 cm with the provided bulk densities to calculate carbon stocks in t C/ha, which was then converted into t $CO_2$/ha by multiplying with 3.67. Decay rates given in (Bell et al., 2011) were then used to estimate the carbon loss/gain that would occur over 20 years, which was then used to derive carbon sequestration rates in t$CO_2$/ha/year ... However, there are 3 LUC where a new carbon stock level is already reached after less than 20 years associated with a loss in carbon. SOC sequestration often occurs over a longer time period with the maximum being 177 years. Gains and losses of SOC will be faster in initial years, so that the rates provided … can only be used over the time period stated. If SOC rate would be used over a longer time period it would be an overestimation of SOC sequestered and either different rates for the whole longer time period (e.g. 40 years) would have to be calculated or for the second time period only (e.g. 20 – 40 years). This is obviously not an option for the LUCs where a new carbon stock level is reached in less than 20 years."

Although some SOC losses occur over shorter periods (some only for 11 years, others for 15), a standard of 20 years is used in the model as a simplification. Given the uncertainty attached to knowledge of SOC loss or gain in LUC, this represents perhaps an *overestimate* of SOC lost during LUC. These values were multiplied by the area of land allocated to each land-use type out of the 'available' land in the model to get total values for SOC lost or gained in the UK over 20 years. We assume SOC stocks remain the same if the land use is unaltered.

**Table 6. SOC change in stocks from Land Use Change ($tCO_2e/ha/yr$); W = woodland; P = permanent grassland; T = temporary grassland; C = Cropland. Taken from Bell et al. (2011). Maximum period over which SOC stocks change = 20 years. Original Broad Habitat type (‘land converted from’)is displayed in the first row; potential land-use in the ZCB scenario (‘land converted to’) is in displayed in the first column.**

| Current Land Type (land converted from) | Broadleaf Woodland | Coniferous Woodland | Temporary grassland | Arable + Horticultral Cropland | Improved grassland | Semi-natural grassland | Mountain, Heath and Bog | Urban Areas | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Classified as** | W | W | T | C | P | P | P | P | | |
| Land Use in ZCB3 (land converted to) | | | | | | | | | Refs | |
| Natural Coniferous Woodland | 0 | 0 | 1.3 | 2.6 | -0.7 | -0.7 | -0.7 | -0.7 | [11] | W |
| Natural Broadleaf Woodland | 0 | 0 | 1.3 | 2.6 | -0.7 | -0.7 | -0.7 | -0.7 | [11] | W |
| Productive Broadleaf Woodland | 0 | 0 | 1.3 | 2.6 | -0.7 | -0.7 | -0.7 | -0.7 | [11] | W |
| Productive Coniferous Woodland | 0 | 0 | 1.3 | 2.6 | -0.7 | -0.7 | -0.7 | -0.7 | [11] | W |
| Short Rotation Forestry | 0 | 0 | 1.3 | 2.6 | -0.7 | -0.7 | -0.7 | -0.7 | [11] | W |
| Short Rotation Coppice | -1.6 | -1.6 | 2.8 | 5.6 | 0 | -11.8 | -11.8 | 0 | [11] * | P |
| Perrennial Grass (Miscanthus) | -1.6 | -1.6 | 2.8 | 5.6 | 0 | -11.8 | -11.8 | 0 | [11] * | P |
| Rotational Grass (Ryegrass) | -2.8 | -2.8 | 0 | 2.1 | -11.8 | -11.8 | -11.8 | -11.8 | [11] | T |
| Intensive Grazing | -1.6 | -1.6 | 2.8 | 5.6 | 0 | -11.8 | -11.8 | 0 | [11] * | P |
| Rough Grazing | -1.6 | -1.6 | 2.8 | 5.6 | 0 | 0 / -11.8 ** | 0 / -11.8 ** | 0 | [11] * | P |
| Annual Grass (Hemp) | -5.4 | -5.4 | 0 | 0 | -13.4 | -13.4 | -13.4 | -13.4 | [11] | C |
| Food Crops | -5.4 | -5.4 | -6.6 | 0 | -13.4 | -13.4 | -13.4 | -13.4 | [11] | C |
| Feed Crops for Livestock | -5.4 | -5.4 | -6.6 | 0 | -13.4 | -13.4 | -13.4 | -13.4 | [11] | C |

* SOC stocks in ‘semi-natural grassland’ and in ‘mountain, heath and bog’ are likely to be much higher than ‘improved grassland’ and so conversion to more managed areas may result in higher SOC loss than currently heavily managed ‘improved grassland’, although they are all classed as ‘permanent.’
** Since some of this land is already roughly grazed (3026kha ‘semi-natural grassland’; and 2531kha ‘mountain, heath and bog’ then no LUC penalty should apply as long as the land dedicated here is less than this value))

### 2.3.2 Management Practices

Soil Organic Carbon can be built up or lost from cropland and grassland because of the management practices used. Values were taken as in table 7 from research by J. Bellarby of the University of Aberdeen:

**"Cropland:** Values for SOC sequestration rates for cropland management practices have been derived from several sources. The most straightforward values were taken from (Smith et al., 2008) for nutrient management and water management/drainage using the mean estimate for a cool moist climate zone. Other values are mainly based on (Smith et al., 2000) using information on land available for respective cropland management practices and accumulation rates in %. Here, rates for manure/slurry/compost and straw incorporation change with potential reduction on livestock numbers. The total amount of arable land that percentages have been related to is 6.2 Mha.

The majority of sewage sludge (62% = 820 000t) is already recycled to agricultural land. Currently 20% only is incinerated and landfilled, which would be available to put additionally on agricultural land for SOC sequestration (WaterUK, 2005). However, this proportion of biosolids has not passed test to be allowed on agricultural land. Therefore, additional measures would have to be taken to make this proportion of biosolids pass as well. It has been assumed that this is the case for 5% of currently incinerated and landfilled sewage sludge, so that about 0.4% of additional agricultural land could be treated with sewage sludge. The accumulation rate of treated agricultural land will be 5.6 t $CO_2$e/ha. The value provided … has been made applicable to all agricultural land by integrating the agricultural land available for treatment into the sequestration rate (0.4% * 5.6 t $CO_2$/ha).

A move towards more no till practices is feasible in 36.5 % of land with an accumulation rate of 0.73 % according to (Smith et al., 2000). This accumulation rate has been applied to the carbon stock value for cropland provided by (Bell et al., 2011) resulting in the carbon sequestration rate provided. It has been questioned whether no till is really feasible on that much arable land as e.g. water saturated soils are not suitable and crops can also be more prone to disease. However, this mitigation potential has to be seen in conjunction with water management and drainage.

SOC sequestration from manure is a result of diverting manure application from grassland to cropland as cropland would benefit more from the carbon input of manure. Currently about 60% is spread on grassland rather than on cropland (Defra, 2012). The majority of manure is produced by dairy and cattle (6.35 t/head/year) with some produced by pigs (2.4 t/head.year) summing up to over 83 Mt manure using animal head numbers from EUROSTAT. That means that almost 50 Mt would be available to divert to cropland, so that at an application rate of 20 t/ha almost 2.5 Mha (40% of arable land) of additional cropland could be spread with manure and current livestock numbers. A reduction of livestock numbers by 30 % would reduce the amount that could be additionally amended by manure to only 23 % of arable land. Applying the accumulation rate provided by (Smith et al., 2000) again to carbon stocks provided by (Bell et al., 2011) and considering a livestock number reduction by 30% results in the value provided.

Straw has various uses of which the main one is bedding for livestock. A large proportion of straw not used for anything else is also already chopped and incorporated into soil (Copeland and Turley, 2008). Additional straw would only become available with a reduction in livestock numbers. With a 30% reduction in livestock numbers about 1.6 Mt of straw would become available that could be incorporated into soil additionally. This would mean 2.6% of total arable land could be amended at a rate of 10 t/ha with an accumulation rate of 3.8 t $CO_2$/ha/year (Smith et al., 2000).

All the various cropland management practices sum up to an SOC sequestration rate of 3.12 $tCO_2e$/ha/year.

**Grassland:** In grassland management nutrient and grazing management are the main mitigation options without a big range of sequestration rates associated to it (Bellarby et al., 2013; Dawson and Smith, 2007). Generally, grassland has already the highest carbon stock compared to any other land use (Smith et al., 2000). Therefore, the estimate has been kept very conservative. The total here assumes that half of the grassland may still be improved by either nutrient and grazing management whereas the other half may be improved by plant diversity/improved grass species (using the lower estimate) resulting in an overall total of 0.9 t $CO_2e$/ha/year. It is acknowledged that much higher sequestration rates could be achieved in particular cases."

One additional change implemented in ZCB is a reduction in the effectiveness of management techniques on cropland. Because the amount of livestock in the scenario is greatly reduced, then the amount of manure available is also reduced. This lowers the effectiveness of the management practices to being 2.18$tCO_2e$/ha/yr. In the model, all techniques are assumed to be applied (J. Bellarby has already taken into account the fact that not all techniques can be applied to all land), and the values are multiplied by the number of hectares allocated to each land-use in the scenario to get $MtCO_2e$/yr changes in SOC over 20 years. We assume SOC stocks do not change due to management in areas that are not managed grassland or cropland.

**Table 7: SOC from Management Techniques ($tCO_2e$/ha/yr); G = grassland (in the ZCB model, this is improved grassland); C = Cropland. Maximum period over which SOC stocks change = 20 years. Original Broad Habitat type is displayed in the first row; potential land-use in the ZCB scenario is in displayed in the first column.**

| **Current land use** | Temporary grassland | Arable + Horticultural Cropland | Improved grassland | | |
|---|---|---|---|---|---|
| **Classified as** | C | C | G | **Classified as** | **Reference** |
| Land Use in ZCB3 | | | | | |
| Short Rotation Coppice | 0 | 0 | 0.9 | G | (Bellarby et al., 2013; Dawson and Smith, 2007) |
| Perrennial Grass (Miscanthus) | 0 | 0 | 0.9 | G | (Bellarby et al., 2013; Dawson and Smith, 2007) |
| Rotational Grass (Ryegrass) | 0.9 | 0 | 0.9 | G | (Bellarby et al., 2013; Dawson and Smith, 2007) |
| Intensive Grazing | 0 | 0 | 0.9 | G | (Bellarby et al., 2013; Dawson and Smith, 2007) |
| Annual Grass (Hemp) | 2.18 | 2.18 | 0 | C | (Smith et al., 2008) |
| Food Crops | 2.18 | 2.18 | 0 | C | (Smith et al., 2008) |
| Feed Crops for Livestock | 2.18 | 2.18 | 0 | C | (Smith et al., 2008) |

## 2.4 Land Allocation in the Scenario

The initial step in allocating land use in the ZCB scenario is to take figures from the '**Food + Diets**' model for the land requires for food production (arable land required for growing crops for both for human consumption, and for livestock feed), and the land required for grazing livestock. The area required for food production is allocated to the area of 'arable and horticultural land' available. Land required for livestock grazing is divided so that the majority resides on 'improved grassland' – intensive grazing; but a portion is grazed on 'semi-natural grassland' or 'mountain heath and bog' – rough grazing. It is possible for a proportion to be in urban areas (for example in city farms), though this is not explicitly allocated in the model.

After this, the rest of the land-use is allocated by area.

Because of potential loss of soil organic carbon (SOC) during land-use change (see 'Soil Organic Carbon', above), then an effort was made to reduce, as far as possible, changing land-use during making the scenario. The following 'rules' were adhered to:

- Current forested land remains forested (and woodland is managed as it is now, more or less – natural forests stay so, and productive forests keep producing wood).
- Land that is currently 'arable and horticultural land' is only used for crops for human and animal feed production, with possibly hemp on rotation if there is sufficient space.
- Land that is currently 'temporary grassland' is used for hemp production or other grasses than are currently grown on rotation, or are harvested annually.
- Land that is currently 'improved grassland' is used for grazing livestock, Miscanthus, SRC, SRF and productive (harvested for timber) forestry, or natural woodland.
- Land that is currently 'semi-natural' grass is used for some grazing, SRF, productive and natural and productive forest. SRC and Miscanthus should not be allocated to this land due to high SOC loss.
- Land that is currently 'Mountain, Heath and Bog' can be used for some grazing, SRF and natural and productive forest. SRC and Miscanthus should not be allocated to this land due to high SOC loss.
- No land-use is allocated to Urban areas since urban grassland is counted under 'improved grassland'. Though some urban areas may be used for food production, this is not counted in the model and no data has been found as to how big an area this might be..

The main aim during allocation of land in the ZCB scenario is to balance the needs of the food production model ('**Food + Diets**'), energy model ('**Power Up**', '**Power Down**', and '**Hourly model**') (biomass for biofuels, heating/CHP and biogas/AD), and those of the entire scenario in terms of providing sufficient carbon sequestration that can 'offset' the residual emissions over a long period of time.

## 2.5 Peatlands

According to Bain et al. (2011), healthy peatland can capture roughly 1.1-2.6 $tCO_2e$ per hectare every year. Since most peatland ('fens' and 'bogs' as defined by NERC (2008b)) is 'protected' land under the ZCB land allocation (i.e. we do not do anything with it in the scenario), then we choose a fraction of it to be restored. It is understood that some peatland is currently used for agricultural purposes – some 161 kha (0.16 Mha – 7% of peatland in the UK) on cropland and temporary grassland (Natural England, 2010). This is not explicitly modelled in the scenario, though if any area is left 'unused' in the 'temporary grassland' and 'arable land' BS categories, then potentially this could be restored. The fraction restored in the scenario should not exceed 0.93 in case no area can be restored on these land-use types. In reality, it may be better to restore arable peatland at the expense of converting some other land-types to arable land. We do not explicitly model this in the scenario.

Since there is an estimated 2.3 Mha of peatland in the UK (ibid.), then we multiply this by the fraction we assume restored, and then by an average of the above figure (1.85$tCO_2e$/ha/yr) to get the value for the annual accumulation of carbon in peatlands. The remaining peatland is assumed to be emitting GHGs at the same rate as today, therefore, we multiply todays' emissions from wetlands by the fractional area remaining 'unrestored' in the scenario. These two figures are added together to get the 'net carbon accumulation' of peatlands.

N.B. As we do not perform an explicit spatial analysis of the location of onshore wind farms, it is difficult to include their effects on the scenario. We do not restore all peatland in the scenario, as we believe this to be unrealistic. Where wind farms have to be located on peatland (it is assumed that areas that are not peat-forming would be prioritised), then we assume that restoration of the rest of the peatland must happen alongside wind farm development. We do not explicitly count these effects, however.

## 2.6 Product allocation and energy production from biomass in the scenario

There are various ‘products’ that come out of the scenario:

- Annual accumulation of carbon stocks in HWP ($MtCO_2e$/yr; over ~100 years)
- Annual tonnage of product from Miscanthus (odt/yr; over 100+ years)
- Annual tonnage of product from short rotation coppice (odt/yr; over 100+ years)
- Annual tonnage of product from short rotation forestry (odt/yr; over 100+ years)
- Annual tonnage of product from rotational grasslands (odt/yr; over 100+ years)
- Annual tonnage of product from hemp (odt/yr; over 100+ years)
- Waste fraction of 0.05 from all products.

These products can be allocated to the ‘uses’ by fraction as described in table 8. Although some products can have many different uses, those for which they are usually recommended are prioritised here.

**Table 8: Potential uses of ‘products’ from ZCB land-use scenario. ‘x’ represents where a product may be allocated (as required), and no mark signifies that the product may not be allocated to this use. If required, conversion between $MtCO_2e$/yr and Modt/yr can be used (divide by $MtCO_2e$/MtC (44/12); and then by MtC/Modt (0.5 – Broadmeadow and Matthews, 2003)).**

| | **Use** | | | | | | |
|---|---|---|---|---|---|---|---|
| | Heating/ CHP (Modt/yr) | Biogas/AD (Modt/yr) | FT Biofuels (Modt/yr) | Buildings and infrastructure ($MtCO_2e$/yr) | Biochar (Modt/yr) | Waste | **Notes** |
| Productive Broadleaf Woodland ($MtCO_2e$/yr) | | | | x | x | 0.05 | * |
| Productive Coniferous Woodland ($MtCO_2e$/yr) | | | | x | x | 0.05 | * |
| Short Rotation Forestry (Modt/yr) | x | | | x | x | 0.05 | ** |
| Short Rotation Coppice (Modt/yr) | x | | x | | | 0.05 | |
| Miscanthus (Modt/yr) | | x | x | | | 0.05 | |
| Rotational Grass (Modt/yr) | | x | | | | 0.05 | |
| Hemp (Modt/yr) | | x | | x | | 0.05 | |

* Waste fraction of 0.05 already applied in long-term annual accumulation of carbon in HWP, so other fractions should add to 1 here (Morison et al., 2012). Also, implicit in the model is a division between long-lived wood produces (e.g. timber) and short-lived products (e.g. paper). Paper is assumed to have a lifetime of roughly 5 years (Morison et al., 2012) and so on a long-term (~100 year) basis passes straight through the HWP stream. It is assumed that almost all of the accumulation of carbon in wood products over this period is therefore in timber and can be allocated as such.
** Waste fraction of 0.05 already applied in long-term annual accumulation of carbon in HWP, so other fractions should add to 1 here (Morison et al., 2012).

**Heating/CHP:** Products allocated to heating/CHP are converted to TWh energy supplied via a standard conversion of 4.72TWh/Modt (17MJ/kg) (Natural England, 2007).

**Biogas/AD:** Products allocated to biogas/AD are converted to TWh energy supplied via a standard conversion of 4.72TWh/Modt (17MJ/kg) (Natural England, 2007).

**FT Biofuels:** Products allocated to FT Biofuels are first converted to TWh energy supplied via a standard conversion of 4.72TWh/Modt (17MJ/kg) (Natural England, 2007; similar values for willow (SRC) and Miscanthus in Biomass Task Force (2005)).

**Buildings and infrastructure:** Any products that are not already measured in $MtCO_2e/yr$ i.e. that from short rotation forestry (HWP from productive coniferous and broadleaf forests are already in $MtCO_2e/yr$), that are allocated to building materials are converted into $MtCO_2e$ by multiplying by the amount of carbon per oven-dried-tonne, 0.5MtC/Modt, (Broadmeadow and Matthews, 2003), and then the amount of $CO_2$ per tonne carbon (44/12), so that in total there is 1.83$MtCO_2e$/Modt product. According to Sadler and Robson (*undated*), up to 22$MtCO_2e$ (net) could be captured in buildings and infrastructure in the UK every year if natural materials were maximally used – we make sure that this limit is not exceeded in the model.

**Biochar:** Any products allocated to biochar production are converted to $MtCO_2e$ stored in the biochar by multiplying by 0.72$MtCO_2e$/Modt (derived using percentage content of carbon per odt of feedstock from Shackley and Sohi (2010) and biochar stability factor of 0.68 from Hammond et al. (2011), then converted into $MtCO_2e$). Were biochar applied to land over the course of 100 years to the maximum recommended ‘stock’ (1800$tCO_2e$/ha as found naturally occurring (Shakley et al., 2011)), then a rate of application of 18$tCO_2e$/ha/yr can be used to calculate the potential land are required for application of biochar to soils. This can be compared to the land area used to produce biochar to see if it forms a ‘closed-loop’ system over 100 years, helping improve nutrient and water retention (Parliamentary Office of Science and Technology, 2010).

Note: The energy produced from the process is added to the Biogas/AD stock (see 3.10 Biomass for hourly energy model). 0.38TWh/Modt is produced according to Shackley and Sohi (2010).

**Waste:** The 0.05 fraction of waste produces does not tie into any other final processes – it is assumed to be unrecoverable waste produced by harvesting product from the land. In all cases therefore, it is assumed that this proportion of the product remains in, or is returned to the land. It is assumed that in the case of forestry and coppice, it is mostly the leaves and fine roots that are lost. Since these contain the highest proportion of nutrients in the plant matter, then instead of depleting nutrient stocks in the ground, the majority of nutrients are returned, completing the nutrient cycle. Zeng (2008) states that the carbon to nitrogen ratio (for example) in leaves and fine roots is much higher than that of the more ‘woody’ biomass of trees, and so comparatively little nutrients are ‘locked up’. In the case of grasses such as Miscanthus, rotational grass and hemp, the waste fraction is also presumed to be the nutrient- and protein-rich parts of the plant matter that are returned to the soil together with their nutrients.

## 2.7 End-of-life

**Landfill/Silo:** The model used to calculate the annual accumulation of carbon in HWP above (in Morison et al., 2012) *includes* the decay of the products after a lifetime in use (equal to the rotation period of the trees) – the products simply completely decay, releasing all their stored carbon back to the atmosphere after this period. An additional factor, therefore, must be used to model any timber or paper that goes into landfill and does not completely biodegrade (there is some additional carbon storage here at the end-of-life).

Current estimates for how much carbon accumulates in landfill annually are varied. Fawcett et al. (2002) estimate that 24.20$MtCO_2e/yr$ was added to landfill in the UK in the form of paper and timber. Corrected for the proportion which comes from UK timber (85% of the carbon sequestered in wood products in the UK is currently in imported timber, according to Broadmeadow and Matthews (2003)), this means roughly 3.6$MtCO_2e/yr$ is added to landfill from timber and paper products.

Assuming eventually, even after re-use and recycling, this timber will end up in landfill, and that landfill is designed with carbon storage in mind (i.e. as a ‘storage soli’), there is an additional portion attributed to the additional HWPs that come out of new forestry. An estimate of this is made by calculating the fractional increase in ‘productive’ forest area in the ZCB scenario (currently, about 90% of UK forest area is productive in some way according to Read et al. (2009) = 0.9 x (1385 + 1508) = 2603.7kha of productive woodland in the UK (FC, 2012)), and then multiplying this by the current carbon accumulating in landfill annually. Therefore, this, *in addition* to the original 3.6Mt$CO_2$e/yr is said to be accumulating in landfill.

Concerns about 'breaking the nutrient cycle' by burying natural materials in this way are unfounded according to Zeng (2008), who states that the carbon to nitrogen ratio (for example) in leaves and fine roots is much higher than that of the more 'woody' biomass of trees, and so comparatively little nutrients are 'locked up'.

**Biochar:** Since we can calculate roughly the amount of material this equates to in Modt (Mt$CO_2$e/yr converted to MtC by dividing by (44/12), and then into Modt by dividing by 0.5MtC/Modt (Broadmeadow and Matthews, 2003)), we can also decide to convert this waste into biochar (see 'Biochar' under 'Product allocation in the scenario') should we want to.

**AD Digestate:** The digestate from anaerobic digestion (AD), once it has been used to produce energy can be re-used to make biochar, however, in this scenario, it was decided that the digestate should be returned to the soil to act as fertiliser – again, completing the nutrient cycle.

## 2.8 Carbon sequestration in the scenario

Multiple values for the annual accumulation of carbon in the scenario, that all stem from the ZCB land-use model. These are:

- Changes in SOC from LUC and management techniques (Mt$CO_2$e/yr; over 20 years).
- Annual accumulation of carbon stocks in biomass (trees + litter) (Mt$CO_2$e/yr; over ~100 years) from natural and productive woodlands, and short rotation forestry.
- Annual accumulation of carbon stocks in HWP in buildings and infrastructure (Mt$CO_2$e/yr; over ~100 years) from productive woodlands, short rotation forestry and hemp (if allocated here).
- Annual accumulation of carbon in storage silos (Mt$CO_2$e/yr; over 100+ years) from end-of life of HWP.
- Annual accumulation of carbon in peatlands (Mt$CO_2$e/yr; over 100+ years).
- Annual accumulation of carbon in the form of biochar (Mt$CO_2$e/yr; over 100 years).

Changes in SOC from LUC and land management are summed and checked to be greater than or equal to zero. This represents no net loss of SOC on an annual basis for the first 20 years of the ZCB scenario. We do not count this towards sequestration totals as the processes do not last long enough, and therefore cannot continuously 'offset' any residual emissions in the scenario.

The accumulation of carbon in biomass (trees + litter), HWP in buildings, storage silos, peatlands and biochar is summed to give a final estimate of the amount of Mt$CO_2$e/yr that is sequestered by the system as a whole. This figure represents an average amount sequestered every year (it may differ annually, mainly due to different growth rates of trees as various stages of development, but also due to fluctuations in the amount of HWP that is harvested and used) that is sustainable for a period of 100 years.

## 2.9 Carbon sequestration/emissions that are not counted in the scenario

Because we calculate emissions reductions on a 'production' accounting basis, we cannot include carbon sequestration from products that are imported. This includes timber and other HWP that are imported, which currently, amounts to 85% of all the HWP used in the UK (Broadmeadow and Matthews, 2003), though in the scenario it is difficult to tell whether:

- This percentage would decrease as more HWP are produced in UK borders, or

- This percentage would increase as the construction industry uses more and more natural materials in buildings.

Were we to conduct emissions accounting on a ‘consumption’ basis, then we could include these imported materials in our model. Similarly, any of these imported materials that ended up in landfill/silos or in biochar production could also be counted as carbon sequestration.

Other potentials for carbon sequestration/emissions that have not been included in the ZCB land-use model include:

- Straw that could be used in buildings (and the potential for other natural building materials), and
- Accumulation of SOC in forest (and other) soils is known to occur on much longer timescales than 20 years. SOC knowledge is very uncertain, and depends heavily on a detailed knowledge of the current carbon levels in the soil (Groenigen et al., 2011). Since we do not have this knowledge (we do not map our land-use changes, but use a measurement of the current ‘available’ area as guidance), then it is impossible to know whether or not there is potential for more sequestration over a longer time period here. Equally, there may be detrimental impacts on SOC in the long-term due to the proposed changes in the model too.
- Although onshore wind plays a significant part in the scenario, again, we have made no estimate of where these wind farms would be. Aside from a rough estimate of what area of peatlands may be affected, we have not explicitly calculated the impact the development of these wind farms might have in various locations.

## 2.10 Biomass for hourly energy model

The land model is constructed such that the energy requirements of the ‘**hourly energy model**’ are met. Values for biomass/CHP and for FT Biofuels (in TWh) are compared directly to the values from the hourly energy model.

In the case of biogas/AD energy from the Anaerobic Digestion of sewage/waste water treatment, waste from agricultural land – straw from cereal production as described in the ‘**Food and Diets**’ model, and manure is added to the biogas produced before compared to the ‘**hourly energy model**’ via fractions of the ‘stretch case’ in National Grid (2009) (for example, with X% reduction in livestock. only X% of the biogas made from manure in National Grid (2009) is assumed). Additionally, there is a small amount of biogas from landfill that remains, and some from biochar production (see below), which is added to the total. The methane content of biogas from AD of waste is assumed to be around 60% (National Grid, 2008).

# References

Andersen, R.S., W.Towers, P.Smith (2005) Assessing the potential for biomass energy to contribute to Scotland’s energy needs, *Biomass and Bioenergy 29 (2) 73-82*

Bain, C.G., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Keenleyside, C., Labadz, J., Lindsay, R., Littlewood, N., Lunt, P., Miller, C.J., Moxey, A., Orr, H., Reed, M., Smith, P., Swales, V., Thompson, D.B.A., Thompson, P.S., Van de Noort, R., Wilson, J.D. & Worrall, F. (2011) IUCN UK Commission of Inquiry on Peatlands. IUCN UK Peatland Programme, Edinburgh.; Table 1 Summary of organic-rich soils extent and bogs and fen UK BAP type extent; adapted with kind permission from JNCC (2011)

Baltic Biogas Bus Project (2009) About Biogas, http://www.balticbiogasbus.eu/web/about-biogas.aspx

Bell, M.J., Worrall, F., Smith, P., Bhogal, A., Black, H., Lilly, A., Barraclough, D., Merrington, G., 2011. UK land-use change and its impact on SOC: 1925–2007. Global Biogeochem. Cycles 25, GB4015.

Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J.P., Smith, P., 2013. Livestock greenhouse gas emissions and mitigation potential in Europe. Global Change Biology 19, 3–18.

Biomass Task Force (2005) Biomass Task Force Report to Government, Oct 2005

Broadmeadow, M. and R. Matthews (June 2003) INFORMATION NOTE: Forests, Carbon and Climate Change: the UK Contribution, *FOREST RESEARCH, Forestry Commission*

Carbon Trust (2004) Energy crops: current status and future prospects, Department of Trade and Industry, 29 Jan 2004
http://webarchive.nationalarchives.gov.uk/+/http://www.dti.gov.uk/energy/renewables/policy/lekreview.pdf

Copeland, J., Turley, D., 2008. National and regional supply/demand balance for agricultural straw in Great Britain.

Dawson, J.J.C., Smith, P., 2007. Carbon losses from soil and its consequences for land-use management. Science of the Total Environment 382, 165–190.

Defra, 2012. The British survey of fertilizer practice: Fertilzer use on farm crops for crop year 2011.

Fawcett, T., A. Hurst and B. Boardman (2002) Carbon UK: ECI RESEARCH REPORT 25, *Industrial Sustainable Development Group Environmental Change Institute, University of Oxford,* March

Forestry Commission (2013) Woodland Carbon Code: 3.4 Project Carbon Sequestration, Carbon Lookup Tables available here: http://www.forestry.gov.uk/forestry/INFD-8jue9t

*Groenigen, Kees Jan van, Astley Hastings, Dermot Forristal, Brendan Roth, Mike Jones, Pete Smith (2011) Soil C storage as affected by tillage and straw management: An assessment using field measurements and model predictions, Agriculture, Ecosystems & Environment Volume 140, Issues 1–2, 30 January 2011, Pages 218–225*
*http://www.sciencedirect.com/science/article/pii/S0167880910003233*

Hammond, Jim, Simon Shackley, Saran Sohi, Peter Brownsort (2011) Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK, Energy Policy 39 (2011) 2646–2655

Kadziuliene, Zydre, Vita Tilvikiene, Zenonas Dabkevicius (2009). Biomass of tall fescue as raw material for biogas production. *International Potash Institute [online] available at: http://www.ipipotash.org/udocs/Biomass_of_tall_fescue_as_raw_material_for_biogas_production_paper.pdf [accessed 01/07/2010]*

Lovett, Andrew A. Gisela M. Sünnenberg, Goetz M. Richter, A. Gordon Dailey, Andrew B. Riche & Angela Karp (2009) Land Use Implications of Increased Biomass Production Identified by GIS-Based Suitability and Yield Mapping for Miscanthus in England. *Bioenerg. Res. 2 17–28. DOI 10.1007/s12155-008-9030-x*

Morison, J., Matthews, R., Miller, G., Perks, M., Randle, T., Vanguelova, E., White, M. and Yamulki, S. (2012) Understanding the carbon and greenhouse gas balance of forests in Britain. *Forestry Commission Research Report. Forestry Commission, Edinburgh. i–vi + 1–149 pp.*

National Grid (2009) The potential of renewable gas in the UK, National Grid. http://www.nationalgrid.com/NR/rdonlyres/9122AEBA-5E50-43CA-81E5-8FD98C2CA4EC/32182/renewablegasWPfinal1.pdf

National Grid (2008) Renewable Gas Project Assumptions Booklet, National Grid

Natural England (2010) England's peatlands: carbon storage and greenhouse gases (NE257), Natural England, 17th Mar http://publications.naturalengland.org.uk/publication/30021

Natural England (2007) Planting and Growing Miscanthus, Best Practice Guidelines For Applicants to Defra's Energy Crops Scheme, Natural England, July 2007, http://www.naturalengland.org.uk/Images/miscanthus-guide_tcm6-4263.pdf

NERC (2008b) Countryside Survey: UK Results from 2007 CHAPTER 2 • The National Picture, Natural Environment Research Council, November 2008; Table 2.3: Estimated area ('000s ha) of selected Priority Habitats in Great Britain in 1998 and 2007. Estimates for 1998 could not be calculated for all Priority Habitats.

Parliamentary Office of Science and Technology (2010) HoP POSTNOTE Number 358 July 2010: Biochar, *The Parliamentary Office of Science and Technology, http://www.parliament.uk/documents/post/postpn358-biochar.pdf*

Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds). 2009. Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office, Edinburgh.

Richter GM, Riche AB, Dailey AG and Powlson DS (2007) Biomass supply for the UK energy market - modelling grass productivity. *3N - Bioenergy Farming Conference, Papenburg, Germany, 13-15 March 2007.*

*Sadler, Piers and David Robson (undated) Carbon Sequestration by Buildings, The Alliance for Sustainable Building Products*

Shackley, Simon and Saran Sohi (editors), UK Biochar Research Centre, Contributing Authors: Peter Brownsort, Sarah Carter, Jason Cook, Colin Cunningham, John Gaunt, James Hammond, Rodrigo Ibarrola, Ondej Mašek, Kirsten Sims and Patricia, Thornley (2010) AN ASSESSMENT OF THE BENEFITS AND ISSUES ASSOCIATED WITH THE APPLICATION OF BIOCHAR TO SOIL: A report commissioned by the United Kingdom Department for Environment, Food and Rural Affairs, and Department of Energy and Climate Change, School of GeoSciences, University of Edinburgh King's Buildings, West Mains Road, Edinburgh, EH9 3JN, UK http://www.geos.ed.ac.uk/homes/sshackle/SP0576_final_report.pdf

Sims REH, Hastings A, Schlamadinger B, Taylor G, Smith P (2006) Energy crops: current status and future prospects. *GlobalChange Biology 12 2054–76.*

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 789 –813.

Smith, P., Powlson, D. s., Smith, J. u., Falloon, P., Coleman, K., 2000. Meeting the UK's climate change commitments: options for carbon mitigation on agricultural land. Soil Use and Management 16, 1–11.

Smyth, Beatrice M., Jerry D. Murphy and Catherine M. O'Brien (2009) What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renewable and Sustainable Energy Reviews 13 (2009) 2349–2360, http://www.grassohol.org/documents/%28Elsevier%29%20Grass%20biomethane%20in%20Ireland.pdf

Spedding, CRW (1980) The Future Role of Grass in the Food Chain*. Proc Nutr. Soc. 9 287.*

Swedish Gas Association (2011) Biogas in Sweden, English summary of the Swedish website Biogasportalen.se - Swedish Gas Association, March 2011, http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&ved=0CCIQFjAA&url=http%3A%2F%2Fwww.biogasportalen.se%2F~%2Fmedia%2FFiles%2Fwww_biogasportalen_se%2FSidhuvud%2FBiogasInSweden.ashx&ei=zHqGUIycNMi_0QWu6ICoBA&usg=AFQjCNGXX999VIFJj6PhnDQTEREtXIP3dA&sig2=ZwSqHz1iQHzcALH4d-MCpg

Taylor, Gail (2007) Improving Trees for Bioenergy Production. *15th European Biomass Conference, Berlin. [online] available at: www.tsec-biosys.ac.uk [accessed 01/07/2010].*

US DoE (2006) Annual Energy Outlook, United States Department of Energy, 2006 p56

WaterUK, 2005. Recycling of biosolids to land.

Weightman, R. and Daniel Kindred (2005) Review and analysis of breeding and regulation of hemp and flax varieties available for growing in the UK. *ADAS. Defra Project NF0530.*

Wenzel, H. (2010) "Breaking the biomass bottleneck of the fossil free society". Report for Concito.

Woods and Bauen (2003) Technology Status Review and Carbon Abatement Potential of Renewable Transport Fuels in the UK, Report commissioned by the DTI, B/U2/00785/REP URN 03/982 p68

Zeng, Ning (2008) Carbon Balance and Management Research Open Access, Carbon sequestration via wood burial, (3 January 2008) *Carbon Balance and Management* 2008, 3:1 doi:10.1186/1750-0680-3-1, http://www.cbmjournal.com/content/3/1/1