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Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000

**James M. Eaton · Nicola M. McGoff ·
Kenneth A. Byrne · Paul Leahy · Ger Kiely**

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Abstract Using both historic records and CORINE land cover maps, we assessed the impact of land cover change on the stock of soil organic carbon (SOC) in the Republic of Ireland from 1851 to 2000. We identified ten principal land cover classes: arable land, forest, grassland, heterogeneous agricultural areas/other, nonvegetated semi-natural areas, peatland, suburban, urban, water bodies, and wetland. For each land cover class, the SOC stock was estimated as the product of SOC density and land cover area. These were summed to calculate a national SOC budget for the Republic of Ireland. The Republic of Ireland's 6.94 million hectares of land have undergone considerable change over the past 150 years. The most striking feature is the decrease in arable land from 1.44 million ha in 1851 to 0.55 million ha in 2000. Over the same time period, forested land increased by 0.53 million ha. As of 2000, agricultural lands including arable land (7.85%), grassland (54.33%), and the heterogeneous agricultural areas/other class (7.91%) account for 70.09% of Irish land cover. We estimate that the SOC stock in the Republic of Ireland, to 1 m depth, has increased from 1,391 Tg in 1851 to 1,469 Tg in 2000 despite soil loss due to urbanization. This increase is largely due to the increase of forested land with its higher SOC stocks when compared to agricultural lands. Peatlands contain a disproportionate quantity of the SOC stock. Although peatlands only occupy 17.36% of the land area, as of 2000, they represented 36% of the SOC stock (to 1 m depth).

1 Introduction

On the global scale, land cover and land use change is estimated to account for 25% of the anthropogenic flux of carbon dioxide to the atmosphere, second only to the combustion of fossil fuels (Houghton and Skole 1990; IPCC 2001). Human induced land cover change (e.g. forest to arable land) and land use change (e.g. extensive grassland management to intensive grassland management) has led to soil degradation and soil loss resulting in decreased soil carbon storage worldwide (Lantz et al. 2001). This anthropogenic

J. M. Eaton (✉) · N. M. McGoff · K. A. Byrne · P. Leahy · G. Kiely
Department of Civil and Environmental Engineering, Centre for Hydrology,
Micrometeorology and Climate Change, University College Cork, College Road, Cork, Republic of Ireland
e-mail: jamesmeaton@gmail.com

disturbance, in the face of climate change, has led to renewed interest in quantifying and understanding soil carbon stocks and in particular soil carbon stock changes over time.

Soil organic carbon (SOC) is of global importance as it is the largest carbon (C) stock in most terrestrial ecosystems, far exceeding the carbon stock in vegetation (Eswaran et al. 2000; Jobbagy and Jackson 2000). Soil organic carbon is of local importance as it is an essential component of soil organic matter. The amount of SOC in an ecosystem is the difference between the input of carbon as surface litter, belowground biomass, and root exudates to the soil profile, and the losses of carbon from the soil profile due to decomposition, erosion and leaching. It is for these reasons that land cover (biota) in conjunction with the other factors of soil formation (climate, topography, parent material, time and human activity; Jenny 1994) influences the stock of SOC. Because SOC is directly proportional to soil organic matter, the levels of SOC indicate soil fertility which decrease with soil depth for mineral soils.

The current global stock of soil organic carbon is estimated to be 1,500–1,550 Pg (Batjes 1996; Lal 2004; Post et al. 2001; Schlesinger 1995). This constituent of the terrestrial carbon stock is twice that in the earth's atmosphere (720 Pg), and more than triple the stock of organic carbon in terrestrial vegetation (560 Pg; Baes et al. 1977; Bolin 1970). Peatlands have a disproportionately large amount of soil organic carbon accounting for a quarter to a third (357–455 Pg) of the global SOC stock (Batjes 1996; Eswaran et al. 1993; Gorham 1991; Post et al. 1982), while occupying only 3% of global land cover.

Grassland for cattle grazing and silage making is the dominant land cover and cultural backbone of the rural economy in Ireland. Due to its extent, economic, and cultural value much research is devoted to sustainable grassland management. Studies which investigated soil organic carbon in the Republic of Ireland are predominantly focused on grassland (Brogan 1966; McGrath 1973, 1980; McGrath and McCormack 1999; Zhang and McGrath 2004). McGrath (1980) found that the carbon content, for 0–10 cm soil depth, of permanent pasture was 5.3% and for tilled (arable) soils was 3.4%. This demonstrated one of the more notable themes in SOC research today; that SOC content changes with land use.

Soil organic carbon has been investigated on a regional and national scale in the Republic of Ireland (McGrath and Zhang 2003; Tomlinson 2005). Using a combination of sources, Tomlinson (2005) estimated the soil organic carbon stock in the Republic of Ireland to be 2,048 Tg in 1990 and 2,021 Tg in 2000 for the entire soil profile. His work was the first national baseline estimate of carbon stocks in Irish soils. Similar work was carried out by Bradley et al. (2005), who estimated the SOC stock to 1 m depth in England (1,740 Tg), Scotland (2,187 Tg), Wales (340 Tg) and Northern Ireland (296 Tg). Cruickshank et al. (2000) used an analogous approach to estimate the carbon in the vegetation of the Republic of Ireland to be 19.3 Tg.

The structure and function of ecosystems are largely defined by their land cover and land use. Historically, spatially explicit land cover information has been difficult to obtain over large areas. More recently, with the use of remotely sensed data and geographic information systems (GIS), this information has become more readily available and relatively easy to use. Combining disparate sources of spatial data (e.g. remotely sensed satellite data, historical agricultural statistics, etc.) helps us understand how humans are altering the structure and function of ecosystems through changes in land cover and land use. National estimates of SOC stocks calculated using soil maps (plus accompanying metadata from soil surveys) or a combination of soil maps and land cover data are becoming increasingly available (Bradley et al. 2005; Cruickshank et al. 1998; Howard et al. 1995; Stolbovoi 2002; Tomlinson 2005; Tomlinson and Milne 2006). Monitoring SOC stock changes is part of the carbon accounting requirements of the Kyoto Protocol.

The objectives of this study were: to estimate SOC stocks in the Republic of Ireland using land cover data and to estimate the change in this stock over time. This study estimates the current and historical SOC stocks in Irish soils using land cover data from agricultural censuses and remotely sensed Coordination of Information on the Environment (CORINE; O'Sullivan 1994; Bossard et al. 2000) data in conjunction with SOC density data. The SOC density data was adopted from nearby regional areas with similar land cover and land use types to that of the Republic of Ireland.

2 Methods

Ten land cover classes of the Republic of Ireland have been devised for the purpose of this study. These land cover classes are: arable land, forest, grassland, heterogeneous agricultural areas/other, nonvegetated semi-natural areas, peatland, suburban, urban, water bodies, and wetland (Table 1). Although these classes are similar to those used by others (Bradley et al. 2005; McGettigan et al. 2006; Penman et al. 2003; Tomlinson 2005), they have been devised with a specific focus on how soil attributes and land management techniques affect SOC. The land cover classes have been devised using CORINE, so the data presented in this paper can in the future be readily compared with future CORINE data. The water body class has been omitted from this paper on the assumption that it does not contain soil carbon.

The areas of each of the ten land cover classes (Table 2) were derived from a variety of sources, but mainly historical and current agricultural census data and current CORINE imagery. To facilitate the comparison of estimates using different historical data sources, all data was first converted to a percentage of land cover based on the total area of land reported. This percent land cover was then converted to an area based on the total land area within the Republic of Ireland, 6.94 million ha (versus the total area including water bodies of 7.11 million ha, CORINE 2000). When the total land area was not reported in the source data used, it was assumed to be 6.94 million ha and thus needed no conversion. Hereafter the name Ireland refers to the Republic of Ireland.

Private forest areas in Ireland tended to be remnant patches between fields which historically were overlooked in agricultural censuses. For this reason, this study moved away from the forest cover data reported in agricultural census data in favour of an initial value of forest cover from 1911 (Department of Industry and Commerce 1931) combined with afforestation data compiled from Forest and Wildlife Service Reports (1933–1975, 1975–1981). Deforestation in Ireland is insignificant, and it is illegal in most cases because afforestation has mostly occurred on public land, or private lands sponsored by government grants. In Ireland when private land owners receive government grants for forestry, they are required by law to keep the land in forestry indefinitely and are not allowed to change the land use.

Soil organic carbon density (SOC density) is a term which denotes a mass of carbon per unit area (herein Mg ha^{-1}). It is used to compare the carbon stocks of differing areas. In line with Cruickshank et al. (1998) and Bradley et al. (2005), urban areas in this study have been given a SOC density value of 0 Mg ha^{-1} and suburban areas have been given SOC values as half that of the grassland class. This is based on the assumption that about half the suburban class has its soil built-over with the other half being most similar to the grassland class.

Omitting inland water bodies, the heterogeneous agricultural areas/other class (see Tables 1 and 2) prior to 1990 was calculated as the difference between the sum of the other eight land cover classes and the total land area of Ireland. One must therefore keep in mind

Table 1 Land cover class definitions with soil organic carbon density values

Land cover class	Definition[a]	CORINE classes	Carbon density[b] ($Mg\ ha^{-1}$) 0–30 cm	Carbon density[b] ($Mg\ ha^{-1}$) 0–100 cm
Arable land	All land tilled for crops	211	80	120
Forest	All forest including transitional woodland—shrub	311, 312, 313, 324	130	250
Grassland	Pasture, silage and hay fields and natural grassland, green urban areas, sport and leisure facilities	231, 321, 141, 142	100	160
Heterogeneous agricultural areas/other[c]	Complex cultivation patterns, land principally occupied by agriculture with significant areas of natural vegetation	242, 243	90	140
Nonvegetated semi-natural areas[d]	Semi natural areas with little vegetation such as beaches, dunes, bare rocks etc.	331, 332, 333, 334	0	0
Peatland[e]	Peat bogs, moors, and heathlands	322, 412	133	443.5
Suburban[f]	Area of which about half is natural land and half is built-over	112	50	80
Urban[d]	Combination of artificial areas heavily disturbed by humans	111, 121, 122, 123, 124, 131, 132, 133	0	0
Water bodies	All water bodies, not including open ocean and sea	511, 512, 521, 522		
Wetland	All wetland not including those in the peatland class	411, 421, 423	150	320

[a] Land cover class definition were derived using CORINE documentation (Bossard et al. 2000).

[b] The soil organic carbon density values were taken from Bradley et al. (2005), with the exception of peatland values which were derived from Cruickshank et al. (1998).

[c] The soil carbon densities of the heterogeneous agricultural area/other class is the average of the arable and grassland class from Bradley et al. (2005).

[d] Nonvegetated semi-natural areas and urban areas were assumed to have a soil organic carbon density of 0 $Mg\ ha^{-1}$ (Cruickshank et al. 1998; Bradley et al. 2005).

[e] The carbon density of peatland is calculated as the average carbon density (Cruickshank et al. 1998) for blanket and basin peat to 1 m, and 30% of this value for the 0–30 cm estimate.

[f] The suburban class was assigned a carbon density as half that of the grassland class (Cruickshank et al. 1998; Bradley et al. 2005; Tomlinson and Milne 2006).

that suppositions as to the extent of these lands and the reasons for their change may be relicts of data manipulation or inconsistencies in source data.

The average SOC density values (to 1 m depth) reported for several land cover classes in the UK (Bradley et al. 2005) were adopted for use with similar classes in this study (Table 1). The SOC stock for each land cover class was then calculated by multiplying the SOC density value of a land cover class by its area. The SOC density value in the case of peatland was adapted from Cruickshank et al. (1998). The total SOC stock in the peatland class (to its full depth rather than to 1 m depth) was calculated for the year 2000. This represents a more accurate SOC stock considering that Irish peatlands are known to have a range of depths from 0.6 to 7.5 m (Tomlinson 2005). Despite peat depth being a crucial factor in many aspects of peatland research, Hammond (1981) is the primary source to have

Table 2 Land cover areas (hectares) in the Republic of Ireland, 1600–2000

Land cover class[a]	1600	1800	1820	1851	1861	1871	1881	1891	1901	1911	1921	1930	1940	1950	1960	1970	1980	1990[b]	2000[b]
Arable land[c]				1,435,323	1,319,901	1,135,555	935,425	807,388	715,682	693,127	737,606	594,874	752,877	721,498	683,071	536,291	558,274	403,717	544,947
Forest[d]	833,265	170,000		107,455	112,128	115,090	116,119	109,617	109,567	105,230	105,821	114,424	137,761	159,318	227,547	323,667	409,974	521,103	638,915
Grassland[c]				3,474,455	3,886,118	4,166,765	4,210,761	4,282,573	4,402,101	4,284,912	4,110,072	4,232,635	3,973,498	4,003,864	3,898,891	4,296,381	4,174,626	3,949,878	3,772,319
Heterogeneous agricultural areas/other[e]				598,640	297,117	190,451	338,146	393,462	358,281	494,943	620,082	627,475	700,636	675,455	745,988	394,522	403,352	551,841	549,492
Nonvegetated semi-natural areas[f]				50,849	50,849	50,849	50,849	50,849	50,849	50,849	50,849	50,849	50,849	50,849	50,849	50,849	50,849	50,990	50,849
Peatland[g]			1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,194,347	1,308,655	1,205,235
Suburban[h]				12,511	12,981	18,707	24,433	30,158	35,884	41,610	45,347	48,716	52,460	56,203	59,946	63,690	67,433	71,183	87,623
Urban[h]				3,681	3,819	5,497	7,181	8,866	10,550	12,242	13,136	13,940	14,834	15,727	16,620	17,513	18,407	19,299	27,879
Wetland[f]				66,616	66,616	66,616	66,616	66,616	66,616	66,616	66,616	66,616	66,616	66,616	66,616	66,616	66,616	67,194	66,616

[a] Areas of land cover have been converted from the recorded area in the original source to a percentage of the known area of Ireland (at the time the area was recorded). This percentage was then converted back to an area (ha) based on the total land area of the Republic of Ireland (6,943,877 ha, according to CORINE 2000 data). The total area of the Republic of Ireland (including water bodies) is 7,111,028 ha (CORINE 2000 data).

[b] All 1990 and 2000 land cover values are derived from CORINE data.

[c] Land cover data for arable land and grassland (1851–1980) were taken from Statistical Abstracts of Ireland 1982–1985 (Central Statistics Office 1986).

[d] Data on forest cover comes from disparate sources including: 1600 from O'Carroll (1984) and Forest Service (2003), 1800 from Forest Service (2003), 1851–1911 from Statistical Abstracts of Ireland 1931 (Department of Industry and Commerce 1931), 1921–1980 from afforestation data (Forest and Wildlife Service 1933–1975, 1975–1981) combined with an initial value from Statistical Abstracts of Ireland 1931, and 2030 from Department of Agriculture, Food, and Forestry (1996).

[e] Heterogeneous agricultural areas/other were calculated as the sum of CORINE Class 242 and 243 for 1990 and 2000 values. Values from 1851–1981 have been calculated as the difference between the sum of all other classes subtracted from the total land area of the Republic of Ireland (6,943,877 ha, according to CORINE 2000 data).

[f] The 2000 values (from CORINE 2000 data) for two land cover classes, nonvegetated semi-natural area and wetland, have been extrapolated for values between 1851 and 1980 as these values are not likely to have changed much over time.

[g] The area of peatland between 1820 and 1980 are based on a Bog Commissioners Survey (1811–1814), which Hammond (1981) notes have been used "then and to-day".

[h] Despite it being difficult to locate objective and spatially explicit values on the extent of urban lands, values for 1851, 1861 and 1911 were taken from the 1861 Census of Ireland (1864) and the 1911 Census of Ireland (1913). The historic data was separated into the suburban and urban class based on the average percentage of urban and suburban lands in 1990 and 2000. Data from 1871–1901 and 1921–1980 were extrapolated linearly using 1861, 1911, and 1990 data.

collated the disparate knowledge on peat depth within Ireland. The total SOC stock in peatlands (Table 3) was based on: the average depth for the various peatland types (Hammond 1981); the areal extents for these classes based on tiers five and six of CORINE (2000); and SOC density values (Cruickshank et al. 1998).

3 Results

Agricultural lands (including the arable, grassland and heterogeneous agriculture/other class) account for the majority (70.09%) of the lands in Ireland. This estimate for the year 2000 represents a decrease from 79.33% in 1851. In 2000, peatlands and forests accounted for an additional 17.36% and 9.20% of the land, respectively. The change over the period 1851 to 2000 in the spatial extent of land cover (Table 2) is presented in this section; while the explanations for these trends and the conversion of land cover data to SOC stocks (Table 4) is in Section 4.

3.1 Agricultural lands

There was a rapid decline in the extent of arable lands in the period from 1851 to 1911 (Fig. 1a), halving the amount of land devoted to the production of crops. A further but more gradual decrease in the amount of arable land occurred in the period 1921 to 1990. A high of 1.44 million ha of arable land in 1851 decreased over the next 139 years to a low of 0.40 million ha in 1990. Since 1990, there has been a small increase in the amount of arable lands up to 0.55 million ha.

It is noted in Fig. 1b that the land area under grassland fluctuated over the period 1851 to 2000. From 1851 to 1901, when the areal extent of arable land decreased (Fig. 1a),

Table 3 Mass of soil organic carbon in the peatlands of Ireland for 2000

Peatland land cover class[a]	Area (ha)	Average depth[b] (m)	Carbon density for average depth[c] (Mg ha^{-1})	Mass of SOC (Tg)
Moors and heathlands[d]	59,060	–	443.5	26.19
Blanket lowland exploited	188,445	3.0	1,860.0	350.51
Blanket lowland intact	222,851	3.0	1,860.0	414.50
Blanket Mountain Exploited	37,728	1.2	636.0	23.99
Blanket mountain intact	171,406	1.2	636.0	109.01
Blanket upland exploited	121,040	1.2	636.0	76.98
Blanket upland intact	182,427	1.2	636.0	116.02
Raised bog exploited	187,277	2.5	1,179.0	220.80
Raised bog intact	35,004	7.0	4,702.0	164.59
Total for depth of soil profile[e]				1,502.60

[a] Peatland land cover classes, not including the moors and heathlands class, are separated according to tier 6 of CORINE 2000.

[b] Average peat depth values are from Hammond (1981).

[c] Carbon density values are adapted from Cruickshank et al. (1998). The moors and heathlands class is an average of the carbon density values for blanket and basin peat to 1 m depth.

[d] The carbon density for the moors and heathland class is to 1 m depth.

[e] Total SOC stock for depth of soil profile is calculated as the sum of above peatland land cover classes.

Table 4 Mass (teragrams) of soil organic carbon in Ireland by land cover class

Year	Arable land		Forest		Grassland		Heterogeneous agricultural areas/other		Peatland		Suburban		Wetland		Total[a]	
	0–30 cm	0–100 cm	0–30 cm	0–100 cm	0–30 cm	0–100 cm	0–30 cm	0–100 cm	0–30 cm	0–100 cm	0–30 cm	0–100 cm	0–30 cm	0–100 cm	0–30 cm	0–100 cm
1851	114.8	172.2	14.0	26.9	347.4	555.9	53.9	83.8	158.9	529.7	0.6	1.0	10.0	21.3	699.6	1,390.8
1861	105.6	158.4	14.6	28.0	388.6	621.8	26.7	41.6	158.9	529.7	0.6	1.0	10.0	21.3	705.1	1,401.8
1871	90.8	136.3	15.0	28.8	416.7	666.7	17.1	26.7	158.9	529.7	0.9	1.5	10.0	21.3	709.5	1,410.9
1881	74.8	112.3	15.1	29.0	421.1	673.7	30.4	47.3	158.9	529.7	1.2	2.0	10.0	21.3	711.6	1,415.3
1891	64.6	96.9	14.3	27.4	428.3	685.2	35.4	55.1	158.9	529.7	1.5	2.4	10.0	21.3	712.9	1,418.0
1901	57.3	85.9	14.2	27.4	440.2	704.3	32.2	50.2	158.9	529.7	1.8	2.9	10.0	21.3	714.6	1,421.6
1911	55.5	83.2	13.7	26.3	428.5	685.6	44.5	69.3	158.9	529.7	2.1	3.3	10.0	21.3	713.1	1,418.7
1921	59.0	88.5	13.8	26.5	411.0	657.6	55.8	86.8	158.9	529.7	2.3	3.6	10.0	21.3	710.7	1,414.0
1930	47.6	71.4	14.9	28.6	423.3	677.2	56.5	87.8	158.9	529.7	2.4	3.9	10.0	21.3	713.5	1,420.0
1940	60.2	90.3	17.9	34.4	397.3	635.8	63.1	98.1	158.9	529.7	2.6	4.2	10.0	21.3	710.1	1,413.8
1950	57.7	86.6	20.7	39.8	400.4	640.6	60.8	94.6	158.9	529.7	2.8	4.5	10.0	21.3	711.3	1,417.1
1960	54.6	82.0	29.6	56.9	389.9	623.8	67.1	104.4	158.9	529.7	3.0	4.8	10.0	21.3	713.2	1,422.9
1970	42.9	64.4	42.1	80.9	429.6	687.4	35.5	55.2	158.9	529.7	3.2	5.1	10.0	21.3	722.2	1,444.0
1980	44.7	67.0	53.3	102.5	417.5	667.9	36.3	56.5	158.9	529.7	3.4	5.4	10.0	21.3	724.0	1,450.3
1990	32.3	48.4	67.7	130.3	395.0	632.0	49.7	77.3	174.1	580.4	3.6	5.7	10.1	21.5	732.4	1,495.5
2000	43.6	65.4	83.1	159.7	377.2	603.6	49.5	76.9	160.4	534.5	4.4	7.0	10.0	21.3	728.1	1,468.5

[a] The land cover classes of nonvegetated semi-natural areas and urban areas were not included as they were assumed to have a soil organic carbon density of 0 Mg ha^{-1}.

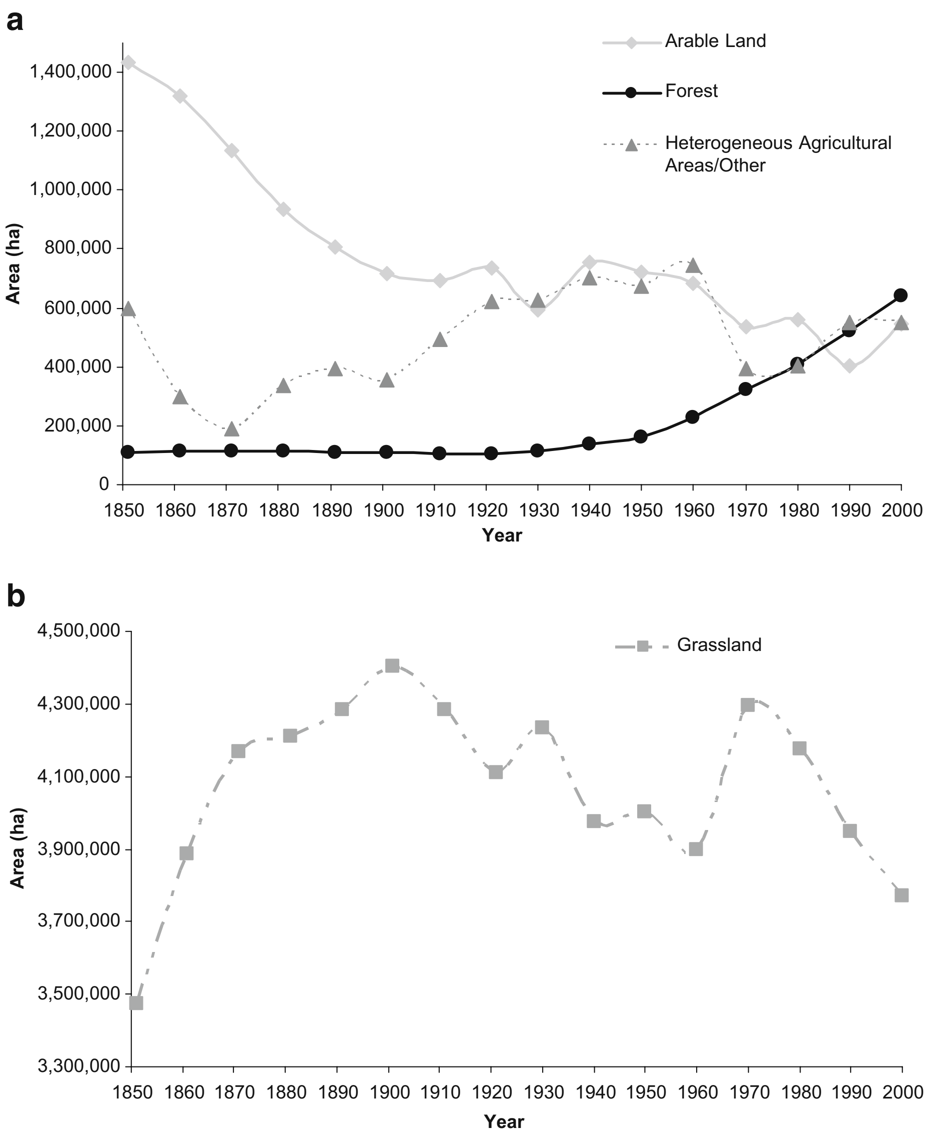

Fig. 1 Areal extent of arable (**a**), forest (**a**), heterogeneous agricultural areas/other (**a**), and grassland (**b**) cover in Ireland, 1851–2000

grasslands experienced an increase of similar magnitude (Fig. 1b). The area of grasslands increased from just below 3.50 million ha in 1851 to over 4.40 million ha in 1901, and then fell to 3.90 million ha in 1960. More recently a large increase in the area of grassland between 1960 and 1970 was followed by a steady decline in the area up to 2000.

In Fig. 1a, we note that the heterogeneous agricultural areas/other class initially mirrored the decrease seen in the arable land. The sharp decrease from 1851 to 1871 (0.60 to 0.19 million ha) was followed by an increase in the area over the next 90 years until peaking at 0.75 million ha in 1960. In the next decade, the area decreased to 0.40 million ha, but rose again to 0.55 million ha by 2000.

3.2 Non-agricultural lands

Data on peatlands were obtained from a limited number of sources. Bog Commissioners Reports (1811–1814) were the sole data on the spatial extent of Ireland peatlands until Hammond (1981). Although Hammond (1981) mapped "The Peatlands of Ireland" his work focused on determining the different types of peatland rather than requantifying the total area of peatland. The Bog Commissioners Reports (1811–1814) estimated that peatland represented 17.20% of the Irish land area which was close to the CORINE estimates of 18.85% and 17.36% in 1990 and 2000, respectively. It is not known to what extent reclamation efforts, in the latter half of the twentieth century, have affected the percentage of peatland coverage. Forests planted on peatland during this period have developed to near maturity and would now be classified as forest.

Forested lands have increased six-fold from 0.11 million ha to 0.64 million ha over the period 1851–2000 (Fig. 1a). Estimates of the extent of non-state owned forest were difficult to obtain as the Irish Forest Service estimates of afforestation initially ignored the growth of private forests. Concerted efforts to increase forest area have led to a large increase since the 1950s, from 0.16 to 0.64 million ha as of 2000.

The separation of peatland from the wetland class resulted in less than 1% of the total land area of Ireland being classified as wetland. Due to a lack of historical data, we extrapolated values for wetlands and the nonvegetated semi-natural class (CORINE 2000) for the period 1851–1980. Nonvegetated semi-natural areas (such as beaches, dunes, and bare rocks) are unlikely to have changed much and represent slightly less than 1% of the land area. The extent of suburban lands increased from 0.18% of the total land area in 1851 to 1.26% as of 2000. Urban lands increased to a similar extent from 0.05% in 1851 to 0.40% as of 2000.

4 Discussion

The Republic of Ireland's 6.94 million ha of land (CORINE 2000) has undergone considerable change in the past several thousand years with ensuing changes in SOC stocks. The main historical change is the conversion of forested lands to agricultural lands. Several millennia ago Ireland was almost entirely covered in forest (Neeson 1991), whereas now 70.09% of the land is devoted to agriculture and is dominated by pasture. This shift from natural forest vegetation has resulted in large losses of carbon contained in the forest vegetation and soils. By investigating the changes between the different land cover classes from 1851 to 2000 and the reason for these changes, we were able to quantify and assess the changes in SOC over this period.

4.1 Land cover trends of agricultural lands

We estimated that arable land has decreased from 20.67% of the Irish land area in 1851 to 7.85% in 2000 which is similar to the 5–8% estimates of McGettigan et al. (2006) and Tomlinson (2005). Most of this decrease in arable lands occurred from 1851 to 1911 (from 1.44 to 0.69 million ha) and was consequent to the Irish potato famine. A large decrease in the population during this period due to emigration and death led to the abandonment of large areas of arable land. Over the same period of time a large rise in grassland area (3.48 to 4.29 million ha) indicated that the abandoned arable land was used as pasture rather than left fallow. The heterogeneous agricultural areas/other class declined at a similar rate to arable land until 1871. After this period, we estimated an increase in the area of the heterogeneous agricultural areas/other class as the rate of increase in the grassland class drops off from 1871–1891 (Fig. 1a and b).

The areal extent of arable land was in the region of 0.70 million ha during the first half of the twentieth century but decreased to current levels (about 0.55 million ha) around 1970. There was a sharp decrease in arable land and an increase in grassland in 1930 (Fig. 1a and b). The extent of grassland fell by over 0.20 million ha from 1930 to 1960. As the amount of arable land was relatively steady during this period, it appears that the decrease in grassland was the result of the government's efforts to increase the area of state owned forestry. Heterogeneous agricultural areas/other class increased from 1871 to 1960. Between 1921 and 1960, much land seems to have undergone succession, transitioning from grassland to heterogeneous agricultural areas before finally being classified as forest. This assessment is what one would expect as small patches of land would still be in the grassland class while surrounding areas would have already become forests. If the land were of a different class, it would have been reported in the agricultural census or forest data.

The increase in the grassland class from about 3.9 to 4.3 million ha between 1960 and 1970 corresponds to the reclamation of marginal lands. Increases in the heterogeneous agricultural areas/other class, forest class, and urban class explain the decrease in grasslands from 4.30 million ha in 1970 to 3.77 million ha in 2000.

Land cover trends are more complex in the latter part of the twentieth century, as information-gathering techniques have been revised and more data has become available for comparison. Figure 2a and b report the yearly estimates of arable land and grassland from 1980 to 2004, respectively. Discontinuities between 1990 and 1991 arose due to changes in how the agricultural statistics are gathered (Central Statistics Office 1991b). This further complicates the integration of new sources of data in the form of remotely sensed imagery (CORINE data). Nevertheless, the 1990 CORINE estimate (0.40 million ha) of arable land are similar to agricultural census data (0.42 million ha). However the 2000 CORINE estimate of arable land (0.55 million ha) is 36% higher than the agriculture census data (0.40 million ha). The 1990 and 2000 CORINE estimates of grassland are 3.95 million ha and 3.77 million ha, respectively. Using the revised estimates of the agricultural census data, these estimates are 6–14% greater than those reported in the agricultural census data, respectively. The overestimate is because the agricultural statistics only report land which is used as grassland, while CORINE reports all land that is grassland including fallow land, green urban areas and sports and leisure fields.

4.2 Soil organic carbon in agricultural lands

Arable soils have the lowest SOC concentration of any land cover class for two reasons: the repeated disturbance and break down of soil aggregates during tilling and the reduced inputs of organic material due to harvesting of crops. There is an initial rapid loss of SOC associated with the loss of soil organic matter when natural land cover is converted to arable land (Beare et al. 1994; Cambardella and Elliot 1992; Post and Kwon 2000). A steady state of SOC, where the amount of carbon lost equals the amount of carbon sequestered, was estimated by Johnston (1991) to occur about 30–40 years after initial cultivation. Others suggest (Jenkinson et al. 1992) that it may take several hundred years for soil carbon dynamics to reach equilibrium. The conversion of natural lands to croplands can result in a 60% decrease in the SOC pool in temperate ecosystems and a 75% decrease in the SOC pool in tropical ecosystems (Lal 2004). Considering that the extent of arable land in Ireland has decreased from 21% in 1851 to below 8% in 2000 (Table 2), this land cover change alone is likely to have resulted in the sequestration of a large amount of carbon as

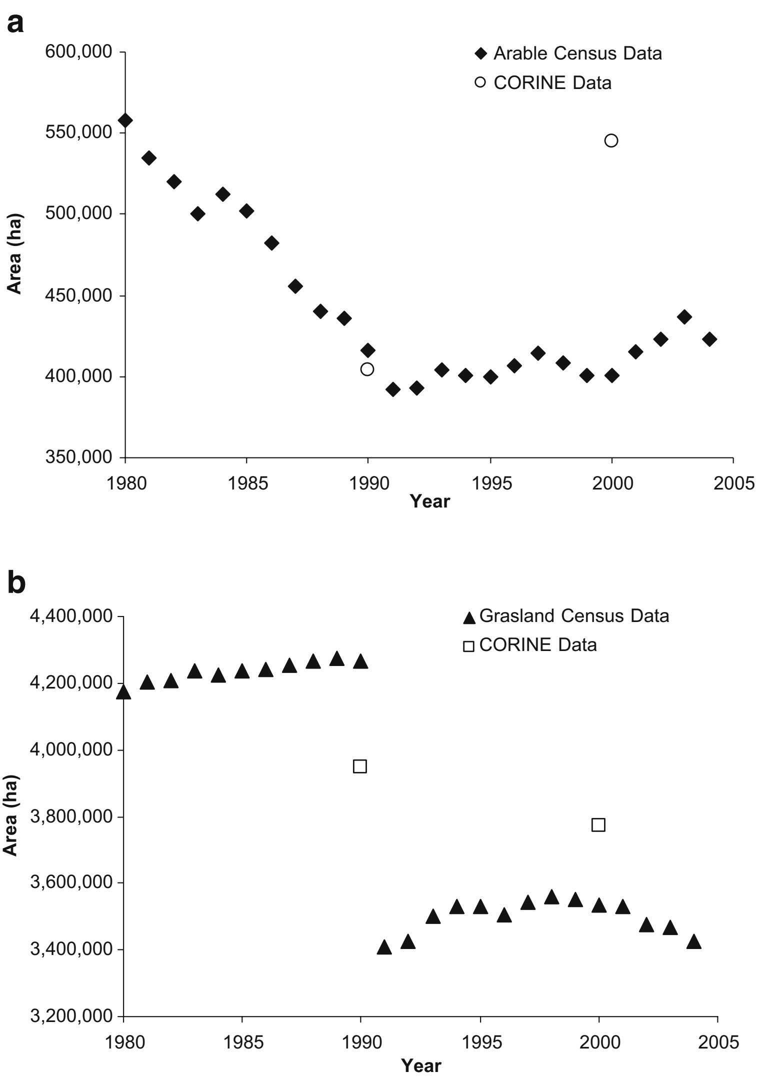

Fig. 2 Arable (**a**) and grassland (**b**) cover in Ireland, 1980–2004. The Central Statistics Office reported the agricultural census data (1986, 1989, 1991a, b, 1997, 2002, and 2006)

arable land was converted to lands which sustain greater soil carbon stocks. After continuous cultivation, Burke et al. (1995) suggest that most SOC can be recovered to precultivation levels within 50 years of agricultural abandonment; however total soil carbon pools will take much longer to recover.

The concept of a static SOC density value for all heterogeneous agricultural areas/other lands is imperfect given the nature of this class. At the very least, this class is a combination of arable lands, grasslands and natural lands each with a different SOC density. It is challenging to estimate the SOC stock when the patchwork combination of lands is changing as the land cover continues to change, either naturally or due to human influence. Although the estimated SOC stock of the heterogeneous agricultural areas/other class fluctuated much over the study period, our estimates of 83.8 Tg (to 1 m depth) in 1851 and 76.9 Tg in 2000 are similar.

It is important to estimate, as accurately as possible, the size and extent of SOC stocks in Irish grasslands as this class alone covers more than half of Ireland (Table 2), mainly in the form of pasture. Land uses such as natural grassland, silage, hay, green urban areas and sport and leisure facilities also represent a small percentage of the grassland class. We estimated (Table 4) that the grassland class accounted for 40–50% of the SOC stock to 1 m depth from 1851–2000, or 25% of the total carbon stock in 2000 (mineral soils to 1 m and peat to average depth).

Globally, the conversion of forest to pasture has led to increases in the SOC stock (Guo and Gifford 2002) but increases are linked with precipitation and are affected by forest type. In contrast to global trends, Bradley et al. (2005) reported woodlands (forests) as containing greater SOC densities than pasture (grasslands) in the four constituent countries of the UK (England, Scotland, Wales and Northern Ireland). Tomlinson and Milne (2006) also suggested that SOC densities (Mg ha^{-1}) in pastures of Northern Ireland contained 75% of the SOC found in forests. These results are interesting as bulk density generally increases when land is converted from forest to pasture, leading to higher SOC densities (Murty et al. 2002). Afforested peaty soils, which are widespread in Ireland, could explain why SOC densities values are higher in forest soils than in grassland for Irish and UK soils. Pasture SOC is strongly influenced by management (Fearnside and Barbosa 1998) and also can decrease or increase depending on the initial concentrations of SOC (Holmes et al. 2006). The historic conversion of Ireland's native forests to grassland could indicate either a significant gain or loss in the SOC stock.

4.3 Land cover trends of non-agricultural lands

Few sources of data exist on the spatial extent of non-agricultural lands with the exception of peatland and forest. In 2000, the nonvegetated semi-natural areas and urban areas comprised approximately of 1.13% of the land area of Ireland and are assumed to have a SOC density of zero. The carbon dynamics of green urban areas and sport and leisure facilities found in urban areas (part of the tier 1 "artificial surfaces" classification in CORINE) are most similar to grassland and are categorized as such for the purpose of this study. Suburban areas covered 1.26% of the land in 2000.

Of the sources which estimate the extent of peatland in Ireland (Bog Commissioners 1811–1814; Gardiner and Radford 1980; Hammond 1981; Connolly et al. 2007), the Bog Commissioners Reports (1811–1814) is the only historic estimate of peatland cover. As such it has been used almost exclusively up to and including in the report by Hammond (1981) "The Peatlands of Ireland". Much of the peatland in Ireland is known to have undergone substantial changes due to differing management techniques, such as private and commercial peat extraction as well as peatland drainage. Changes in peatland carbon dynamics resulting from land cover change (i.e. peatland conversion to grassland through drainage) have been accounted for in this paper. However, it was beyond the scope of this paper to quantify changes due to peatland disturbances, such as peat extraction, which have not resulted in a land cover change within our land cover classes.

The nature and extent of private peat harvesting during the period 1851–2000 is unknown. Therefore the impact of this activity on peat carbon stocks can not be quantified. However, it is likely to have been significant given that peat was the only source of fuel in much of the country during much of this period. Bord na Móna (the Irish Peat Board) currently manages 80,000 ha of midland raised bogs and Renou et al. (2006) has commented on the fate of these commercially harvested bogs. Recent afforestation on peat soils have decreased the area of the peatland class, which is not reflected in the land cover data. The small change in peatland cover from 17.20% (Bog Commissioners 1811–1814) to 17.36% (CORINE 2000) is likely due to: the paucity of data on the extent of peatlands from 1814 to 1980; the inaccuracies of the Bog Commissioners Reports (1811–1814); and the different manner in which peatlands are classified.

Ireland's original mixed temperate woodland forest was dominated by oak, pine, ash, elm, hazel, and yew and was largely extinct by the year 1600 with only 12% remaining (O'Carroll 1984; Forest Service 2003). This remaining cover was further reduced to 2.45% forest (0.17 million ha) as of 1800 (Forest Service 2003). As of 1851, forests accounted for less than 2% of the land cover (107,455 ha; Department of Industry and Commerce 1931). The lowest amount of forest cover, 1.52%, was realized in 1911 at 105,230 ha. Since 1911, forest cover increased steadily. After almost a century's effort of afforestation, encouraged by state initiatives for public and private afforestation, Ireland is still the least forested country in the European Union with estimates of forest cover at the beginning of the twenty first century in the range of 8.3–9.4% (this study; Forest Service 2000; McGettigan et al. 2006; Tomlinson 2005).

Irish farmers tended to devote their lands for cattle, food production and agricultural crops rather than forest. This means that afforestation efforts started in the early twentieth century occurred almost entirely on state land. With the introduction of improved incentive schemes in the 1980s, farmers began to turn to forestry as a viable economic opportunity for the poor quality parts of their land. It is government policy to increase forest cover to 17% of the land by 2030 (Department of Agriculture, Food, and Forestry 1996). Forests now occupy lands which were previously peatland, grassland, and arable land. With 44% of Irish state forest lands occurring on peaty soils (Coillte Teoranta 1999), more research into the carbon dynamics of forested mineral versus peat soils is required.

Wetlands, not including peatland, currently occupy less than 1% of the country (66,616 ha, CORINE 2000). Few sources report land cover data on wetland as different from that of peatland. Of those sources that do, only exploited peatland is identified, rather than peatlands as a whole (McGettigan et al. 2006). Several sources report a semi-natural class, which seems to include wetland, peatland, and exploited peatland (Bradley et al. 2005; Tomlinson 2005; Tomlinson and Milne 2006). This indicates that there are few sources of data on wetland soils apart from peatland and none to our knowledge on their spatial extent and carbon stock.

4.4 Soil organic carbon in non-agricultural lands

The peatlands of Ireland include raised bogs, blanket bogs, and fen peats. Although differing in vegetation type and morphology, all peatlands are similar in that they were formed by the accumulation of organic matter due to slow decomposition rates caused by anaerobic subsurface conditions. It is this accumulation of organic matter which gives peatlands their high carbon density (444 Mg ha^{-1}) compared to other land cover classes (80 to 320 Mg ha^{-1}, Table 1).

In this study we found that peatlands account for almost 62% of the total Irish SOC stock, which is greater than the 53% reported by Tomlinson (2005). The lack of knowledge on the spatial variability of peat depth and how its carbon density changes with depth make both estimates difficult to verify. Nevertheless, peat represents the bulk of SOC in Ireland because its carbon concentration, 44–50% (McGrath and McCormack 1999; Hammond 1981, respectively), is many times greater than that of mineral soils, 0.1–8.2% (Little and Bolger 1995; McGrath 1980; Sanger et al. 1997).

Soil organic carbon stocks in peaty soils have the potential for the greatest change because they have the highest carbon concentrations. Currently, peatlands in Ireland and the UK (Cannell et al. 1999) are subject to a range of anthropogenic disturbance, including industrial peat harvesting, private turf cutting, drainage, conversion to pasture, afforestation and combinations of these disturbances. These disturbances affect SOC dynamics in the peatland in a variety of ways, most leading to a loss of SOC. While disturbed peatlands may be a source of carbon, Sottocornola and Kiely (2005) found that an undisturbed blanket bog in County Kerry, Ireland, was a modest CO_2 sink.

Afforestation of peatlands is common in Ireland and has numerous effects on peatland ecosystems. Drainage, often prior to the planting of trees, can increase the decomposition and SOC losses and can cause subsidence of the land surface with a possible increase in bulk density. Once a forest is established, trees may increase litter inputs to the forest floor, thereby replacing some of the SOC lost due to increased decomposition. Conversion of peatland to forest can lead to increased aeration and evapotranspiration rates and thus increased decomposition, although CO_2 fluxes from afforested peatland soils do not always increase (Byrne and Farrell 2005).

Investigations of SOC dynamics in Irish forests requires a focus on mineral versus peat soils, yet this is hard to do as many peaty soils, such as peaty podzols, exist which blur the distinction between soil types. It is for this reason that Irish forest soils contain a greater soil carbon stock than grassland, despite global trends which indicate otherwise (Guo and Gifford 2002). The SOC stocks in forested land, to 1 m depth have increased, from 26.9 to 159.7 Tg, over the period from 1851–2000 because there has been a large increase in the extent of forest cover. More information is required on the extent of afforestation on peat soils versus mineral soils along with information on the SOC dynamics for each soil type, so as to improve the estimates of SOC in forests (Byrne and Milne 2006). This land cover change, from semi-natural peatland to afforested peatland, could have important implications for SOC stocks.

Limited knowledge of wetlands (not including peatlands), make the carbon in this land cover class difficult to estimate as no sources could be found dealing solely with wetlands. The SOC density value assigned to the wetland class (Table 1) is most likely to be the least accurate of all land cover classes. This is because the SOC density values comes from Bradley et al. (2005) who did not include a wetland class, but instead included a semi-natural class which accounts for wetlands, among other semi-natural areas, such as peatland. This SOC density value of 150 Mg ha^{-1} for 0.3 m depth and 320 Mg ha^{-1} for 1.0 m, may yet be correct as the organic horizon in many wetland soils is highly organic (pers. obs.). Wetlands are often used as pasture, which further complicates the SOC dynamics in this class.

Little is known of the SOC of suburban areas due to a lack of published research. Even so, this study estimated the SOC stock in suburban areas to be 7.0 Tg in 2000, up from 5.7 Tg in 1990 and 1.0 Tg in 1851. This stock is estimated in a slightly different manner than other land cover classes, because the calculations use a decreased SOC density (half that of the grasslands class) to account for the fact the only a portion (30–80%; Bossard et al. 2000) of the suburban class is covered by soil. The increase from 1990 to 2000 reflects the increase in suburbanization during these years. Land cover change leading to increased suburban areas is a net source of carbon to the atmosphere, as the suburban class has the lowest SOC density of any land cover class apart from urban and nonvegetated semi-natural areas (Table 1).

4.5 Carbon stocks

We estimated that the SOC stock to 1 m depth has increased from 1,391 Tg in 1851 to 1,496 Tg in 1990 and then decreased to 1,469 Tg in 2000 (Table 4). Tomlinson (2005), who

Table 5 Estimated soil organic carbon stocks in the Republic of Ireland

Description	Year	Peat SOC stock (Tg)	Total SOC stock (Tg)	Source
Stock to 1 m depth	1990	580	1,496	This study
	2000	535	1,469	
Complete soil profile	1990	1,089	2,048	Tomlinson (2005)
	2000	1,065	2,021	
Mineral to 1 m + peat (complete soil profile)	1990[a]	–	–	This study
	2000	1,503	2,437	

[a] These values could not be reasonably estimated, as CORINE 1990 Tier 6 information is not available (see Table 3).

reported the only other national estimate (Table 5) of the SOC stock, calculated a stock of 2,048 Tg (for 1990) and 2,021 Tg (for 2000). Although Tomlinson's (2005) estimates are approximately 35% larger than our estimates, this was because he calculated the entire stock of SOC rather than that to only 1 m depth. When calculating the total SOC stock to 1 m depth for mineral soils and the entire soil profile for peat soils, our estimate for the year 2000 is 2,437 Tg. Of this 2,437 Tg of SOC, peatlands represent 62% of the total SOC stock in Ireland on 17.36% of the land. Using different sources of data, Tomlinson and this study estimated the same decrease (27 Tg, Table 5) in the SOC stock between 1990 and 2000. For more accurate estimates of SOC stocks further research should be directed towards quantifying the extent, depth, and degree of exploitation of the different types of peatlands in Ireland.

Over the period 1851–2000, Irish soils have been a sink of CO_2 (Table 6). Soil carbon stocks increased from 1851–1901 because of the abandonment of arable land. Later increases, from 1940–1980, resulted from the large increase in the area of forested land. The increase in the soil carbon stock from 1980 to 1990 (45 Tg) is due to the transition in the sources of the spatial information, from agricultural census data and disparate sources of spatial information to CORINE data, rather than an actual increase in the SOC stock. The only notable decrease in SOC stocks from 1851 to 2000 occurred between 1990 and 2000 (27 Tg). This SOC loss seems to reflect the expanding Irish economy with a decrease in

Table 6 Estimated soil organic carbon stock changes in the Republic of Ireland

From	To	Δ C (Tg)
1851	1861	+11
1861	1871	+9
1871	1881	+4
1881	1891	+3
1891	1901	+4
1901	1911	−3
1911	1921	−5
1921	1930	+6
1930	1940	−6
1940	1950	+3
1950	1960	+6
1960	1970	+21
1970	1980	+6
1980	1990	+45
1990	2000	−27
1851	2000	+78

+ Indicates an increase in the SOC stock, CO_2 sink; − indicates a decrease in the SOC stock, CO_2 source peatland and grassland area and an increase in arable, suburban, and urban lands. Over the past 150 years, the 78 Tg (Table 6) increase in the SOC stocks has occurred over an area of 6.94 million ha, suggesting an average carbon density increase of 11.18 Mg ha^{-1}. We recognize that this increase of SOC has occurred predominantly on areas which have undergone land cover change.

5 Conclusion

While acknowledging that we overlook site and region specific information on soil types, this approach enables an estimate of SOC stocks over large spatial areas without extensive fieldwork and laboratory analysis. Arguably, this approach draws on the most significant drivers of soil organic carbon, land cover and land use. The 0.89 million ha decrease in the extent of arable lands, from 1851–2000, resulted in the expansion of other land cover types which have a higher SOC density than arable land. Concurrently, the expansion of forests in the Republic of Ireland by 0.53 million ha has led to an increase in the SOC stock. It remains to be seen as to what affect afforesting peatland will have on SOC stocks. Increases in the extent of urban and suburban lands are thought to represent an important loss of soil organic carbon in Ireland, yet little is known surrounding the fate of these soils. Greater SOC stocks are feasible with management strategies focused on increasing and retaining soil organic matter. With 70.09% of the land devoted to agriculture, it is clear that farmers as well as land managers have a role in maintaining and/or increasing SOC stocks.

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