PATHWAYS TO A ZERO-CARBON OXFORDSHIRE ANNEX 1: METHODOLOGY FOR LAND USE ANALYSIS

This Annex contains further details on the methodology used to analyse the role of the land use sector in pathways to a zero carbon Oxfordshire, as presented in Chapter 9 of the main report.

1 CURRENT LAND USE IN OXFORDSHIRE

Land use analysis is based on the Natural Capital map of Oxfordshire[1], which combines multiple data sources:

- Ordnance Survey Mastermap: a very detailed map that goes down to the level of individual buildings, gardens and even roadside verges.
- The Thames Valley Environmental Records Centre Habitat and Land Use map, which maps semi-natural habitats such as different types of woodland, shrub, heath and wetland, and identifies Priority Habitats with high biodiversity value.
- The CROME crop map provided by the Rural Payments Agency, which was used to distinguish arable land from intensive pasture ('improved grassland').
- Nature and cultural designations, such as nature reserves, local wildlife sites and ancient monuments.

2 ESTIMATE OF CURRENT CARBON STORAGE AND SEQUESTRATION

Carbon storage and sequestration was calculated using the areas of each type of habitat multiplied by estimates of carbon stored or sequestered per hectare. For non-woodland habitats we used a range of literature sources. For woodland, we calculated average sequestration rates in different types of Oxfordshire woodland using the Woodland Carbon Code Calculator[2]. We used the Forestry Commission's Ecological Site Classification tool[3] to work out what types of woodland are suitable for Oxfordshire's soil types and climate (warm dry, or warm moist on higher land), and what the range of yield classes (productivity) would be in different soils:

- On carbonate soils only Beech is suitable, with a yield class of 5 (low).

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[1] Smith (2019) Natural capital mapping in Oxfordshire – Short report.

[2] www.woodlandcarboncode.org.uk

[3] Forest Research, Ecological Site Classification Decision Support System

- On non-carbonate soils, Beech ranges from yield class 4 to10; Oak 7 to 8; Ash 9, Sycamore 8, Scots pine 9 to 13, Sitka Spruce* 9 on one soil type, otherwise 15 to 19; Larch. 8-10.

We then assumed the following average compositions for different woodland types:

- Semi-natural broadleaved: 50% Beech; 25% Oak; 25% Sycamore, Ash and Birch. Not thinned; planted at 3m spacing.
- Broadleaved plantations: 80% Beech, 20% Oak. Managed with regular thinning and planted at 2.5m spacing.
- Mixed plantations: 25% Beech, 25% Oak, 25% Scot's pine, 25% Larch,
- Conifer plantations, split equally between Scot's pine, Larch and Sitka Spruce*, managed with regular thinning and planted at the closest recommended spacing.

*Note that Sitka Spruce is in fact rarely used in Oxfordshire; it is far more common to see Douglas Fir for example. However, the Forestry Commission's Ecological Site Classification tool predicts that Douglas Fir is not suitable on most woodland soil types in Oxfordshire, so we have assumed Sitka Spruce instead in order to keep the methodology consistent. This could be changed in future but would make little difference to the estimates of carbon storage and sequestration.

For semi-natural woodlands we assume that the woodlands are currently 100 years old, so we take the average sequestration rate from ages 100 to 130 years to estimate sequestration from 2020 to 2050. For plantations we take average sequestration rates over 60 years (the typical rotation length), and then subtract the amount lost due to decay of harvested wood products, which we assume to be 50% (i.e. we assume that 50% of all harvested wood is currently locked up in timber construction or other long lived products, with the rest used for short-lived products such as paper, cheap furniture or fuel combustion).

These figures should be treated as a scoping estimate because metrics of carbon storage and sequestration in ecosystems are highly dependent on a range of factors including soil type, soil depth, soil density, soil and vegetation condition, habitat age, tree species, climate, and management. Even if all these parameters are known, data on how carbon storage and sequestration varies with all these factors is patchy and different sources are not in good agreement.

The breakdown of carbon storage and sequestration by habitat is shown in Table A1 and Figures A1 and A2. The table shows the area of each type of habitat, the estimated carbon storage in tonnes per hectare, the total carbon storage in soil and vegetation, the estimated annual carbon sequestration in tonnes per hectare per year, and the estimated total sequestration from 2020 to 2050. Arable land is a source of emissions due to carbon loss as soils are disturbed during cultivation. This loss is estimated at 0.25 tC/ha/y, or 28,000 tC/y, responsible for an estimated 837,000 tC between 2020 and 2050. It is offset by sequestration, primarily by woodlands and hedgerows[4] (109,000 tC/y) but also by grasslands and other semi-natural habitats, with a small contribution from urban green spaces. As noted above, these estimates are highly uncertain. Individual trees such as street trees and field trees are not included in these estimates due to lack of affordable data.

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[4] Hedgerows and lines of trees come from an experimental dataset provided for research purposes only by Ordnance Survey, and this data should be treated with caution. We have assumed a width of 2.5m for hedgerows and 6m for lines of trees, and subtracted this area from the areas of arable and improved grassland (half and half).

It is estimated that around 23 Mt of carbon is stored in Oxfordshire's soils and vegetation, and an additional 115,000 tonnes is sequestered each year, so that around 3.5 Mt C would be sequestered between 2020 and 2050 if there was no further land use change. However, the carbon stored in soil and vegetation is lost when land is cleared and topsoil removed for new developments of housing and infrastructure. Analysis of land use change from 2014 and 2020 using OS Mastermap shows that 2,710 ha of agricultural land and other natural surfaces were converted to sealed surfaces and buildings. Even if all the land converted was arable, with a relatively low carbon content of 66 tC/ha, this would equate to a loss of 178,880 tonnes of carbon, equivalent to 29,813 tonnes per year, which reduces the net annual sequestration to 85,000 tC/y, or 312,000 t CO_2/y.

Sequestration calculation methodologies

The figures for Oxfordshire produced by BEIS (see Chapter 3, Figure 3.1) indicate annual sequestration of 26,700 t C, or 98,000 t CO_2. This represents only 31% of our estimate, but with a rising trend over time. BEIS produce their regional figures by scaling-down national land use datasets, and by extrapolating from trends in land use change prior to 2007. Our land use figures are based on the detailed natural capital map of Oxfordshire, which is more accurate, and based on more recent data than the BEIS figures. However the main difference arises because we assume continued sequestration of carbon by all woodlands, in line with the figures calculated from the Woodland Carbon Code as described above, whereas BEIS assume that all woodlands older than 100 years have reached an equilibrium and no longer sequester carbon. We also take account of carbon sequestration by hedgerows and lines of trees, gardens, and urban green spaces, which are ignored in the BEIS estimates.

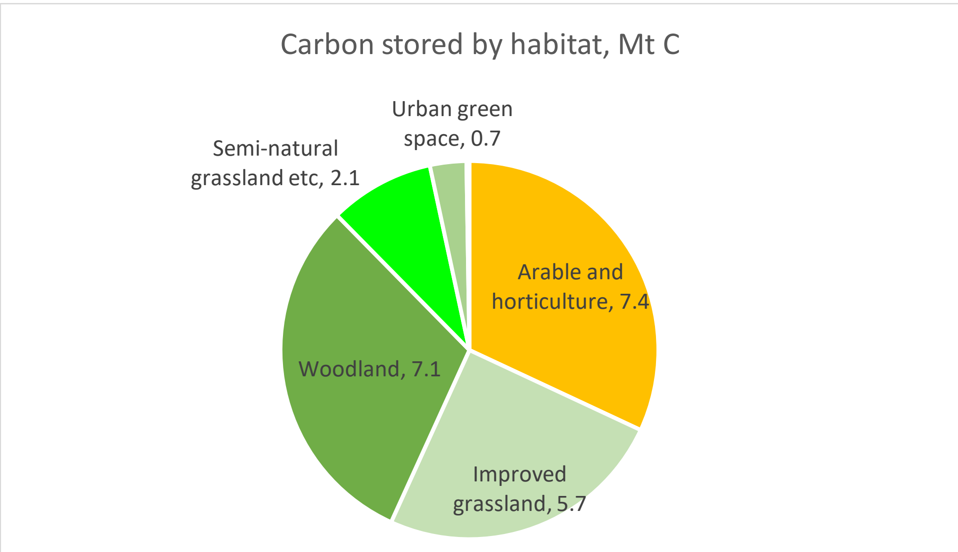

Figure A1: Carbon stored in soils and vegetation, by habitat (Mt C)

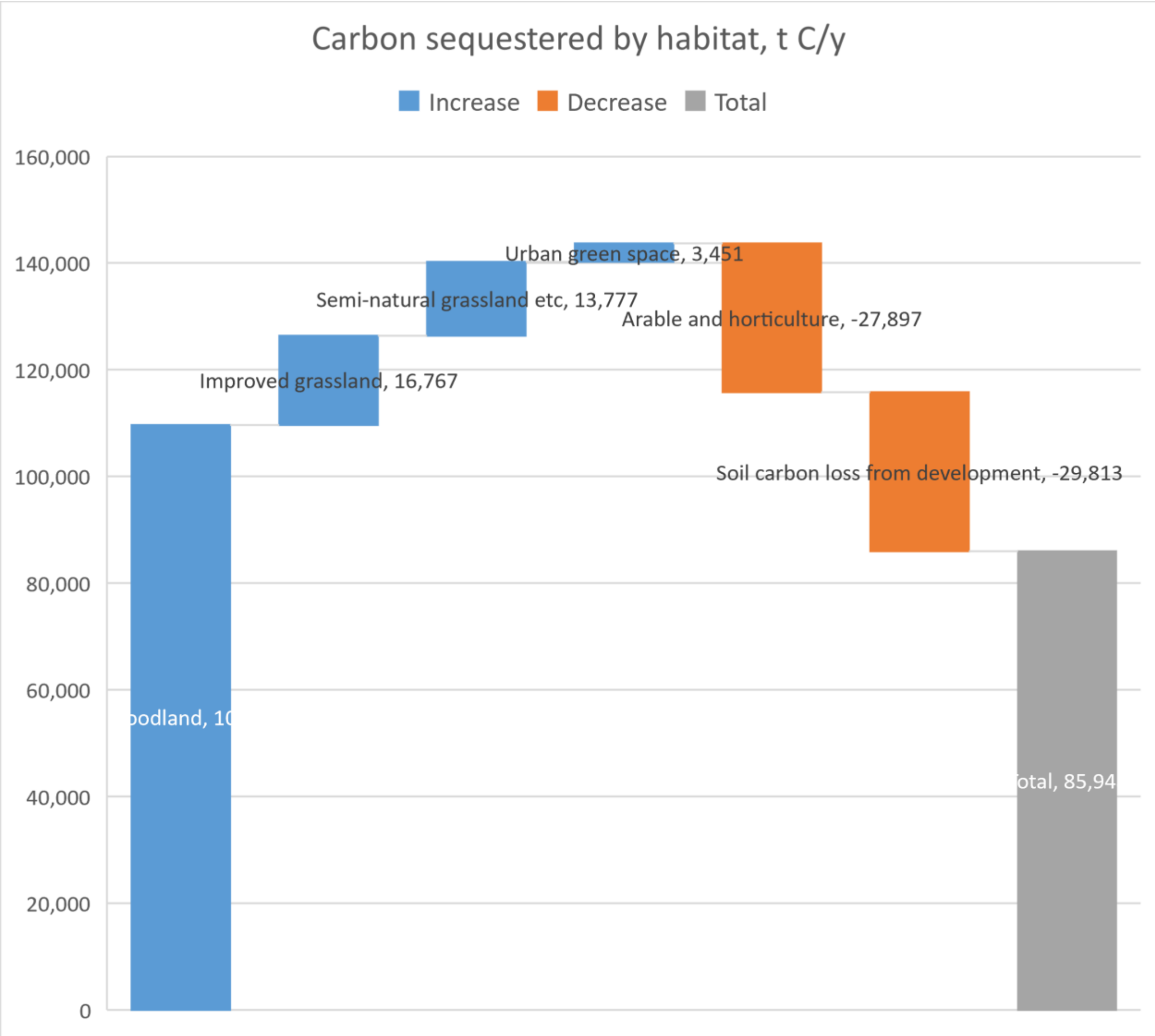

Figure A2: Split of carbon sequestered, t C/y

Table A1 Carbon stored and sequestered by habitat type in Oxfordshire

Habitat	ha	C t/ha	C t	C t/ha/y	C t/y	C sequestered 2020-2050 (t)
Arable and horticulture	109,039	68	7,374,354	-0.26	-27,897	-836,898
Improved grassland	67,105	86	5,737,998	0.25	16,767	503,008
Total intensive farmland	176,144		13,112,352	-0.06	-11,130	-333,890
Conifer plantation	3,279	218	714,888	3.92	12,855	385,646
Mixed woodland	2,977	232	690,317	4.16	12,371	371,136
Broadleaved plantation	1,607	246	394,888	4.39	7,056	211,668
Semi-natural broadleaved woodland	6,698	273	1,828,502	4.08	27,327	819,812
Unknown and other broadleaved woodland	8,758	273	2,390,960	4.08	35,733	1,071,991
Orchards	297	137	40,513	0.16	47	1,421
Hedgerows and lines of trees	5,354	206	1,100,293	2.49	13,356	400,683
Total woodland	28,971		7,160,361	3.75	108,745	3,262,357
Wood pasture and parkland and scattered trees	3,183	137	416,928	1.42	4,504	135,135
Scrub	1,545	164	240,548	0.99	1,529	45,877
Heath	6	109	633	0.97	6	167
Semi-natural grassland	9,681	110	1,034,679	0.61	5,862	175,848
Wetland	3,345	164	379,539	0.55	1,839	55,164
Open mosaic habitats on previously developed land	267	21	5,293	0.14	37	1,109
Total non-woodland semi-natural habitats	18,026		2,077,619	0.76	13,777	413,300
Standing water (lakes, canals, reservoirs)	1,735	27	47,310	0.00	0	0
Running water (rivers, streams, drains)	1,354	5	10,966	0.00	0	0
Total water	3,090	27	58,276	0.00	0	0
Buildings, roads, sealed surfaces, building sites	12,735	0	0	0.00	0	0
Manmade unsealed surface (rail, quarry, track, felled woodland)	1,979	12	23,596	0.00	3	79
Total buildings and manmade surfaces	14,714		23,596	0.00	3	79
Gardens	10,479	18	191,419	0.12	1,257	37,725
Amenity grassland	8,807	55	482,869	0.24	2,115	63,463
Allotments	241	55	13,195	0.00	0	0
Cemeteries and churchyards	121	73	8,808	0.62	75	2,257
Total gardens and urban green space	19,647		696,291	0.18	3,448	103,445
Total	260,592		23,128,495	0.44	114,843	3,445,290
Annual loss of soil carbon from change to sealed surface	2,710			-67.63	-29,813	
Net sequestration (tC/y)					85,030	

3 FOOD PRODUCTION

Analysis of the area of land required to feed Oxfordshire was based on an MSc thesis by Bruce Winney[5]. This in turn was based on scaling up the analysis in Low Carbon Oxford's report on the foodprint of Oxford City[6], using the relative population levels of the county and the city. We calculate the equivalent food demand that can be met in terms of the amount of farmland needed to produce the required calories per food group; there will still be imports and exports of food. The analysis shows that with current diets, there is only enough farmland in the county to produce the equivalent of 76% of our food requirements (Table A2).

Table A2. Farmland area required to feed Oxfordshire with current diets and with the WWF Livewell diet that consumes 75% less meat

Land required to feed Oxfordshire (ha)		
	Current diet	Livewell diet
Fruit & veg	7,930	14,470
Grain & starch	18,488	26,610
Oils & fats	24,458	17,459
Alcohol	5,925	4,308
Red meat	124,993	39,164
Dairy	17,771	21,277
Eggs	5,925	3,707
Other*	3,270	6,660
White meat	28,066	8,331
Total required	**236,826**	**141,986**
Arable & orchards	56,801	62,847
Grassland	142,764	60,441
Other	37,261	18,698
Current farmland in Oxfordshire (ha)		
Arable & orchards	109,039	
Grassland	67,105	
Total	176,144	
Percentage of equivalent food requirements produced in Oxon		
	Current diet	**Livewell diet**
Arable & orchards	192%	173%
Grassland	47%	111%
Total	74%	124%
Spare farmland (ha)	**-60,682**	**34,158**

*Note: in the Low Carbon Oxford analysis 'other' was used as a balancing category to top up the diet to current calorie consumption; however this is probably mainly sugar. An alternative approach would have been to keep 'other' the same as in the current diet, to reduce current overconsumption of calories.

[5] Winney (2020) Land-use trade-offs between a proposed Nature Recovery Network, housing and food production in Oxfordshire. MSc dissertation, Environmental Change Institute, University of Oxford.

[6] Low Carbon Oxford (2016) FoodPrinting Oxford: How to feed a city.

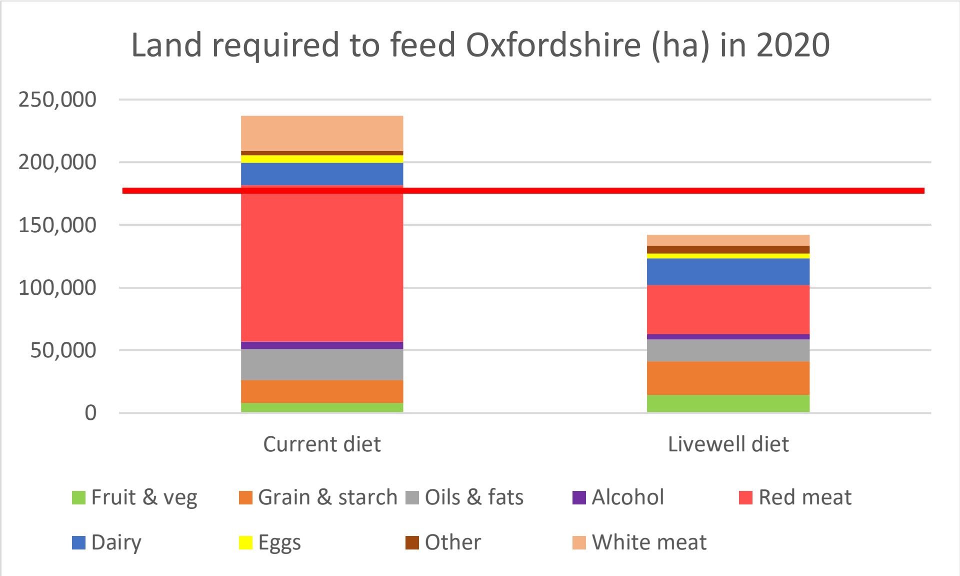

Figure A3: Land required to feed Oxfordshire under current diet and Livewell diet (75% less meat), for 2020 population. Red line shows available farmland in 2020.

As population grows in line with the planned housing growth (assuming all current allocations are built by 2031, and 4,000 dwellings per year built between 2031 and 2050), the demand for farmland for food production will also grow (Table A3). As the population grows from 650,000 to 1,000,000, driven by construction of new housing, the percentage of food demand than can be met locally falls from 74% to 43% by 2050 if current diets are maintained. This means that Oxfordshire imports a significant level of 'embodied emissions' in the food that is produced elsewhere. With the low meat Livewell diet, we can more than meet the equivalent food demand at first, but by 2050 we can only meet 72%.

Table A3: Growth in food demand as number of dwellings and population grows.

Population growth	**2019**	**2030**	**2050**			
Dwellings	295,500	350,000	430,000			
Population	687,524	814,326	1,000,458			
Land required to feed Oxfordshire (ha)	Current diet			Livewell diet		
Arable & orchards	56,801	67277	97899	62,847	74438	108319
Grassland	142,764	169094	246060	60,441	71588	104173
Other	37,261	44133	64221	18,698	22147	32227
Total	**236,826**	**280,505**	**408,179**	**141,986**	**168,173**	**244,719**
Percentage of equivalent food demand met in Oxon	**74%**	**63%**	**43%**	**124%**	**105%**	**72%**

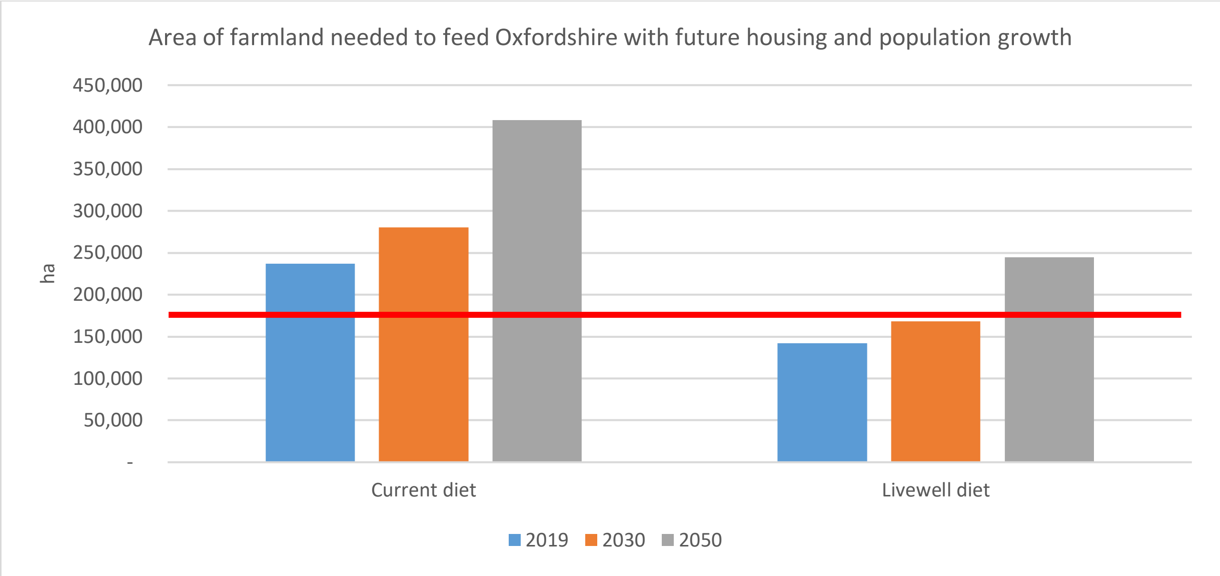

Figure A4: Area of farmland needed to feed Oxfordshire with future housing and population growth (ha) under current diet (SP and TT scenarios) or Livewell diet (ST and OLW scenarios). Red line shows current area of farmland.

Under the *Technological Transformation* scenario, there is no dietary change but there is a focus on increased productivity in farming. This includes use of gene editing and GMO techniques, more use of artificial intelligence for precision agriculture, and more indoor cultivation for horticulture such as vertical farming and hydroponics (although horticulture uses a very small proportion of farmland). In the CCC scenarios[7], there is an assumption that crop productivity increases by 39% (Medium ambition) or 65% (High ambition), though this is acknowledged to be very ambitious as yield increases for the main UK cereal crops have stalled in recent decades[8]. In our scenario we assume that crop productivity increases by 39%, in line with the CCC Medium Ambition scenario, and that livestock productivity increases by 10% due to improvements in animal health. For *Steady Progression* we assume an increase of 10% for crops, in line with recent trends, and no increase for livestock. For the other two pathways we assume an intermediate increase of 20% for crops and 5% for livestock.

We assume that under *Steady Progression* and *Technological Transformation*, regenerative agriculture remains a niche activity, growing to cover only 1% of farmland by 2050. Under *Societal Transformation* and *Oxfordshire Leading the Way*, we assume that there is widespread uptake of these techniques, reaching 50% of all farmland by 2030 and 80% by 2050, with consequent benefits for carbon sequestration as well as biodiversity and soil erosion.

[7] CCC (2018) Land use: Reducing emissions and preparing for climate change

[8] For example the five year average wheat yield has increased by 6% since 2000, from 7.8 to 8.4 t/ha. From analysis of Defra (2020) Agriculture in the UK, Table 7.2.

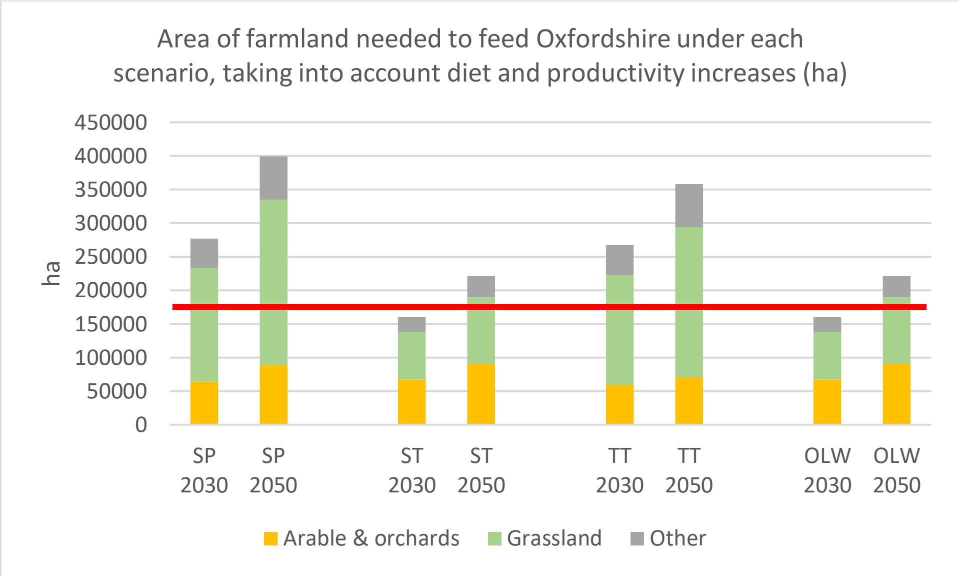

Figure A5: Area of farmland needed to feed Oxfordshire under each scenario, taking into account diet and agricultural productivity increases (ha). Current farmland area shown by the red line. SP and TT have current diet; ST and OLW have Livewell diet. SP has the lowest productivity increase and TT has the highest.

4 PLANTING TREES AND RESTORING OTHER HABITATS

Ongoing work to create an Oxfordshire Tree Opportunity Map[9] considers opportunities for different types of woodland, agroforestry, hedgerows and street trees. The goal is to double tree cover in Oxfordshire from the current 9% (23,000 ha) to 18%, which is consistent with the High Ambition scenario in the CCC land use and climate report. We have built on the methodology being used to create the Tree Opportunity Map for our scenario assumptions, shown in Table A4.

Under *Steady Progression*, we assume a modest rate of new woodland planting of 60 ha per year, driven by continued agri-environment and biodiversity net gain funding. This is consistent with the National Forest Inventory, which records a 72 ha increase per year from 2014 to 2018, some of which could be due to improved accuracy of the inventory. Restoration of other habitats is limited to 5 ha per year of semi-natural grassland.

Under *Societal Transformation* and *Oxfordshire Leading the Way*, we assume that dietary change frees up large amounts of farmland for tree planting and habitat restoration, enabling tree cover to be doubled. With farmers, local authorities and residents all committed to this goal, this is achieved not just through planting woodlands on farmland but also through agroforestry, new hedgerows (half of field boundaries currently have hedgerows; we assume this increases to 90%), and new trees in urban parks and amenity green space (such as round the outside of playing fields) and residential gardens.

A range of other carbon-rich habitats are also restored, doubling the area of shrub, heath, wetlands, chalk grassland, dry acid grassland and floodplain meadows from 4.5% to 9% (Table A5). This habitat restoration and native woodland planting will be primarily targeted within the Nature Recovery Network in order to help connect existing habitats.

In contrast, under *Technological Transformation*, there is less willingness to change behaviour (including diet), as society relies on technical solutions. This constrains the amount of land available for tree planting, and there is also reluctance from farmers, local authorities and residents to add agroforestry, hedgerows and urban trees. As a result, the target to double tree cover is not met, with only around 6,000 ha being added by 2050. The trees planted are mainly fast-growing non-native monocultures destined for harvested wood products including biofuel, so there are few benefits for biodiversity, and even a loss of biodiversity as, with a less strategic and co-ordinates approach to land use, some trees are

[9] Oxfordshire Trees for the Future, Creating a Tree Opportunity Map

planted on high-value habitats such as floodplains and high grade farmland. There is no further restoration of open habitats as tree-planting is prioritised.

5 BIOENERGY

All four scenarios depend on increasing use of bioenergy, as a transport fuel for HGVs, aviation and shipping; for biomass heating; and for BECCS as a negative emission technology. However, to produce the feedstocks locally would require between 37% and 56% of the land in Oxfordshire (Table A6), which would displace food production to other locations in the UK or overseas. We have therefore specified a much lower area of biofuel production in our scenarios, acknowledging that the remainder must be imported.

6 CONSTRAINTS ON AVAILABLE LAND

Although there is good potential to enhance carbon storage and sequestration by Oxfordshire's ecosystems, there will be trade-offs with other carbon reduction options and housing development, as shown in Table A7. The top part of the table shows the land use change for the different carbon reduction options in each scenario and the lower part shows how this affects the proportion of Oxfordshire's demand for food and bioenergy feedstock crops that can be met within the county.

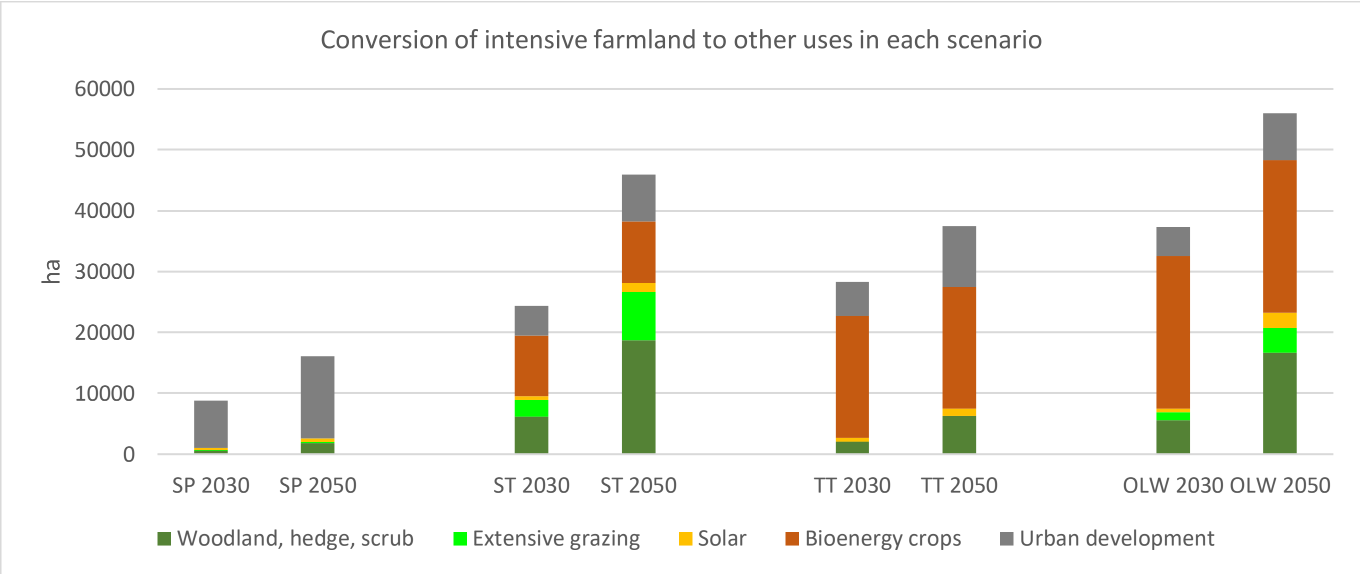

Figure A6: Conversion of intensive farmland to other uses under each scenario.

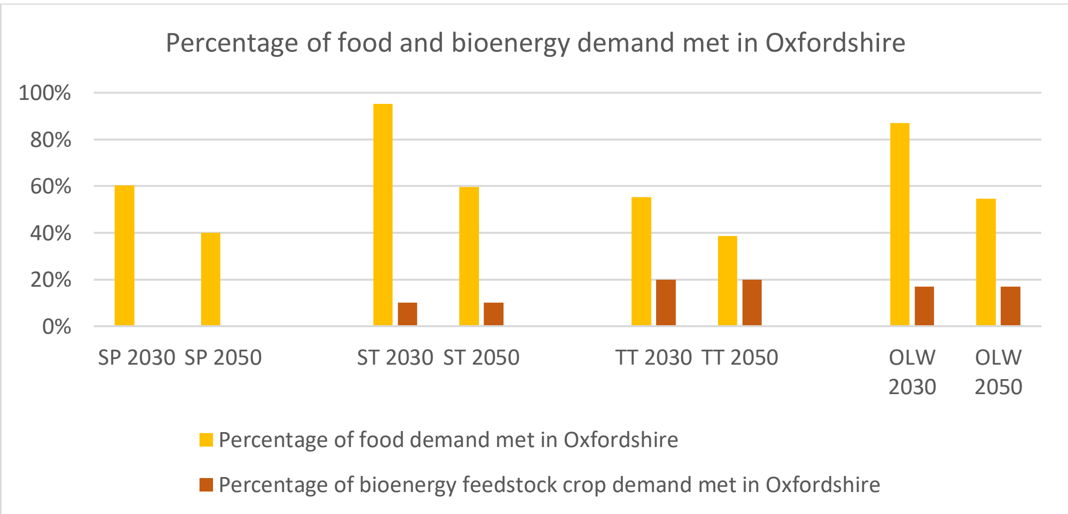

Figure A7: Percentage of food and bioenergy demand that can be met in Oxfordshire under each scenario

Table A4 Assumptions regarding tree planting and habitat restoration in each scenario

Proposed change	Current ha	% cover	SP % changed	SP Ha affected	ST % changed	ST Ha affected	TT % changed	TT Ha affected	OLW % changed	OLW Ha affected
Pasture to woodland	69,782	100%	1.0%	698	10.0%	6978	5.0%	3489	10.0%	6978
Arable to woodland	111,716	100%	1.0%	1117	5.0%	5586	2.5%	2793	5.0%	5586
Arable to silvo arable	111,716	20%	0.0%	0	20.0%	22343	0.0%	0	20.0%	22343
Pasture to silvopasture	69,782	30%	0.0%	0	25.0%	17445	0.0%	0	25.0%	17445
Arable to hedgerow	111,716	100%	0.0%	0	1.2%	1318	0.0%	0	1.2%	1318
Pasture to hedgerow	69,782	100%	0.0%	0	1.2%	823	0.0%	0	1.2%	823
Urban green space	9,168	30%	0.0%	0	5.0%	458	0.0%	0	5.0%	458
Residential gardens	10,479	12%	0.0%	0	20.0%	2096	0.0%	0	20.0%	2096
Total area affected, ha				1,815		57,049		6,282		57,049
Total area of tree or hedge cover added, ha				1,815		24,797		6,282		24,797
New woodland, ha/y				434		434		209		434
New agroforestry, hedges, garden trees, ha/y						1,396		-		1,396

Table A5 Target areas of semi-natural open habitats to restore in the ST and OLW scenarios (split evenly between restoration from arable and pasture)

	Existing area (ha)	% of county	Target new area (ha)	New total area (ha)	% of county
Neutral grassland	5,673	2.2%	5000	10,673	4.1%
Calcareous grassland	1,223	0.5%	1000	2,223	0.9%
Lowland dry acid grassland	58	0.0%	1000	1,058	0.4%
Dense scrub	1,545	0.6%	1000	2,545	1.0%
Heath	6	0.0%	1000	1,006	0.4%
Fen, marsh and swamp	3,345	1.3%	3000	6,345	2.4%
Total	11,849	4.5%	12000	23,849	9.2%

Table A6 Bioenergy feedstock production in the four scenarios

	Forestry residues	SRC willow	Miscanthus	Biodiesel (rapeseed)	Bioethanol (sugar beet)	Bioethanol (wheat)	Biogas (slurry)	Biogas (sugar beet)	SP	ST	TT	OLTW	SP	ST	TT	OLTW
ha/MWh*	0.10	0.02	0.02	0.09	0.03	0.06	0.14	0.02	% of UK elec demand, 2050							
									1.48%	1.41%	1.46%	1.42%				
	Assumed split between feedstocks								Oxfordshire demand (TWh)				Area required for feedstock (ha)			
Power Generation		50%	50%						0.79	2.35	2.21	2.69	14,913	44,106	41,486	50,633
Residential Heat	50%							50%	0.08	0.20	0.17	0.24	5,059	11,959	10,056	14,555
Industrial Heat	50%						25%	25%	-	0.03	0.04	0.03	-	2,808	3,103	2,825
Road Transport				20%	40%	40%			0.07	-	-	-	3,559	-	-	-
Aviation				100%					0.24	0.45	0.47	0.46	20,888	39,851	41,349	40,337
Shipping				100%					-	-	-	0.44	-	-	-	38,656
Hydrogen Production		50%	50%						-	-	0.22	-	-	-	4,119	-
Biomethane Blending							25%	75%	1.01	-	-	-	52,027	-	-	-
Total									2.21	3.04	3.11	3.87	96,447	98,724	100,113	147,006
Percentage of Oxfordshire area													37%	38%	38%	56%
Actual area included in scenario due to land area constraints													0	10,000	20,000	25,000
Area that must be produced elsewhere unless demand is reduced further													96,447	88,724	80,113	122,006

*Source for bioenergy feedstock yields per ha is Forest Research web page Potential yields of biofuels per ha

Table A7 Constraints on land use and implications for imported impacts

	Steady progression		Societal transformation		Technological transformation		Oxfordshire leading the way	
	2030	2050	2030	2050	2030	2050	2030	2050
Farmland used for tree planting, hedgerows, scrub or wetland (ha)	605	1815	6235	18706	2094	6282	5569	16706
Farmland restored to rough grazing (grassland or heath) (ha)	50	150	2667	8000	0	0	1333	4000
Hectares of land used for ground-mounted solar generation	390	670	610	1,500	610	1,200	600	2,600
Hectares of land used for bioenergy feedstock crops	0	0	10,000	10,000	20,000	20,000	25,000	25,000
Land converted to buildings and sealed surfaces	6,000	9,342	2,225	3,483	4,539	6,974	2,225	3,483
Land converted to private gardens	1,289	2,272	980	1,429	859	1,576	980	1,429
Land converted to public urban green space	1,879	3,213	1,667	2,838	1,621	2,795	1,667	2,838
Total area of new development	9,168	14,827	4,871	7,751	7,020	11,345	4,871	7,751
Farmland lost to development	7,746	13,404	4,871	7,751	5,597	9,922	4,871	7,751
Total farmland lost for housing and carbon reduction	8,778	16,001	23,717	43,956	28,301	37,404	37,040	55,056
Crop productivity increase compared to 2020	5%	10%	10%	20%	13%	39%	10%	20%
Livestock productivity increase compared to 2020	0%	0%	2%	5%	3%	10%	2%	5%
Population (driven by housing increase)	814,326	1,000,458	814,326	1,000,458	814,326	1,000,458	814,326	1,000,458
Farmland required to feed Oxfordshire (ha) without productivity improvements	280,505	408,179	168,172	244,717	280,505	408,179	168,172	244,717
Farmland required to feed Oxfordshire (ha) with productivity improvements	277,301	399,279	160,001	221,703	267,310	358,342	160,001	221,703
Farmland remaining (ha)	167,366	160,143	152,434	132,208	147,843	138,740	139,111	121,108
Percentage of food demand met in Oxfordshire	60%	40%	95%	60%	55%	39%	87%	55%
Percentage of bioenergy feedstock crop demand met in Oxfordshire	0%	0%	10%	10%	20%	20%	17%	17%
Hectares of land outside Oxfordshire needed for food (assuming same productivity)	109,934	239,136	7,573	89,515	119,467	219,602	20,897	100,615
Hectares of land outside Oxfordshire needed for bioenergy feedstock crops	96,447	96,447	88,724	88,724	80,113	80,113	122,006	122,006