The impact of agricultural land cover change on soil organic carbon stocks in Ireland

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I. Introduction

Changes in land cover and land use influence soil organic carbon (SOC) stocks (Guo and Gifford, 2002). The land area of the Republic of Ireland is 6.94 million hectares. This land has undergone extensive change in the past which have resulted in changes in the SOC stock. Ireland has been converted from a country almost entirely covered in forest (Neeson, 1991) to one which is currently 70.1% agriculture land, largely in the form of pasture. Soils that are continuously under arable crops lose carbon to the atmosphere and through leaching (Follett, 2001). When converted to grassland these lands sequester carbon (Gebhart et al., 1994; Römkens et al., 1999). Countrywide estimates of SOC stocks calculated using soil maps or a combination of soil maps and land cover data are common (Bradley et al., 2005; Cruickshank et al., 1998; Howard et al., 1995; Stolbovoi, 2002; Tomlinson, 2005; and Tomlinson and Milne, 2006). By investigating the changes in land cover from 1851 to 2000, we have been able to estimate the SOC stocks in Ireland and the changes in this stock over time.

II. Methods

The current and past SOC stocks in Ireland were estimated for ten land cover classes (Table 1) using 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. All 1990 and 2000 land cover data are derived from CORINE. Land cover data for arable land and grassland classes (1851-1980) were taken from Statistical Abstracts of Ireland 1982-1985 (Central Statistics Office, 1986). The area of bogland between 1820 and 1980 are based on a Bog Commissioners Survey (1811-1814), which Hammond (1981) notes have been used „then and today". Data on forest cover comes from disparate sources including: 1851-1911 from Statistical Abstracts of Ireland 1931 (Department of Industry and Commerce, 1931), 1921-1980 from afforestation data (Forest and Wildlife Service, 1933-1980) combined with an initial value from Statistical Abstracts of Ireland 1931. Heterogeneous Agricultural Areas/Other were calculated as the sum of CORINE classes 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. One must therefore keep in mind 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 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. The 1990 value (from CORINE 1990 revised) for the suburban and urban land cover class has been extrapolated for values between 1851 and 1980, as it was difficult to locate objective and spatially explicit values on the extent of urban lands.

SOC density values (to 1 m depth) reported for several land cover classes in the United Kingdom (Bradley et al., 2005) were adopted for use with similar classes in this study (Table 1). The SOC density for bogs was adopted from Cruickshank et al. (1998). 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 total SOC stock in the bog class (to its full depth rather than to 1 m depth) was also calculated for the year 2000. This represents a more accurate SOC stock considering that Irish bogs are known to have a range of depths from 0.6 m to 7.5 m (Tomlinson, 2005).

III. Results and Discussion

The land cover based estimates of the SOC stock to 30 cm and 1 m depth can be found in Table 2. Fluctuations in the area of agricultural lands over the past 150 years have led to shifts in the stock and distribution of SOC. As of 2000, agricultural land covered 70.1% of the country. Arable land covered 7.9%, heterogeneous agricultural areas/other class 7.9% and grassland 54.3% of the total land area. Although Ireland's arable land contains a large SOC stock (172.2 Tg in 1851 down to 65.4 Tg in 2000), they have the lowest SOC concentration of any major land cover class because of the rapid loss of SOC associated with the decrease 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). Estimates of the SOC stock in the heterogeneous agricultural areas/other class have changed over time, yet our estimates of 73.4 Tg (to 1 m depth) in 1851 and 76.9 Tg in 2000 are similar. The estimates in this class are likely to be the least accurate of any class given the patchwork nature of this class. Ireland's grasslands cover more than 50% of the country. We estimated that the grassland class accounted for 40-50% of the SOC stock to 1 m depth from 1851-2000, and alternatively 25% of the total SOC stock in 2000. Globally, the conversion of forest to pasture typically leads to an increases in the SOC stock (Guo and Gifford, 2002) but increases are linked with precipitation and are affected by forest type. Woodlands and forests of Ireland and Great Britain are reported to have greater SOC densities than pasture (Bradley et al., 2005; Tomlinson and Milne, 2006). This suggests that the conversion of natural woodland forest to agricultural land is marked by a large decrease in ecosystem carbon contained in vegetation and soils.

The Republic of Ireland's non-agricultural lands include: bogland, forest, nonvegetated semi-natural areas, suburban areas, urban areas and wetlands. As of 2000, bogland covered 17.4%, forest 9.2%, nonvegetated semi-natural areas 0.73%, suburban areas 1.26%, urban areas 0.40% and wetlands 0.96% of the total land area. Boglands represents the bulk of SOC in Ireland because the carbon concentration of peat, 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). This study reports that boglands contain 530-580 Tg of SOC to 1 m depth or 36-39% of the SOC stock. When estimating the total SOC stock (to 1 m depth for mineral soils and the average depth of peat soils) for year 2000 boglands contain 1503 Tg (Table 3). When calculated for the entire peat profile, boglands account for almost 62% of the total Irish SOC stock, which is greater than the 53% reported by Tomlinson (2005). In order to improve estimates of SOC, better knowledge on the extent of bog exploitation and the associated effect on SOC stocks is needed.

We estimated that SOC in forests has increased from 26.9 Tg to 159.7 Tg, over the period from 1851-2000, because of the large increase in forest cover. Although there is good information as to the extent of forested land, SOC dynamics in forest soils are more uncertain. Coillte (1999) estimated that 44% of state owned forest occurred on peaty soils. Additional research on the SOC dynamics for peat and mineral forest soils are needed to improve estimates of SOC in forests (Byrne and Milne, 2006).

It is difficult to assess whether estimates of SOC in nonvegetated semi-natural areas, suburban areas, urban areas, and wetlands are accurate. As spatial land cover data did not exist for these classes, 1990 and 2000 data has been extrapolated. In addition to a lack of land cover data, we could not find any empirical research investigating SOC of these classes in Ireland or other similar regions.

Our estimate of the summed SOC stocks (to 1 m depth) has increased from 1385 Tg in 1851 to 1496 Tg in 1990, followed by a decreased to 1469 Tg in 2000 (Table 2). The only other national estimate of Ireland's SOC stock (Tomlinson, 2005; Table 3) reported values of 2048 Tg (for 1990) and 2021 Tg (for 2000). Tomlinson's (2005) estimates are 35 % larger than ours because he calculated the entire stock of SOC rather than that to only 1 m depth. When we calculated the total SOC stock (to 1 m depth for mineral soils and the average depth for peat soils), our estimate for the year 2000 is 2437 Tg. Tomlinson (2005) and this study estimated the same decrease (27 Tg, Table 3) in the SOC stock between 1990 and 2000.

Since 1851 Irish soils have been a sink for CO_2. SOC increased during the period 1851-1901 due to abandonment of arable land. Increases in the extent of forested land, mainly from 1940-1980, have also contributed to the increase in the SOC stock. The apparent increase in the SOC stock from 1980 to 1990 (40 Tg) reflects the transition from agricultural census data to CORINE data, rather than a genuine increase in the SOC stock. The 27 Tg decrease in the SOC stock from 1990 to 2000 points toward the decrease in the extent of boglands and increased arable, suburban and urban lands. Over the period, 1851-2000, the 83 Tg increase in the SOC stocks occurred over 6.94 million ha (the area of the Republic of Ireland). As of 2000, boglands represent 62% (1503Tg) of the total SOC stock (2437 Tg) in Ireland on only 17.4% of the land. Quantifying the extent, depth, and degree of exploitation of the different types of boglands would greatly improve estimates of SOC stocks in Ireland.

IV. Conclusion

This approach to estimating SOC stocks draws on the most significant drivers of SOC, land cover and land use. A decrease in arable lands over the period from 1851-2000 has resulted in the expansion of other land cover types which contain more SOC than arable land. Concurrently, the large expansion of forests (0.53 million ha) has increased SOC stocks in Ireland. The expansion of urban and suburban areas is thought to signify a loss of SOC, yet little is actually know about SOC in urban and suburban areas. Continued sequestration of carbon in Irish soils is possible with management strategies focused on increasing and retaining soil organic matter in agricultural lands and sustainable policies on urban growth.

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VII. Tables

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	0-100 cm
Arable Land	all land tilled for crops	211	80	120
Bog[c]	peat bogs, moors, and heathlands	322, 412	133	443.5
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[d]	complex cultivation patterns, land principally occupied by agriculture with significant areas of natural vegetation	242, 243	90	140
Nonvegetated Semi-natural Areas[e]	semi natural areas with little vegetation such as beaches, dunes, bare rocks etc.	331, 332, 333, 334	0	0
Suburban[f]	area of which about half is natural land and half is built-over	112	50	80
Urban[e]	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 bog 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 bogland values which were derived from Cruickshank et al (1998).

c The carbon density of bogland 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.

d 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).

e 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).

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).

Table 2.
Mass (Tg) of soil organic carbon in Ireland by land cover class.

Year	Arable Land		Bog		Forest		Grassland		Heterogeneous Agricultural Areas/Other		Suburban		Wetland		Total[a]	
	cm															
	0-30	0-100	0-30	0-100	0-30	0-100	0-30	0-100	0-30	0-100	0-30	0-100	0-30	0-100	0-30	0-100
1851	114.8	172.2	158.9	529.7	14.0	26.9	347.4	555.9	47.2	73.4	3.6	5.7	10.0	21.3	695.9	1,385.1
1861	105.6	158.4	158.9	529.7	14.6	28.0	388.6	621.8	20.1	31.3	3.6	5.7	10.0	21.3	701.3	1,396.2
1871	90.8	136.3	158.9	529.7	15.0	28.8	416.7	666.7	11.2	17.4	3.6	5.7	10.0	21.3	706.1	1,405.8
1881	74.8	112.3	158.9	529.7	15.1	29.0	421.1	673.7	25.1	39.1	3.6	5.7	10.0	21.3	708.6	1,410.8
1891	64.6	96.9	158.9	529.7	14.3	27.4	428.3	685.2	30.8	47.9	3.6	5.7	10.0	21.3	710.3	1,414.1
1901	57.3	85.9	158.9	529.7	14.2	27.4	440.2	704.3	28.3	44.0	3.6	5.7	10.0	21.3	712.4	1,418.3
1911	55.5	83.2	158.9	529.7	13.7	26.3	428.5	685.6	41.2	64.2	3.6	5.7	10.0	21.3	711.3	1,415.9
1921	59.0	88.5	158.9	529.7	13.8	26.5	411.0	657.6	52.9	82.3	3.6	5.7	10.0	21.3	709.2	1,411.6
1930	47.6	71.4	158.9	529.7	14.9	28.6	423.3	677.2	54.0	83.9	3.6	5.7	10.0	21.3	712.2	1,417.9
1940	60.2	90.3	158.9	529.7	17.9	34.4	397.3	635.8	61.0	94.8	3.6	5.7	10.0	21.3	708.9	1,412.1
1950	57.7	86.6	158.9	529.7	20.7	39.8	400.4	640.6	59.1	92.0	3.6	5.7	10.0	21.3	710.4	1,415.7
1960	54.6	82.0	158.9	529.7	29.6	56.9	389.9	623.8	65.9	102.5	3.6	5.7	10.0	21.3	712.5	1,421.9
1970	42.9	64.4	158.9	529.7	42.1	80.9	429.6	687.4	34.7	53.9	3.6	5.7	10.0	21.3	721.7	1,443.3
1980	44.7	67.0	158.9	529.7	53.3	102.5	417.5	667.9	39.6	61.6	3.6	5.7	10.0	21.3	727.5	1,455.8
1990	32.3	48.4	174.1	580.4	67.7	130.3	395.0	632.0	49.7	77.3	3.6	5.7	10.1	21.5	732.4	1,495.5
2000	43.6	65.4	160.4	534.5	83.1	159.7	377.2	603.6	49.5	76.9	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}.

Table 3.
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	1496	This study
	2000	535	1469	
Complete soil profile	1990	1089	2048	Tomlinson 2005
	2000	1065	2021	
Mineral to 1 m + peat (complete soil profile)	1990[a]	——	——	This study
	2000	1503	2437	

[a] These values could not be reasonable estimated given current data sources.