Environmental RTDI Programme 2000–2006

CLIMATE CHANGE –

Land Use, Land-Use Change and Carbon Stocks

(2000-LS-5.1.2a-M1)

Synthesis Report

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Prepared for the Environmental Protection Agency

by

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CLIMATE CHANGE

The Climate Change Section of the Environmental RTDI Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in this area. The reports in this series are intended as contributions to the necessary debate on climate change and the environment.

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1 Introduction

The Framework Convention on Climate Change (FCCC), which opened for signature in 1992 and extended into legally binding commitments at Kyoto in 1997, required countries in the developed world to introduce policies that would return greenhouse gas emissions to their 1990 levels by 2000. The European Union (EU) agreed an 8% reduction on 1990 levels by 2008–2012; Ireland's agreed contribution to this aim was a maximum increase (not a reduction because of the stage and expected growth of its economy) of 13% by the 2008–2012 commitment period over its 1990 emissions. Within the group of greenhouse gases, the EU also agreed to stabilise CO_2 emissions at the 1990 level by 2000. Government strategy in Ireland is to limit CO_2 equivalent emissions to 13% above the 1990 levels.

The targets for emissions of greenhouse gases in general and CO_2 in particular have been exceeded through growth of both the population and the economy. Recent estimates of annual emissions have shown that the limit for greenhouse gases had already been reached by the date of the Kyoto Protocol (1997) and the total increase to 2001 was 31% (McGettigan and Duffy, 2003). In the present economic conditions, it is unlikely that emissions from industry, vehicles, residential growth, energy production and other activities that burn fossil fuels, will be reduced to meet the targets. Limiting emissions from other sources and increasing sequestration of carbon from the atmosphere into 'sinks' therefore may become important.

Plants absorb CO_2 from the atmosphere during photosynthesis and it becomes part of the plant tissue; standing vegetation, or biomass, therefore contains carbon and is a biomass carbon store. The amount of carbon (t C or Mt C) is the biomass carbon stock. Some plant material falls to the ground as plant litter and may become incorporated into the soil; soil therefore contains organic carbon as well as carbon derived from rocks or other deposits from which it developed. Thereby, soil is also a carbon store, indeed a larger store of carbon than biomass (in Ireland soil holds around 80 times more carbon than biomass). However, vegetation is the conduit through which organic carbon (as CO_2) is taken from the atmosphere and stored in soil. If government policy for land-cover includes the aim of reducing emissions and increasing sequestration of atmospheric CO_2, it is essential to know the carbon stores and fluxes (emissions to or fixation from the atmosphere) of land-cover types and land-cover/soil combinations so that policy may be directed. Baseline inventories of carbon stocks in vegetation (biomass) and in soils are required.

In mid-2000, the Environmental Protection Agency (EPA) began implementation of the Environmental RTDI sub-Measure of the Operational Programme for the Productive Sector (2000–2006). Large-scale, medium-sized projects and desk studies were established. Within one of the large-scale integrated projects (2000-LS-5-M1 Greenhouse Gas Emissions and Climate Change) is Project LS-2000-5.1.2-M1 *CLIMATE CHANGE – Land Use, Land-Use Change and Carbon Stocks.*

2 Biomass Carbon

2.1 Methodology

Completion of an inventory of the amount of carbon held in biomass requires the area (ha) occupied by each land-use type (land-cover type) and the carbon density (t C/ha) of each land-cover type. Carbon density multiplied by area gives the stock of carbon in each land-cover type; the sum of these stocks gives the biomass carbon stock for Ireland.

Areas of land-cover types were obtained from CORINE Land-Cover Mapping (Ireland) of 1990 and 2000. This mapping methodology was developed by EU research agencies and has been applied to most EU countries as well as some candidate member and adjacent countries. Mapping is based on interpretation of images obtained from a satellite-borne scanner that records reflectance of light from land objects; the satellite system used was LANDSAT Thematic Mapper which records average reflectance for several bands of light in cells that are approximately 30 m by 30 m on the ground. Because the assignment of an area of land to a particular land-cover class is based on reflectance properties, it may not be classed in the same way as if classification was made on the ground. For example, a field interpreted as bare soil would be classed as in preparation for arable in the CORINE mapping of Ireland, but a farmer may know that it is actually grass re-seeding and would class the field as 'grassland'. The CORINE methodology allows only units of 25 ha or greater to be mapped, so that some land-cover units are omitted and thereby under-recorded – an example is individual houses or small groups of houses. Similarly, only the widest roads are mapped. Certain CORINE classes are broad and encompass large areas of land with a complex cover (in which individual units are <25 ha); this also may lead to under-recording. For example, omission of small patches of trees could reduce the total area under forest or omission of small bogs could reduce the total peatland area. Use of CORINE land-cover mapping in this study therefore had limitations, but it is the only complete land cover for Ireland, it is available for two dates and it is an internationally recognised approach to land-cover mapping.

Carbon densities for land-cover types were obtained from reported measurements in Ireland where possible, but otherwise adapted from carbon densities used in similar research in Northern Ireland and Great Britain. Carbon densities were calculated for 1990 and 2000 and multiplied by the area totals for each land-cover type at each date to give the carbon stock in each land-cover type in 1990 and 2000. Summation of the totals for each land-cover type at each date gave the total biomass carbon stock for Ireland in 1990 and 2000.

Of most importance in attempts to reduce emissions through land-cover change and management is the direction of any change in carbon stocks of biomass and soils, i.e. whether there is currently a net gain or a net loss in carbon stocks. Subtraction of the biomass stocks in 1990 and 2000 gave an estimate of the difference in stocks, and division by 10 gave an annual average gain (fixation) or loss (emission) of carbon in biomass.

2.2 Results

- The total biomass carbon stocks estimated were 24.2 Mt in 1990 and 22.7 Mt in 2000 (Table 2.1).
- The difference in estimated stocks showed a carbon loss of 1.5 Mt or an average annual loss of 0.15 Mt.
- Forest carbon stocks were estimated as 14.1 Mt in 1990 and 12.4 Mt in 2000.
- Forest carbon stocks showed a loss of almost 1.7 Mt (3.5%) or an average annual loss of 0.17 Mt. This was despite an increase in area of over 22% and is explained by lower carbon densities estimated for 2000; these were related to the young age class of trees in new plantations and in restocking.

Forests comprise over 50% of the total biomass carbon stock, on less than 10% of the land area, at both dates. However, different estimates of forest carbon densities and areas can lead to variation in the estimated stocks for forests and thereby for the total biomass stock, as well as for forest and total biomass carbon fluxes (carbon emission/fixation). The calculation of a carbon density for forests involves several components: data on the species of trees (or groups of species) by age classes and net productive area, planting and thinning practices, volume of trees for the yield class of each species (or species

Table 2.1. Biomass carbon stocks using CORINE area data. Negative values are emissions of carbon.

CORINE class		Area (ha)		% Area		Carbon density (t C/ha)		Carbon stock (t C)	% Stock	Carbon stock (t C)	% Stock
		1990	2000	1990	2000	1990	2000	1990		2000	
1.1.1	**Continuous urban fabric**	5,024	5,024	0.07	0.07	0.00	0.00	0	0	0	0
1.1.2	**Discontinuous urban**	70,645	87,003	1.03	1.27	5.24	4.30	370,180	1.5	374,113	1.7
1.2.1	**Industrial/commercial units**	3,898	6,112	0.06	0.09	0.00	0.00	0	0.0	0	0.0
1.2.2	**Road, rail, associated land**	264	2,037	0.00	0.03	0.00	0.00	0	0.0	0	0.0
1.2.3	**Port areas**	1,022	1,079	0.01	0.02	0.00	0.00	0	0.0	0	0.0
1.2.4	**Airports**	2,162	2,273	0.03	0.03	0.50	0.50	1,081	0.0	1,137	0.0
1.3.1	**Mineral extraction**	5,550	8,181	0.08	0.12	0.00	0.00	0	0.0	0	0.0
1.3.2	**Dumps**	348	343	0.01	0.01	0.00	0.00	0	0.0	0	0.0
1.3.3	**Construction sites**	992	2,791	0.01	0.04	0.00	0.00	0	0.0	0	0.0
	Subtotal	**89,905**	**114,843**	**1.31**	**1.67**			**371,261**	**1.5**	**375,249**	**1.7**
1.4.1	**Green urban areas**	3,513	3,726	0.05	0.05	0.90	0.90	3,162	0.0	3,353	0.0
1.4.2	**Sport and leisure**	9,447	16,376	0.14	0.24	4.50	4.50	42,512	0.2	73,692	0.3
	Subtotal all Class 1	**102,865**	**134,945**	**1.50**	**1.97**			**416,934**	**1.7**	**452,295**	**2.0**
2.1.1	**Non-irrigated arable land**	403,617	545,044	5.88	7.95	2.17	2.53	875,849	3.6	1,378,961	6.1
2.3.1	**Pastures**	3,821,388	3,638,316	55.69	53.04	0.90	0.90	3,439,249	14.2	3,274,484	14.4
2.4.1	**Annual crops with permanent crops**	0	0		0.00	3.20	3.20	0	0.0	0	0.0
2.4.2	**Complex cultivation patterns**	114,954	122,557	1.68	1.79	1.54	1.72	177,029	0.7	210,798	0.9
2.4.3	**Principally agriculture, significant areas of natural vegetation**	430,570	420,740	6.28	6.13	2.00	2.00	861,140	3.6	841,480	3.7
	Subtotal all Class 2	**4,770,529**	**4,726,657**	**69.53**	**68.91**			**5,815,874**	**24.0**	**6,235,064**	**27.5**
3.1.1	**Broad-leaved forest**	30,701	30,658	0.45	0.45	57.08	34.69	1,489,551	6.2	903,997	4.0
3.1.2	**Coniferous forest**	248,588	240,783	3.62	3.51	46.51	37.79	9,827,554	40.6	7,734,311	34.1
3.1.3	**Mixed forest**	23,236	22,112	0.34	0.32	51.79	36.25	1,022,884	4.2	681,326	3.0
3.2.4	**Transitional woodland–scrub**	214,389	340,007	3.12	4.96	7.40	8.67	1,586,479	6.6	2,947,861	13.0
	Subtotal woods	**516,914**	**633,560**	**7.53**	**9.24**			**13,926,467**	**57.6**	**12,267,495**	**54.1**
	plus non-treed15% area of 3.1.1, 3.1.2 and 3.1.3							**14,052,932**	**58.1**	**12,389,937**	**54.7**
3.2.1	**Natural grassland**	94,520	93,537	1.38	1.36	1.50	1.50	141,780	0.6	140,306	0.6
3.2.2	**Moors and heathland**	60,305	59,630	0.88	0.87	3.00	3.00	180,915	0.7	178,890	0.8
3.3.1	**Beaches, dunes, sands**	14,392	14,202	0.21	0.21	1.50	1.50	21,588	0.1	21,303	0.1
3.3.2	**Bare rocks**	16,726	16,726	0.24	0.24	0.00	0.00	0	0.0	0	0.0
3.3.3	**Sparsely vegetated areas**	20,228	20,228	0.29	0.29	0.80	0.80	16,182	0.1	16,182	0.1
3.3.4	**Burnt areas**	31	90	0.00	0.00	0.00	0.00	0	0.0	0	0.0

Table 2.1. ***Contd.***

	CORINE class	Area (ha)		% Area		Carbon density (t C/ha)		Carbon stock (t C)	% Stock	Carbon stock (t C)	% Stock
		1990	2000	1990	2000	1990	2000	1990		2000	
4.1.1	**Inland marshes**	18,501	17,964	0.27	0.26	1.50	1.50	27,752	0.1	26,946	0.1
4.1.2.1	**Peat bogs – unexploited**	1,169,760	1,067,982	17.05	15.57	3.00	3.00	3,509,280	14.5	3,203,946	14.1
4.1.2.2	**Peat bogs – exploited**	73,651	71,000	1.07	1.04	0.00	0.00	0	0.0	0	0.0
4.1.2		1,243,411	1,138,982	18.12	16.60			0	0.0	0	0.0
	Sub total (3.2.1–4.1.2)	**1,468,114**	**1,361,359**	**21**	**20**			**3,897,497**	**16.1**	**3,587,573**	**15.8**
4.2.1	**Salt marshes**	3,150	3,105	0.05	0.05	2.00	2.00	6,300	0.0	6,210	0.0
4.2.3	**Intertidal flats**	46,923	46,939	0.68	0.68	0.00	0.00	0	0.0	0	0.0
5.1.1	**Water courses**	9,291	9,291	0.14	0.14	0.00	0.00	0	0.0	0	0.0
5.1.2	**Water bodies**	123,174	120,988	1.80	1.76	0.00	0.00	0	0.0	0	0.0
5.2.1	**Coastal lagoons**	1,011	1,011	0.01	0.01	0.00	0.00	0	0.0	0	0.0
5.2.2	**Estuaries**	33,662	33,662	0.49	0.49	0.00	0.00	0	0.0	0	0.0
	Total (excluding 4.2.3 to 5.2.2)	**6,861,572**	**6,859,626**	**100.00**	**100.00**			**24,189,538**		**22,671,078**	
								Difference (t C)	–1,518,460	–0.15	Mt/year
								% loss 1990–2000		–6.28	
								Forest difference	–1,662,996		

group), a biomass expansion factor to convert above-ground stemwood volume to 'whole-tree' volume, the wood density for each species (or representative species for a group) and the percentage carbon for each species (species group). Small changes in any of these components make substantial changes to estimated forest carbon stocks and fluxes. In this study, there were difficulties in obtaining areas of species (or species group) by age classes, in a manner that was consistent for 1990 and 2000. Estimating a carbon density for CORINE Class 3.2.4 – Transitional woodland/scrub – was particularly difficult because that class appeared to include young plantations, poorly grown plantations, and areas of scrub and other poorly grown semi-natural woodland. The area of Class 3.2.4 was large in 1990 (40% of the forest area) and even larger in 2000 (over 50% of the forest area) (Table 2.1) and therefore has a considerable impact on forest carbon and total biomass carbon stocks and fluxes.

These uncertainties regarding forest carbon densities and stocks led the researchers to consider other approaches by which forest carbon densities, stocks and fluxes could be estimated. The C-FLOW model (Dewar and Cannell, 1992), which used afforestation data 1906 to 2000, produced forest carbon stocks of 11.8 Mt in 1990 and 17.7 Mt in 2000 (an average annual gain of 0.59 Mt). These estimates were quite different from those in Table 2.1 even though they were based on similar forest areas to those in CORINE; the difference arises from different estimates of carbon densities. The carbon densities estimated in C-FLOW were from afforestation data; evidence that is apparent on satellite imagery of poor growth and forest structure in Class 3.2.4 is not considered.

The map of biomass carbon stock 1990 (Fig. 2.1) highlights the contribution of the various land-cover types. The high carbon density associated with forests (red areas) may be observed and the impact of semi-natural vegetation (mainly peatland) in the west, in the uplands and in the Midlands is also apparent (blue shading). Suburban areas are also shown in blue, because trees in mature suburban areas raise the carbon density. Grassland accounts for the predominant yellow shading, whereas green shading is either arable land or, in the North-west, a mix of semi-natural vegetation and farmland.

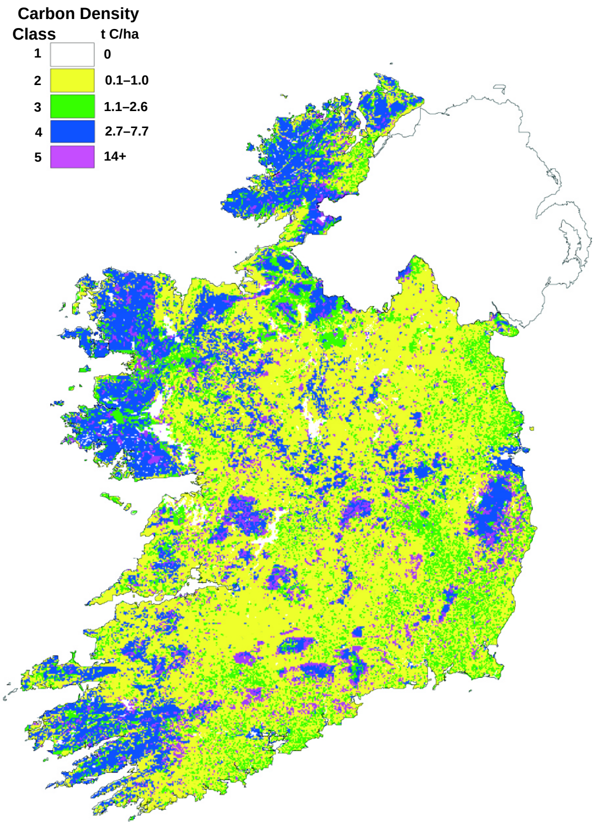

Figure 2.1. Biomass carbon stocks – spatial distribution 1990 – shown as carbon density.

3 Soil Carbon

3.1 Methodology

The inventory of soil carbon stocks required the areas (ha) of soil types in Ireland and a carbon density for each soil type; area multiplied by carbon density is the carbon stock for each soil and the sum of those products gives the soil carbon stock for Ireland.

As a source for area, the mapping of soils in Ireland is restricted; only around half of the counties have a soil survey leading to maps at 1:126,720, the remainder of Ireland is mapped at 1:575,000 (the General Soil Map (GSM)). Whereas the county soil maps show Soil Series that are based on soil parent materials and soil profile types, the GSM shows Soil Associations; these are geographical units with particular topography and dominated by a Principal profile type. These two sources of information on soils were brought together in a common system of recording by 2 km × 2 km grid squares (based on the Irish grid). The dominant soil (that accounting for the largest area) was taken as the soil for the whole grid square; both peat and mineral soils were recorded in this way.

Carbon density of a soil is calculated from its thickness, percentage carbon and bulk density (dry weight per wet volume). For mineral soils, *Soil Bulletins* which accompany county maps and the GSM, provided data for modal profiles on thickness and percentage carbon but bulk density was calculated from the mechanical analysis (percentage sand, silt or clay) and the percentage organic carbon.

Peat was treated separately because modal soil profiles rarely recorded the full depth of peat. Estimates of peat depths/thickness for both raised and blanket bogs were based on information from published sources, soil surveyors, satellite imagery (semi-natural bog vegetation or man-modified) and by considering the topography. Peat depths of bogs that have had, or are undergoing, extraction were estimated for 1990 and 2000 using publicly available information on the average rate of extraction (1 m in 10 years), initial depth of the bogs (based on the sources listed), and evidence on the date at which extraction began and, in some cases, ceased.

Bulk density and percentage carbon for peat were obtained from modal profiles supplemented by other published sources and recent results from complete profiles of lowland bogs in Northern Ireland. The carbon density for ‘extraction bogs’ considered not only the estimated loss of depth in 1990 and 2000, but also the layers of peat of different carbon densities that had been removed.

The carbon density of a soil varies with land cover; a mineral soil with semi-natural vegetation cover or with trees has a higher carbon density than that soil with a cover of grass. A soil with grass cover has a higher carbon density than that soil under arable cover. The cover for the dominant soil of a 2 km × 2 km grid square was the dominant cover at the date of soil survey. Soil survey in Ireland lasted many years; 1970 was taken as a median ‘date of survey’. Carbon densities were required for 1990 and 2000; dominant land cover on the dominant soil in each grid square for these dates was obtained from CORINE land-cover mapping. Some grid squares had changed cover between 1970 (date of survey) and 1990, so carbon density for 1990 was changed. It was assumed, following international guidelines, that in 20 years the soil had achieved its new equilibrium carbon density; factors applied in a similar study in Northern Ireland were used to modify the carbon densities. For example, where cover had changed from grass at the time of survey to arable in 1990, the original carbon density was multiplied by a conversion factor of 0.84. Changes in cover occurred also between 1990 and 2000; in these cases it was assumed that only half the change towards the new equilibrium level was achieved. The carbon density for peat with a vegetation cover other than its original semi-natural cover was calculated, bearing in mind any loss of peat and such evidence as could be obtained for ‘man-modified’ peats.

All the data on dominant soil, dominant cover, horizon thickness, carbon density and other variables for each grid square were recorded in a spatially referenced database (over 17,500 grid squares) to facilitate calculation and mapping of soil carbon stocks. Total soil carbon stocks for Ireland were calculated for 1990 and 2000; subtraction of these gave the difference in soil carbon stock between the two dates and division of this by

10 gave an annual average flux (gain or loss of soil carbon).

3.2 Results

- Total estimated soil carbon stock was 2,048 Mt in 1990 and 2,021 Mt in 2000 (Table 3.1)
- Approximately 47% of the stock (at both dates) were in predominantly mineral soils and 53% in peat (17% of the land area).
- Basin peat accounted for 25% of the soil carbon stock in 1990 (on 5% of the land area) despite a relatively long history of extraction, particularly in the Midlands.
- Lowland blanket peat accounted for 19% of the soil carbon stock and upland blanket peat 9%.
- Of the predominantly mineral soils, podzols, brown podzolics, grey–brown podzolics and gleys each held about 10% of the soil carbon stock.
- Subtraction of the stocks in 1990 and 2000 revealed a carbon loss from the soil of approximately 26.7 Mt.
- Of this, around 23 Mt C appear to be lost through industrial peat extraction; excluding this gave a loss of 3.7 Mt C as a result of land-use change or an annual loss of 0.37 Mt.
- The difference in stocks (26.7 Mt) is 1% of the 1990 soil carbon stock and the difference due to land-use change (3.7 Mt) is 0.2% of the 1990 stock; the small scale of the latter difference is such that the ‘loss’ may better be regarded as ‘no change’.

The map of soil carbon stocks in 1990 (Fig. 3.1) emphasises the importance of peat and peaty soils. Highest carbon densities (>1,501 t C/ha) stretch from the Midlands north–westward and mirror the distribution of raised bogs. The majority of grid squares with soil carbon densities between 250 and 1,000 t C/ha are along the western seaboard and in uplands, reflecting both altitude and oceanicity of climate. In all these areas the presence of blanket bog gives the high carbon densities. Elsewhere, the majority of soils have densities between 100 and 250 t C/ha, but in the Midlands, away from the raised bogs, lowland podzolic soils and shallow brown earths are dominant and soil carbon densities are low.

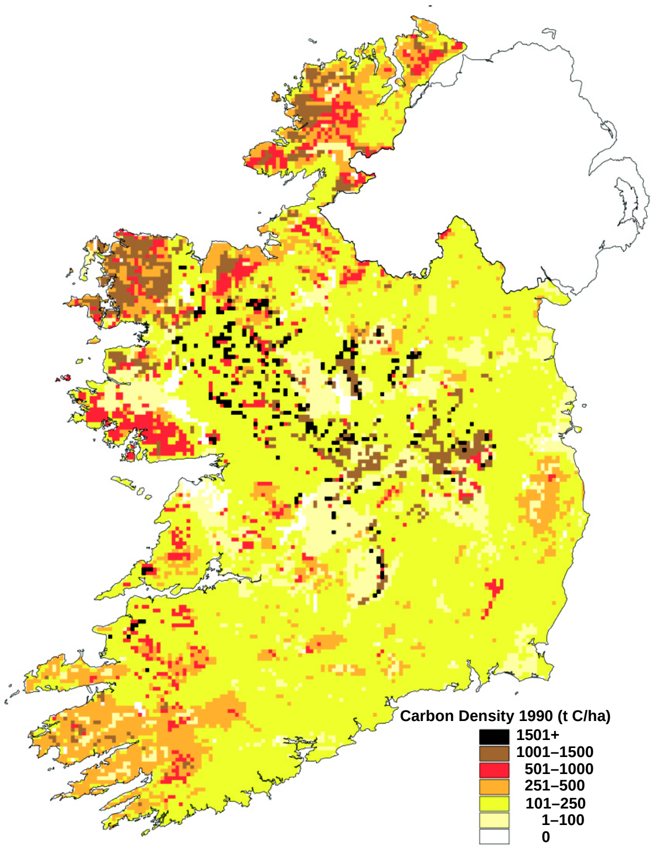

Figure 3.1. Soil carbon stocks – spatial distribution 1990 – shown as carbon density.

Table 3.1. Soil carbon stocks from soil carbon database – by Great Soil Groups. Negative values are emissions. Note some grid squares have 'no soil', e.g. built-up areas.

Great Soil Group	1990					2000					Difference
	Mean C density (t/ha)	No. grids	Area (ha)	Stock (t C)	% Stock	Mean C density (t/ha)	No. grids	Area (ha)	Stock (t C)	% Stock	t C
Podzol	342.40	1,399	559,600	191,607,418	9.36	342.77	1,399	559,600	191,814,412	9.49	206,994
Brown podzolic	206.17	2,116	846,400	174,501,025	8.52	205.63	2,115	846,000	173,967,051	8.61	–533,974
Grey–brown podzolic	137.42	4,138	1,655,200	227,461,910	11.11	137.00	4,134	1,653,600	226,543,062	11.21	–918,848
Brown earth	136.78	2,201	880,400	120,419,267	5.88	136.27	2,201	880,400	119,975,448	5.94	–443,819
Gley	144.03	3,548	1,419,200	204,408,400	9.98	143.67	3,548	1,419,200	203,895,881	10.09	–512,520
Rendzina	58.89	91	36,400	2,143,734	0.10	58.89	91	36,400	2,143,734	0.11	0
Regosol	142.36	23	9,200	1,309,727	0.06	139.90	23	9200	1,287,083	0.06	–22,644
Lithosol	100.51	629	251,600	25,288,034	1.23	100.24	629	251,600	25,220,803	1.25	–67,231
Basin peat	1,373.99	939	375,600	516,068,768	25.20	1,313.51	939	375,600	493,354,368	24.41	–22,714,400
Lowland blanket peat	1,026.59	955	382,000	392,156,384	19.15	1,022.10	955	382,000	390,441,184	19.32	–1,715,200
Upland blanket peat	420.20	1,078	431,200	181,190,948	8.85	420.20	1,078	431,200	181,190,948	8.96	0
Unclassified	159.55	179	71,600	11,424,008	0.56	159.51	179	71,600	11,420,720	0.57	–3,288
Total		**17,296**	**6,918,400**	**2,047,979,623**			**17,291**	**6,916,400**	**2,021,254,694**		**Loss of –26,724,929**

4 Discussion

4.1 Emission/Fixation of Carbon by Biomass and Soils

This study applied a range of methods to calculate biomass and soil carbon stocks and fluxes (Tomlinson, 2004). The preferred methods gave:

- An annual average combined biomass and soil carbon **emission** of 0.52 or 0.59 Mt C (1.91 or 2.17 Mt CO_2 equivalent), i.e. due to Land-Use Change and Forestry (LUCF). It excludes peat extraction losses.
- This emission due to LUCF represents 2.7% or 3.1% of the estimated national emission of CO_2 in 2000.
- Projecting agriculture, forestry and other land-use trends forward to 2010 suggests that the scale and direction of overall fluxes due to LUCF will be similar to those in 2000.

4.2 Need for Further Research

The study has shown a need for further research and improvements in the data available. The greatest difficulties and uncertainties in the research were experienced for the most carbon-rich components of biomass and soils (forests and peat, respectively) although both involved relatively small areas.

- Forests account for a large proportion of biomass carbon stocks, but, in determining a preferred method of estimation, it was noted that there was a range of estimated areas of forests and little agreement between researchers on the components used in calculating forest carbon densities. There is a need to consolidate the experience of researchers and the different approaches to agree estimates or a range of estimates for forest biomass carbon stocks and fluxes.
- As there is little evidence from Ireland of the impact of land cover and land-cover change on the carbon density of soils, there is a need for a monitoring network of sampling points that covers the main soil types (Soil Series or at least Great Soil Groups) and the principal land-cover types on each. This should improve the soil-property data available and in particular establish experimental evidence for the impact of land-cover type and change on the carbon density of a soil.
- There is a need to continue monitoring areas of national land cover so that information on soil and cover from a soil network can be used to estimate national biomass and soil carbon stocks and fluxes. This monitoring could be through sampling of satellite imagery. Annually published statistics, including the Census of Agriculture, have been shown to be inadequate to trace changes in land use/biomass and soil stocks (Tomlinson, 2004).
- Peat extraction is a significant component of soil carbon loss, but information on thickness of peat remaining in 'extraction bogs' is weak. There is also a need for better data on thickness and bulk densities for all peat types.

Despite the difficulties and uncertainties, this study has for the first time produced estimates of total biomass and soil carbon stocks and fluxes; all the major land-cover and soil types were included.

In future, better data could become available and analysis techniques could improve. Previous work by the researchers found estimating UK carbon stocks and fluxes to be an iterative process and one that needed to consider not only change in land cover, but also changes in land management and farming practices. There is scope to examine, for example, the impact of field drainage, liming, slurry and inorganic fertiliser application on carbon density of Irish soils. Results from parallel research programmes on gas emissions from land-cover types also may inform the work reported here.

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