Report on agricultural drainage and greenhouse gas abatement in Scotland

Prepared on behalf of ClimateXChange

Authors:

Allan Lilly, Nikki Baggaley, Bob Rees, Kairsty Topp, Ian Dickson, and Gavin Elrick

James Hutton Institute and SRUC

November 2012

Contents

Executive Summary

The drainage of agricultural land in Scotland is essential to support crop production. This report reviews the development of land drainage in Scotland and identifies historical records of the installation of large scale drainage systems across the agriculturally important areas of the country. Evidence for the current condition of drainage systems in Scotland has been provided by a small survey of farmers and contractors. Drainage not only supports agricultural production, but also has a number of potential impacts on the environment. Its contribution to greenhouse gas mitigation has been assessed by an analysis of research studies that have examined the effects of soil wetness on nitrous oxide emissions and by modelling. The potential for carbon loses from cultivated, mineral soils under arable, rotational and permanent, improved grassland was examined using data held in the Scottish soils Database.

Key Findings

- Large scale investment in the drainage of agricultural land began in the 1950s and continued for a period of 30 years. Investment by land owners appears to be related to grant aid.

- There is uncertainty in the statistics as drainage is estimated as a function of cost, is recorded in different ways over time, as the same fields may have had multiple drainage treatments.

- It appears that $^{2}/_{3}{}^{rd}$ of cultivated land with wet soils (620 000ha) has been drained at some point. Identifying the extent of more marginal land goes some way to describing the discrepancy between the extent of wet soils and the extent of field drainage.

- Nitrous oxide emissions are promoted by wet soil conditions and therefore likely to be more prevalent in wetter soils that receive N fertilisers. However there is a lack of good quality, direct experimental evidence to be able to adequately quantify the magnitude of the potential for mitigation that could be achieved by improving farm drainage systems.

- There is insufficient evidence to suggest that wet soils store more carbon.

- Drainage has multiple benefits increasing yields/trafficability and workability as well as reducing GHG emissions. Current production levels could not be maintained if there was a complete failure of old drains.

- The annual statistics of land drained seem to tie in with the survey of drains being between 20-50 and 50-100 years old; and also that most drains are in good to moderate condition.

- The most pressing concern on the reinstallation/maintenance of drainage is cost and is substantiated by the annual statistics in that drainage in the past has been related to grant aid.

- There is need for a national scale assessment of the extent and condition of current drainage in Scotland similar to a recent study undertaken in England and Wales.

- There is a need for further field experimentation for quantification of the improvement of drainage on N_2O emissions and for the validation of laboratory experiments.

- Drainage will not totally mitigate N_2O emissions in extreme rainfall events and degassing in streams and ditches needs to be considered so management of N inputs is critical.

- Conflicting policy could be potentially preventing drainage installation (General Binding Rules).

- This report did not consider those highly organic and peaty soils where drainage would promote carbon loss and increased greenhouse gas emissions but concentrated on those mineral soils that are regularly cultivated to maintain productive pastures or to grow arable crops

List of Figures

List of Tables

Background

The following request was received from the Scottish Government via ClimateXChange to undertake a review of the consequences of improved field drainage on greenhouse gas mitigation in Scotland.

1. *What data exists on the extent and current condition of field drains in Scotland?*
2. *What assumptions can be made regarding the proportion of land (or area of land) where installing or improving field drainage would reduce GHG emissions, and on what basis?*
3. *What assumptions can be made regarding the magnitude of GHG abatement from installing or improving drainage, and on what basis?*
4. *What are the potential impacts or benefits of installing or improving field drainage for other climate change mitigation policies (such as preservation of carbon rich soils), and other environmental priorities and regulations (such as sustainable flood management and water quality, including how they might vary by land type/location)?*

The review was undertaken between March and October 2012 by members of staff from the James Hutton Institute and SRUC.

1. The extent and current condition of field drains in Scotland

Introduction

Artificial drainage to regulate the degree of waterlogging in Scottish soils has been practiced for generations by Scottish farmers and included the use of stone culverts, rig and furrow as well as stone drains, trenches filled with gravel, straw or even wood (Livesley, 1960) although many of these had a limited life span. In the 18th century, intercept drains were being used to tap spring water and divert it away from the agricultural land.

By the early 19th century, hand-made horse-shoe shaped clay tiles were being installed in some fields but these were expensive to make. However, by the middle of the 19th century these and other tile drains were being mass produced by machines (RCAHMS) and government loans and tax exemptions made drainage of land more cost effective. According to Livesley (1960) many of these drainage systems were inadequate for the soil conditions and many failed. A lack of investment in the early 1900s meant that many of these existing drainage systems silted up and ceased to be effective. Recently, Anthony et al. (2012) estimated the area of drainage installed between 1847 and 1899 based on money loaned for agricultural improvements. Although there is considerable uncertainty, they estimated that between 810 000 and 1 000 000ha of land was drained during this time.

With the introduction of grant aid specifically for drainage work in 1921 (MacKay, 1973), the Government also began to collect information on the extent and type of drainage systems being installed. The collection of this information continued until the late 1980s when the grant aid was withdrawn for all except the crofting areas.

What data exists on the extent of field drains in Scotland?

The information on the extent of drainage in Scotland previously held by the Government is no longer available, however, there are a number of sources which have been compiled from these Government statistics such as Green (1979a & b and 1980), MacKay (1973) and Robinson et al. (1990) but none of these give a complete record from the start of grant-aided drainage schemes in 1921 to its cessation in the late 1980s. There is also a separate assessment of drainage need reported by Laird (1946).

Laird (1946) summarised the data collected by the Agricultural Executive Committees for all the designated ‘Districts’ in Scotland during 1941-42. As well as collating statistics on the extent of arable land and acreages of crops grown, these bodies were asked to ascertain if ‘crop production was less than the maximum possible’ and to assess ‘what acreage was suffering from the following defects:’. Amongst these ‘defects’ was ‘Obvious lack of drainage’ (Figure 1).

4. Where the crop production at June 1941 was less than the maximum possible, state what acreage was suffering from the following defects:

Acres

(a) Obvious lack of drainage . . . . ________

(b) Lack of fertilizers, including lime . . . . . . ________

and were the following contributing factors?

(c) Lack of adequate buildings and other owner's equipment . Yes/No

(d) Lack of tenant's capital . . . . Yes/No

(e) Other reasons . . . . Yes/No

Figure 1: Extract from the report by Laird, 1946, p6)

Although the data presented by Laird was by Agricultural Executive Committee 'District', we have summarised these statistics by county (Table 1). This summary shows that, a small proportion (4.38%) of Scottish farmland was, in the opinion of the Agricultural Executive Committees, under producing due to the lack of adequate drainage. The assumption would be that the remaining land was adequately drained. However, this assessment was based on contemporary land management practices and predates most of the research into the improvements in trafficability and crop yields that can be gained through the installation of modern drainage systems and it is therefore likely that it underestimated the true extent of land that was adequately drained by modern standards. Figure 2 shows the proportion of land in each county that was assessed by the Agricultural Executive Committees as benefiting from drainage.

Figure 2: Land deemed by the Agricultural Executive Committee that would benefit from drainage from Laird (1946) by Scottish Counties.

Table 1: The area of cultivated land by 1951 County boundaries under arable, rotational or permanent grass and area exhibiting a lack of drainage (Laird 1946)

County (1951)	Area showing lack of drainage (ha)	Area of arable crops (ha)	Area of rotational grass (ha)	Area of permanent grass (ha)	Total area of cultivated Land (Laird 1941)	Land showing a lack of drainage as a percentage of cultivated Land in 1941
ABERDEEN	9941.13	132722.1	104468.1	11416.95	248607.2	4.00
ANGUS	202.5	61285.41	28872.05	6891.48	97048.94	0.21
ARGYLL	3495.15	10753.97	9719.19	22395.29	42868.44	8.15
AYR	10799.33	31998.65	25113.65	62071.92	119184.2	9.06
BANFF	2432.025	32307.66	25939.04	4284.9	62531.6	3.89
BERWICK	5285.25	33022.08	21484.85	19782.63	74289.56	7.11
BUTE	1440.99	3163.86	3636.495	3444.525	10244.88	14.07
CAITHNESS	3996.14	14641.56	15974.82	8315.46	38931.84	10.26
STIRLING &CLACKMANNAN	4976.24	17884.8	8046.54	22771.94	48703.28	10.22
DUMFRIES	2474.15	29461.32	25496.37	40477.32	95435.01	2.59
DUNBARTON & RENFREW	1154.66	13491.36	7533	24699.74	45724.1	2.53
EAST LOTHIAN	2690.82	25701.71	9328.77	7612.38	42642.86	6.31
MIDLOTHIAN	3197.48	20578.46	10322.64	14004.5	44905.59	7.12
FIFE & KINROSS	8560.49	55461.51	22053.47	26095.37	103610.3	8.26
INVERNESS	7369.38	18176.81	12029.72	25144.83	55351.35	13.31
KINCARDINE	2088.99	27565.11	16437.33	2189.025	46191.47	4.52
KIRKCUDBRIGHT	2419.07	18849.51	18298.31	31411.8	68559.62	3.53
LANARK	7863.48	29514.38	22636.67	40869.36	93020.4	8.45
MORAY	1515.11	20456.15	14164.88	2493.99	37115.01	4.08
NAIRN	356.4	5288.895	4122.495	483.57	9894.96	3.6
ORKNEY	4086.86	17736.17	18972.63	6526.575	43235.37	9.45
PEEBLES	654.48	5460.615	4216.455	7854.57	17531.64	3.73
PERTH	6522.12	62504.87	29999.57	34451.33	126955.8	5.14
ROSS AND CROMARTY	5426.19	25413.35	18017.24	13237.43	56668.01	9.58
ROXBURGH	508.28	25081.25	21023.15	23838.71	69943.1	0.73
SELKIRK	728.19	3105.945	3084.075	5333.04	11523.06	6.32
SUTHERLAND	1155.87	3936.195	3996.945	4146.39	12079.53	9.57
WEST LOTHIAN	763.02	10223.01	3536.46	6930.765	20690.24	3.69
WIGTOWN	6768.77	20225.7	20129.72	18539.69	58895.1	11.49
SHETLAND	335.34	3705.345	886.545	3532.005	8123.895	4.13
SCOTLAND	109207.855	1110656	733473.6	647996.8	2492126	4.38

In 1979, Green (1979a & b) attempted to quantify the extent of field, forest and hill drainage (defined as drainage of out-bye land) in Scotland from 1949 to 1976. The extent of field drainage by county was estimated from the grant application statistics held by the Department of Agriculture and Fisheries for Scotland (Table 2). Green (1979b) quotes that nearly 50% of the grant applications in southern Scotland were to re-drain areas affected by the failure of old drains. However, it may be that this was a convenient 'catch-all' used in the grant application to justify having the work done.

Green (1979a) gave a total area of land drained during the period 1946-1979 as 255 067ha (although summing the values quoted for each of the individual counties gives a total of 241 459 ha), thus just over 3% of Scotland's total land area was drained between 1949 and 1976. This was almost 10% of the area of cultivated land recorded by Laird in 1946 and just over twice the area of land identified by the Agricultural Executive Committees as requiring drainage in 1942 (figure3).

There is clearly a mismatch between the areas identified by the Agricultural Executive Committees as requiring drainage and the subsequent extent of drainage installation. For example, the eastern counties north of Fife had the lowest requirement for drainage as a proportion of the individual county areas but were amongst the counties with the greatest proportion of drainage installed during the period 1949 to 1976. This is probably a reflection of the growth in research into new and more efficient drainage systems and the increases in crop yield that can be achieved through improved drainage.

Figure 3: The proportion of land drained between 1949 and 1976 according to Green (1979a and b) by Scottish Counties.

Table 2: The area of land in each County that had drainage installed between 1949 and 1976 (Green 1979a)

County Name	Land drained from 1949-1976 (ha)	County Area (ha)	Percentage of County area drained	Percentage of cultivated area (from Laird) in each County drained between 1949 and 1976.
ABERDEEN	38905	514987	7.55	15.65
ANGUS	12869	227877.51	5.65	13.26
ARGYLL	10754	822800	1.31	25.09
AYR	9239	293028	3.15	7.75
BANFF	14887	163934	9.08	23.81
BERWICK	7587	118486	6.40	10.21
BUTE	1153	56921	2.03	11.25
CAITHNESS	9285	180442	5.15	23.85
STIRLING & CLACKMANNAN	8757	133180	6.58	17.98
DUMFRIES	13149	278641	4.72	13.78
DUNBARTON & RENFREW	4758	129386	3.68	10.41
EAST LOTHIAN	3977	69319	5.74	9.33
MIDLOTHIAN	3630	97061	3.74	8.08
FIFE & KINROSS	4781	154822	3.09	4.61
INVERNESS	7542	1126856	0.67	13.63
KINCARDINE	6524	96862	6.74	14.12
KIRKCUDBRIGHT	6887	233676	2.95	10.05
LANARK	12163	236924	5.13	13.08
MORAY	7449	125813	5.92	20.07
NAIRN	2657	42832	6.20	26.85
ORKNEY	3675	100980	3.64	8.5
PEEBLES	4307	90741	4.75	24.57
PERTH	28639	660440	4.34	22.56
ROSS AND CROMARTY*	1529	833817	0.18	2.7
ROXBURGH	6366	173337	3.67	9.1
SELKIRK	1338	68860	1.94	11.61
SUTHERLAND	1317	546827	0.24	10.9
WEST LOTHIAN	2108	31303	6.73	10.19
WIGTOWN	4876	126980	3.84	8.28
SHETLAND	351	147306	0.24	4.32
SCOTLAND	241459	7884440	3.06	9.69

* There is a large discrepancy between the estimate of cultivated land in Ross and Cromarty between Laird and Green.

The most comprehensive statistics on drainage in Scotland were published by MacKay in 1973. The extent of drained land quoted by MacKay (1973) was based on grant applications and covered the period from 1921 to 1972. These statistics were further augmented by Robinson et al. (1990) who extended the period covered to 1988 (Table 3). Unfortunately, the actual data on the area of land drainage undertaken during the period 1972 to 1988 is no longer available and the extent of the land drained was estimated from a graph in Robinson et al. (1990) and Robinson (1990). The statistics for the period 1921 to 1949 were taken by MacKay from the *Report of the Land Drainage (Scotland) Committee (Cmd 7948).* Separate statistics on the extent of either arterial or field drainage were not recorded until 1958. As arterial and field drainage were grouped together and separated from hill drainage, we can perhaps assume that arterial drainage referred to the canalisation of streams and rivers and the creation and maintenance of ditches in lowland areas. Hill drains were often open ditches in land with low agricultural value where it would be uneconomical to install tile drains. Robinson et al. (1990) also reported that data were not available for the extent of land drained from 1939 to 1945, only the cost of the works, therefore there has been some interpretation in the data presented by McKay as to how this translates to the actual area drained. Clearly there will be some subjectivity in the ‘acreage improved’, particularly where field drains and arterial drains are not listed separately.

Despite these uncertainties, the annual area of land drained in Scotland as calculated from grants awarded between 1921 and 1988 can be determined from data from both MacKay (1973) and from Robinson (1990). The data show a marked peak for both hill and arterial/field drainage during 1940s until the mid 1950s at which time the grants for the maintenance of existing drainage schemes were withdrawn (Figure 4). These grants were reinstated in the late 1960s and there was an observable rise in the extent of the land drained. This is an important observation as it indicates that we cannot simply rely on these statistics to calculate the total area of land drained as clearly some areas had received multiple grants for installation and subsequent maintenance.

When compared to the figures presented by Green (1979a) for the period 1946 to 1979, Mackay (1973) and Robinson (1990) estimated the area of land drained to be over 100 000 ha greater (341 835 ha). However this value includes the area of arterial drainage, not considered by Green, thus, during this period it could be assumed that 30% of the grant-aided drainage in cultivated land was for arterial drainage rather than the installation of field drains. For the period from 1958 to 1971 where MacKay shows the extent of land drained both though arterial works and installation of field drains the percentage allocated to arterial was only 18%. This discrepancy makes it difficult to apply a correction factor to the pre-1958 data to separate the area of land drained solely by field drainage from the combined total arterial and field drainage.

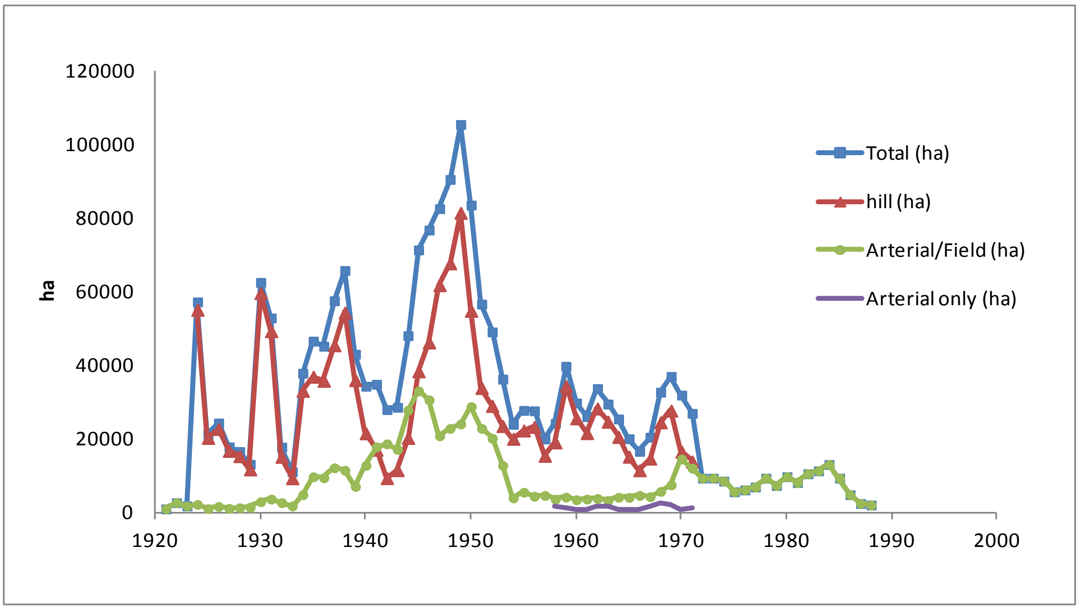


Figure 4: Extent of land drained in Scotland from 1921 to 1988 (after MacKay, 1973 and Robinson, 1990) - Note, from 1973 to 1988 only statistics for the Arterial/Field drainage area are known.

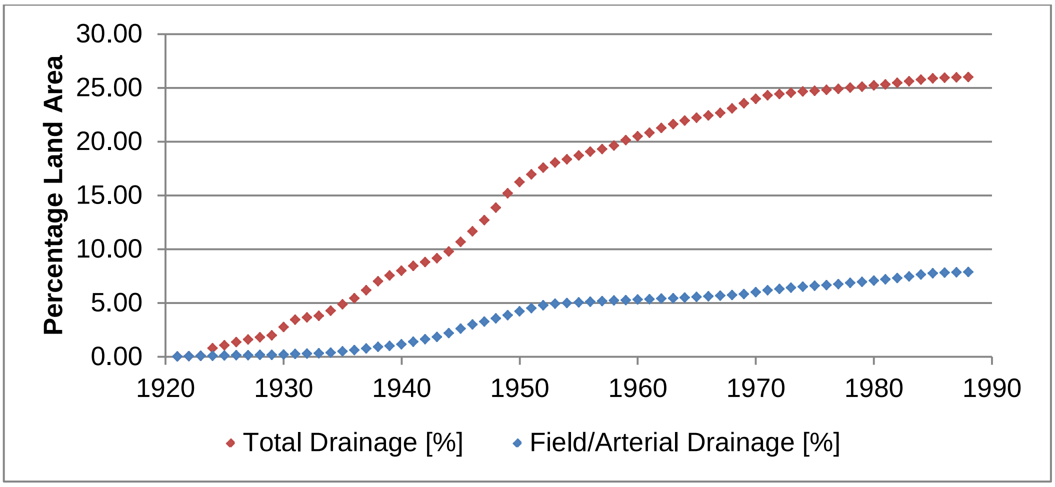


Figure 5: The cumulative land area of Scotland where grants had been made for drainage works from 1921 to 1988.

Figure 5 shows the cumulative land area of Scotland where grants had been made for drainage works from 1921 to 1988. It is also reasonable to assume that some areas were drained where no grant was applied for and that there has been new areas drained since 1988 as well as some remedial works. The total for field and arterial drainage since 1921 is 620 000 ha which is just less than 8% of the land area of Scotland compared with a total of 2 000 000 ha or 26% for all drainage including hill drains (Figure 5).

According to the Land Cover of Scotland dataset (MLURI, 1993), approximately 25% of Scotland's land area is under regular cultivation as either arable land or permanent, improved pastures, implying that a third of this cultivated land area has been drained at sometime in the past bearing in mind that some of this land may have had multiple drainage treatments. Equally, not all the soils in Scotland require artificial drainage therefore it is important to compare the extent of drainage with the area of soils that are not naturally free draining.

Table 3: Extent of drained land in Scotland from 1921 to 1988 (from MacKay, 1973 and Robinson, 1990).

Year	Arterial/Field (ha)[1]	hill (ha)	Total (ha)[2]	Arterial only (ha)
1921-22	931.5		931.5	-
1922-23	2632.5		2632.5	-
1923-24	1741.5		1741.5	-
1924-25	2146.5	55080	57226.5	-
1925-26	1012.5	20250	21262.5	-
1926-27	1599.75	22680	24279.75	-
1927-28	1073.25	16726.5	17799.75	-
1928-29	1255.5	15288.75	16544.25	-
1929-30	1377	11684.25	13061.25	-
1930-31	2883.6	59636.25	62519.85	-
1931-32	3584.25	49268.25	52852.5	-
1932-33	2632.5	15106.5	17739	-
1933-34	1741.5	9274.5	11016	-
1934-35	4791.15	33048	37839.15	-
1935-36	9679.5	36879.3	46558.8	-
1936-37	9387.9	35781.75	45169.65	-
1937-38	12107.07	45428.445	57535.515	-
1938-39	11441.655	54328.32	65769.975	-
1939-40	7037.685	35959.14	42996.825	-
1940-41	12779.37	21511.98	34291.35	-
1941-42	17820	17010	34830	-
1942-43	18630	9315	27945	-
1943-44	17089.38	11481.345	28570.725	-
1944-45	27783	20250	48033	-
1945-46	32998.995	38355.12	71354.115	-
1946-47	30571.02	46194.3	76765.32	-
1947-48	20807.685	61768.98	82576.665	-
1948-49	22820.13	67711.95	90532.08	-
1949-50	24022.575	81445.5	105468.075	-
1950-51	28750.14	54809.055	83559.195	-
1951-52	22816.485	33821.145	56637.63	-
1952-53	20121.615	28936.44	49058.055	-
1953-54	12744.54	23482.305	36226.845	-
1954-55	3922.02	20012.265	23934.285	-
1955-56	5468.31	22258.395	27726.705	-
1956-57	4377.24	23236.875	27614.115	-
1957-58	4593.915	15379.875	19973.79	-

cont

Table 3 cont

Year	Arterial/Field (ha)[1]	hill (ha)	Total (ha)[2]	Arterial only (ha)
1958-59	3595.59	19017.99	24204.825	1591.245
1959-60	4141.935	34361.415	39712.68	1209.33
1960-61	3426.3	25567.245	29738.745	745.2
1961-62	3602.07	21554.505	26028.135	871.56
1962-63	3768.525	28229.31	33659.955	1662.12
1963-64	3245.67	24659.235	29450.79	1545.885
1964-65	4088.475	20508.39	25383.78	786.915
1965-66	4059.315	15143.76	20027.655	824.58
1966-67	4608.09	11454.21	16583.535	521.235
1967-68	4267.08	14624.55	20431.845	1540.215
1968-69	5701.59	24481.44	32676.615	2493.585
1969-70	7465.365	27668.385	36951.795	1818.045
1970-71	14524.515	16503.75	31883.22	854.955
1971-72	12025.665	13828.32	26921.97	1178.55
1972-73	9300	-	9300	-
1973-74	9300	-	9300	-
1974-75	8500	-	8500	-
1975-76	5600	-	5600	-
1976-77	6100	-	6100	-
1977-78	6900	-	6900	-
1978-79	9300	-	9300	-
1979-80	7300	-	7300	-
1980-81	9700	-	9700	-
1981-82	8100	-	8100	-
1982-83	10500	-	10500	-
1983-84	11300	-	11300	-
1984-85	13000	-	13000	-
1985-86	9300	-	9300	-
1986-87	4800	-	4800	-
1987-88	2400	-	2400	-
1988-89	2000	-	2000	-
Total	**619 093**	**1 411 003**	**2 047 629**	**17 643**

[1] Until 1958, the extent of arterial and field drainage was not recorded separately.

[2] Total extent of field drainage from 1972 was estimated from Robinson (1990).

Extent of wet soils in relation to the extent of drainage installation

It is clear that many soils in Scotland would not require drainage therefore it is important to match the county and national scale statistics to the extent of imperfectly or poorly drained mineral soils. Mackay (1973) and subsequently Robinson (1990) summarised the extent of drainage in Scotland from the start of the grant period until 1988. Although there are a few issues with this dataset, it remains as the best dataset on the extent of drainage systems in Scotland. For example, the fact that arterial and field drainage was not recorded separately until 1958, the area of drainage was calculated from the cost of the works, some areas may have been drained more than once and there may have been drainage done that was not grant-aided.

It appears that the total area of field drainage installed since 1921 (including arterial drainage which is most likely to have been done in lowland situations) is around 620 000 ha but according to the Soil Survey of Scotland mapping (Soil Survey Staff, 1981) there is a total area of mineral soils that are not free draining but are in regular cultivation of around 970 000 ha. There will also be some areas mapped as freely drained soils that have some form of artificial drainage system installed, for example, where a spring or seepage line was tapped to avoid water periodically flowing over the soil surface.

The discrepancy between the area drained and the extent of wet soils may be partly explained by the occurrence of wet soils that are only occasionally cultivated and for which the expense of draining outweighs the economic benefit. To try and establish the extent of wet soils in this more marginal land, the 1:250 000 scale Land Capability for Agriculture map of Scotland (Soil Survey Staff, 1983) was overlain with the soil map.

Land in Land Capability for Agriculture (LCA) classes 4 and 5 have limited agricultural potential being primarily capable of sustaining improved pastures. Overlay of the extent and location of these LCA classes (Soil Survey Staff, 1983) with the soils map (Soil Survey Staff, 1981) showed that there was a total of 355 000 ha of mineral soils that had inhibited drainage within these LCA classes (Figure 6). When the extent of this marginal land is subtracted from the total extent of these wet, cultivated soils, the extent of the remaining land (615 000 ha) is almost the same as the area of arterial and field drainage installations since 1921 (620 000 ha). Although this appears to explain the discrepancy between the area of wet soils and of drainage, some of this land would probably be classed as out-bye land and therefore any grant-aided drainage system installed may have been classified as 'hill drainage' within the Government statistics rather than included in the 'field drainage' category. This is particularly applicable to land in LCA class 5 which accounted for 72 000 ha. Although some of the remaining class 4 land (283 000 ha) may have been classed as hill land, there is still a discrepancy between the area of land drained since 1921 and the extent of wet soils. The extent and location of this land is unknown.

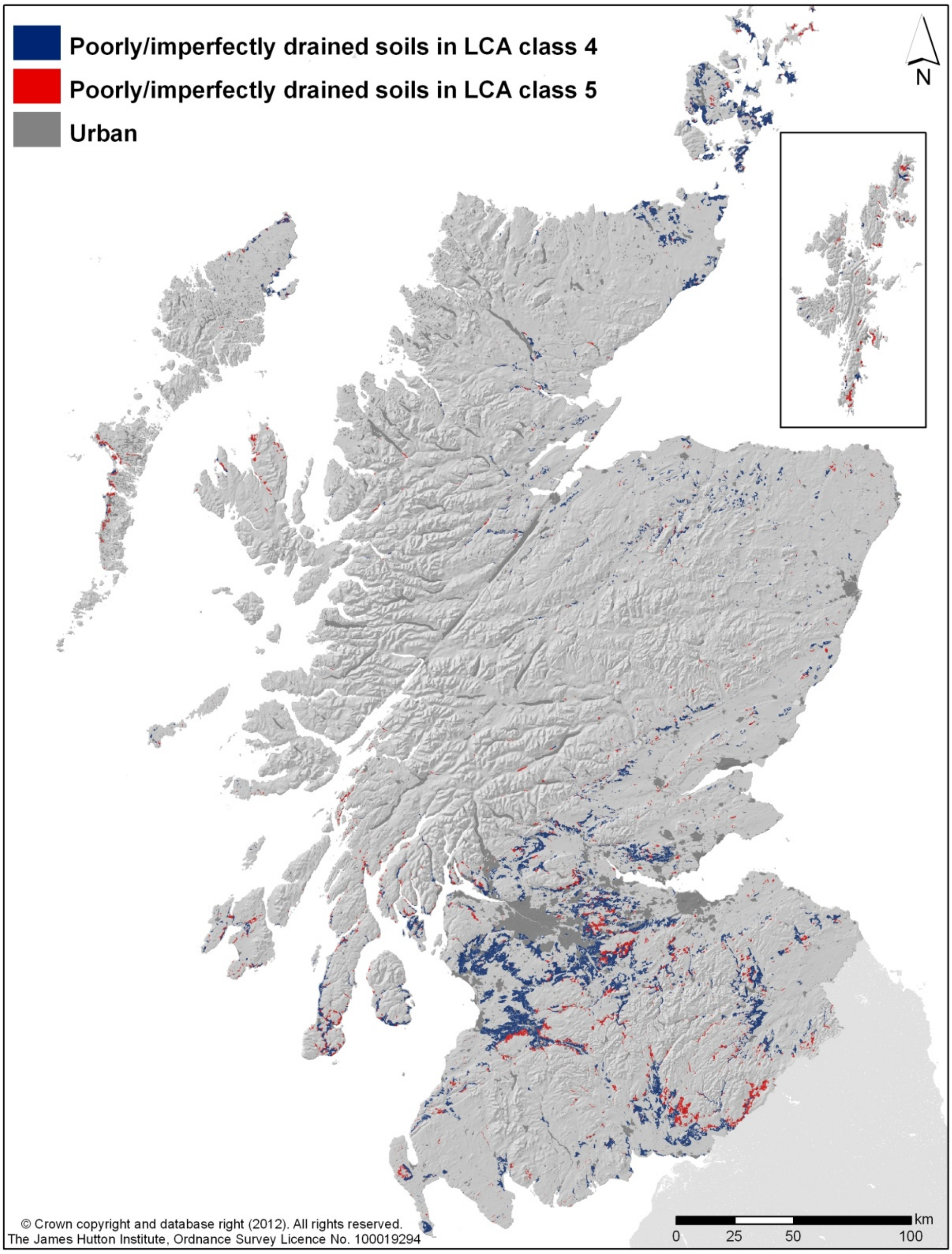


Figure 6: The distribution of wet soils in Land Capability for Agriculture classes 4 and 5

Types of drainage problems found in Scotland

Not all drainage systems have been installed in imperfectly or poorly drained soils. Some have been installed in areas mapped as freely drained for a variety of reasons. One possible reason is that at the scale of mapping, small inclusions of wet soils could not be delineated. Another is that there are spring or seepage lines that affect localised areas. These are often easily dealt with by the installation of a single drain that taps the spring and diverts the water to a river or stream. Spring lines may require the installation of more drains.

Morris and Shipley (1986) identified 15 drainage problems normally encountered in Scotland and listed a series of guidelines to address these problems. Apart from a few specific to the drainage of peat or alluvial soils (and those freely drained soil map units with occasional, localised areas of wetter soils), the drainage problems normally encountered were grouped into 3 broad classes; soils with high groundwater tables, soils with perched water tables and soils affected by spring and seepage line problems. Each of these groups requires a different method to drain the land effectively and for most, some form of secondary treatment such as subsoiling or moling is recommended. These secondary treatments are more likely to become less efficient with time than the primary drainage system.

In terms of GHG emissions, the type of drainage problem is unlikely to have much of an influence on the total emissions as it is the degree of wetness of the soil that drives the emissions.

Effect of soil drainage

MacKay (1973) also reported on some experimental work underway to investigate various aspects of soil drainage, soil hydrology and secondary drainage treatments. The three Agricultural Colleges (North, East and West), the Macaulay Institute and Aberdeen University conducted much of this work. Of the various studies, the following are the most relevant to the assessment of GHG emissions from cultivated soils in Scotland:

- The Slamannan Drainage Project - (see below).
- Assessment of Subsoiling and Moling, Fore Rogerton, Cumnock.
- Subsoiling experiment in West Perthshire.
- Assessment of mole drainage and subsoiling on soils at Tillycorthie and Craibstone Farms, Aberdeenshire. Lack of rainfall limited the scope of the experiment.
- Effect of Drainage on soils with low permeability at Crosswoodhill, West Calder.
- Visual assessment of effect of subsoiling of Balrownie and Stirling series soils in Perthshire.

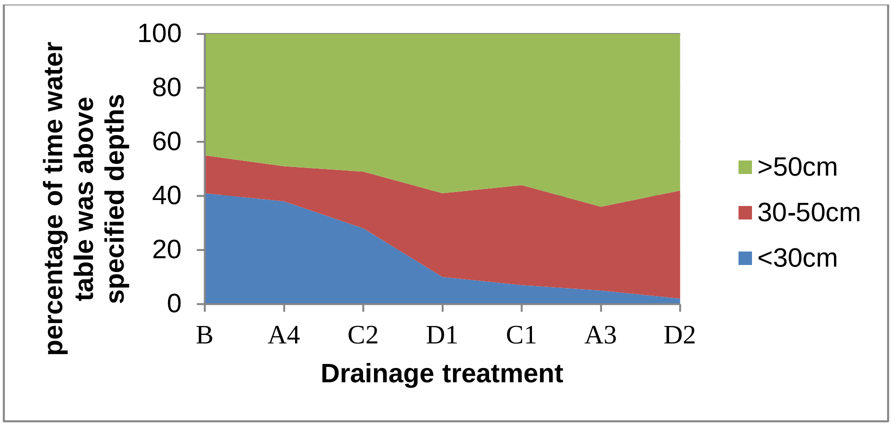
Unfortunately, only the report on the Slamannan Drainage Project (Howat et al., 1978) has been found. This report focussed on a drainage experiment on the Wester Greenhill and Glenrig farms on the Slamannan Plateau. The trials were set up to examine the effect of different drainage and secondary treatments on the soil water regime of poorly drained, slowly permeable soils. Neither site had under-drainage but did have rig and furrow drainage. Both sites were under permanent pasture.

The experiment at Wester Greenhill comprised six different treatments while the experiment at Glenrig comprised 4 different treatments (Table 4). The effect of these treatments on the height and duration of the perched water table was recorded. Figures 7 (a) and (b) clearly show a marked decrease in the time the soil was saturated (that is, had an observed water table) within 30 cm of the soil surface for many of the drainage treatments and a corresponding, but less pronounced, decrease in the degree of saturation between 30 and 50 cm. This decrease in soil wetness in the topsoil means that the land is workable for a longer period, has a greater bearing capacity and has less rush infestation. According to Howat et al. (1978) the carrying capacity of Wester Greenhill farm almost doubled in terms of livestock units due to the improved drainage and sward.

Table 4: Drainage treatments at Wester Greenhill and Glenrig.

Code (from report)	**Drainage treatment**
Wester Greenhill	
B	Control - no drainage apart from rig and furrow
A4	50mm plastic pipe; gravel to base of plough; no secondary treatment
C2	75mm tiles; gravel to surface; Mole drains @2.2 m interval
D1	75mm tiles; no gravel; subsoiled
C1	75mm tiles; gravel to surface; Mole drains@1.1m interval
A3	50mm plastic pipe; gravel to base of plough; Mole drains@1.65m interval
D2	75mm tiles; gravel to 30cm from surface; Mole drained@2.2m intervals
Glenrig	
C	Control - no drainage apart from rig and furrow
B2	75mm tiles; gravel to base of plough
A1	75mm tiles; no gravel
A2	75mm tiles; no gravel; subsoiled
B2	75mm tiles; gravel to base of plough

a)



b)

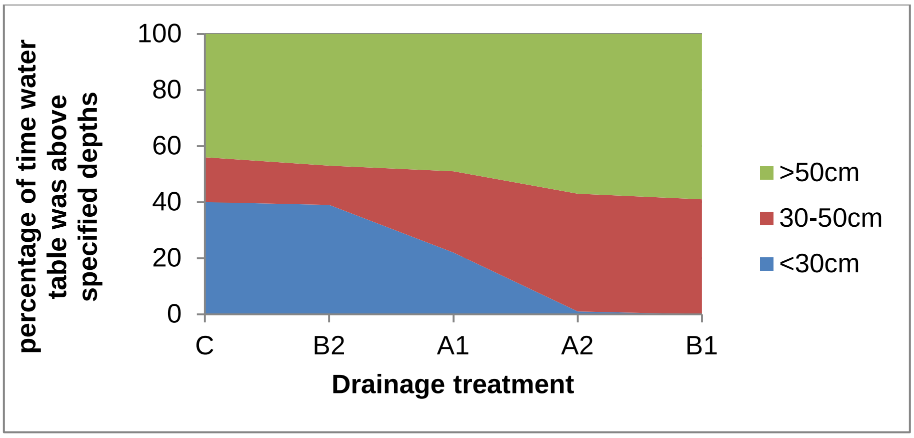


Figure 7: Percentage of time the water table was within 30cm of the soil surface; between 30 and 50cm from the soil surface and at depths greater than 50cm in a) Wester Greenhill and b) Glenrig drainage experiment sites.

As part of an investigation into the soil water regimes of Scottish soils along an east/west climate gradient a number of dipwells were established in 1984 primarily on soils of the Balrownie soil series (Lilly,1995, 1999). At one site, there were adjacent fields where one had a recent, modern drainage system installed while the other was reputed to have 100 year old stone drains. The height and duration of a perched water table was recorded approximately every week from October 1984 until November 1990 (Figure 8). These observations clearly show that the site with the modern drainage system was saturated for less time and at greater depths in the soil (dark colour in Figure 8) than the site with the considerably older and less efficient drainage system (light colour in Figure 8). While the site with the modern drainage system was under arable, the other site was rush-infested grass pasture. From 265 observations, the site with the modern drainage system had a water table within 30 cm of the soil surface (that is, below plough depth) 31% of the time while the site with the older drainage system had a water table at this height 68% of the time with the wettest times for both sites coinciding with the winter months. A drop in watertable height to within 45cm of the soil surface was achieved for 55% of the time in the drained site compared with 86% for the undrained soil.The period between autumn 1988 and autumn 1989 seems to be an exception where the soils at both sites were saturated at shallower depths for an extended period.

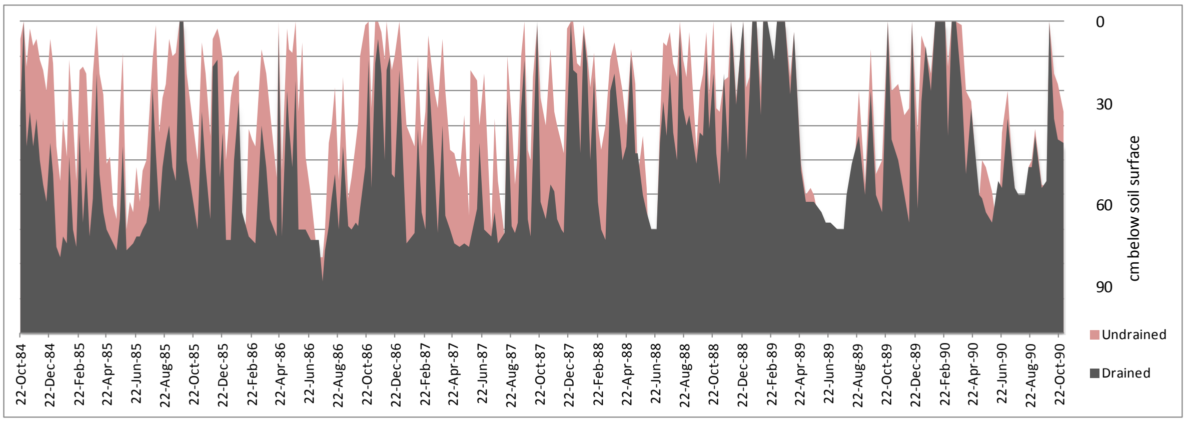


Figure 8: Observed water table height in a soil with a slowly permeable subsoil from Drumdowie, Perthshire.

What each of the experiments at Drumdowie, Wester Greenhill and Glenrig tell us about soil drainage in Scotland is that current production levels could not be maintained without adequate drainage and although drainage schemes may be becoming less efficient, they are clearly still operating at an effective level compared to the undrained sites or those with older forms of drainage such as rig and furrow or stone drains.

Farm and Contractor Survey

A survey of farmers and drainage contractors was undertaken during the summer of 2012 to assess the current state of farm drainage across Scotland, and the current workload of some of the major Scottish contractors. A series of questions were prepared and used in two small focus groups, one in the north-east of Scotland (in an area supporting a range of mixed farming enterprises), and one in the south-west of Scotland (in an area supporting mostly pasture-based livestock farming).

Modified questionnaires were sent to 3 of the largest Scottish contractors to collect the views of drainage contractors. Both questionnaires are included in Appendix 1.

Results

Most farmers considered their drainage to be in a moderate or good condition, with none identifying their drainage as excellent or poor (Figure 9). Several respondents commented on deterioration in their drainage systems over recent years.

Condition of drainage

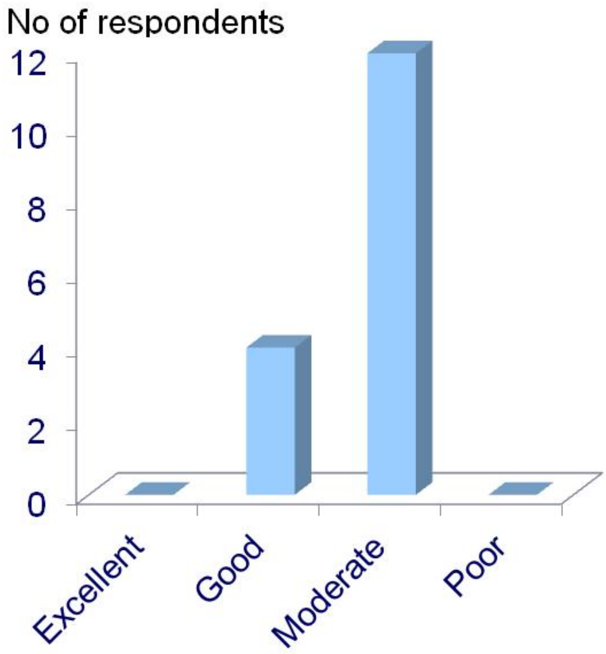


Figure 9: Farmers were asked to assess the current state of their drainage system.

Age of drainage

The estimates of the age of drainage systems provided by farmers was consistent with the age associated with historic data (Section 1), with the most common class being 20-50 years (Figure 10).

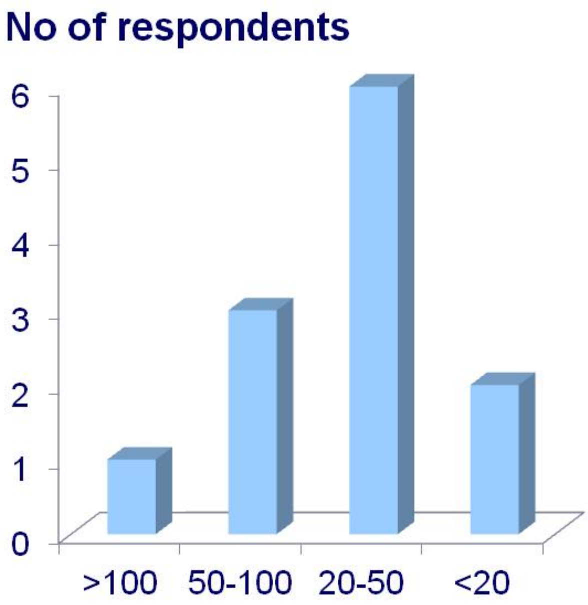


Figure 10: Estimated age of drainage.

Constraints

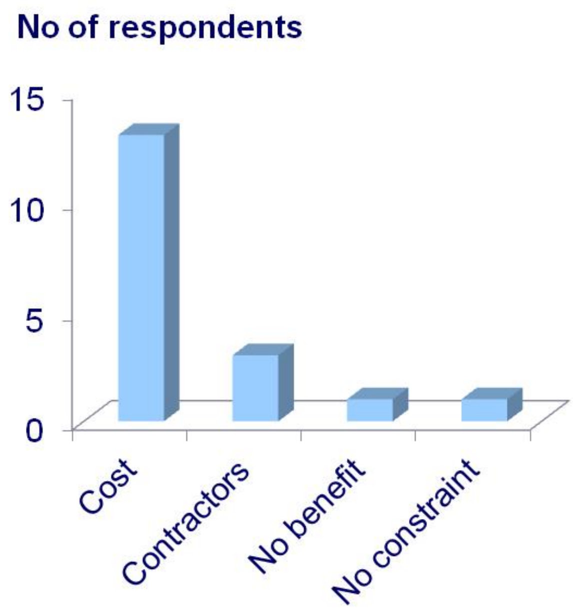


Figure 11: Cost of new drainage is by far the most important constraint identified by farmers. Costs can be >£25k /ha.

Farmers identified the costs and cost benefits as being the biggest single constraint to the installation of new drainage systems (Figure 11). It was noted that emergency repairs would be undertaken (often by the farmer themselves), but that there was little long term maintenance or renewal of drainage systems being undertaken at the present time. Some farmers also noted that regulatory issues (CAR General binding rules) could deter the installation of new drainage systems.

Contractors

Three of the larger drainage contractors in Scotland were contacted. All agreed that the current state of drainage is poor and reported low rates of installation (<100ha/y). They also considered that future work in this area would decline. These views appear to be consistent with those expressed by farmers in the earlier part of this survey.

The results of this survey represent only a small snapshot of the perceptions of drainage systems of Scottish farmers, and it is acknowledged that a larger and more comprehensive survey would be required to generate a reliable evidence base.

2. Assumptions regarding the proportion of land where installing or improving field drainage would reduce GHG emissions and rationale.

Land drainage is an essential component of Scottish agriculture as approximately half of the cultivated land in Scotland has soils with some degree of seasonal waterlogging. Unless these soils are drained, their ability to sustain agricultural production at current levels would be compromised. Therefore it is highly likely that soil drainage systems will undergo some maintenance to ensure that they continue to function. Although there are uncertainties in the statistics, it is also likely that almost all the highly productive land with imperfect or poorly drained soils already have a functioning drainage system although a more extensive survey of the extent of drainage would be required to validate this assumption.

This report is based on ongoing collaborative work funded by DEFRA (Defra code FFG0913 / AC0114) to establish the amount of land in the UK that has artificial land drainage schemes installed. This work will help to establish the area of land currently under cultivation that has waterlogged soils and no artificial drainage. It will also help to establish potential uptake beyond the maintenance of current drainage systems.

The maintenance of artificial drainage systems is essential to keep a large proportion of Scotland's productive land, workable. In the past, a proportion of this cost was borne by the tax payers in a form of grants to land owners who installed drainage systems. The provision of grants ended in the late 1980s.

The need to drain land to support agricultural production depends on soil and landscape characteristics. The Soil Survey of Scotland digital soil spatial dataset (Soil Survey of Scotland Staff, 1981 was used to identify soils with inhibited drainage and therefore identify areas of agricultural land that have inhibited drainage and potentially subject to periodic waterlogging. Based on this approach we have calculated that 970 000ha of agricultural land has these types of soils and which would benefit from artificial drainage. As shown above when this is compared to published national level drainage statistics we suggest that much of the most highly productive agricultural land (620 000ha) has already been drained to some extent in the past and therefore maintenance of these older drains becomes an important issue. This evidence is underlined by the responses to the farmer survey which suggest maintenance of old drains is a key issue rather than the installation of new drainage systems. A more extensive, spatially distributed survey on the extent and status of existing drainage systems would be required to explicitly determine the potential for drainage to mitigate GHG emissions.

3. The magnitude of GHG abatement from installing or improving drainage

Rationale for improving soil drainage

The main benefit of drainage in contributing to greenhouse gas mitigation is that it has the potential to reduce emissions of the greenhouse gas nitrous oxide (N_2O). Scotland is committed to reducing its greenhouse gas emissions by 80% by 2050. Although individual sectoral targets have not been set, it is anticipated that greenhouse gas savings will be achieved by all sectors of the economy. Within agriculture there is a preference for mitigation strategies that reduce emissions while maintaining or increasing production. The cost per unit of carbon saved incurred by mitigation measures is also an important consideration. A recent study on marginal abatement cost curves identified a range of measures that provide cost-effective mitigation of agricultural greenhouse gas emissions. Drainage was identified as a measure with a large potential for mitigation, with potentially large uncertainties in both mitigation potential and cost. These uncertainties arise because of the complex role the drainage plays in contributing to greenhouse gas mitigation.

Two microbial processes that occur commonly in soils generate nitrous oxide: nitrification and denitrification. The organisms responsible are described as nitrifiers and denitrifiers. These processes are widespread, and each is favoured by a different set of environmental conditions. However, it is common for both processes to go on simultaneously, making it difficult to attribute emissions to a particular source.

Effects of Soil Conditions on Nitrification and Denitrification

The various source processes outlined above are promoted by different soil conditions. Because nitrification is an aerobic process, it tends to be most prevalent in well-drained and aerated soils. The process is not dependent upon a supply of organic carbon, but it does require a readily available source of ammonium-N (the nitrogen contained in ammonium ions). High rates of nitrification can therefore be observed in mineral soils containing high concentrations of ammonium (often provided by additions of fertilisers and manures), as well as more organic soils that release ammonium through mineralisation. Water-logging and low temperatures are known to lower the rates of nitrification (Maag and Vinther, 1996). Nitrifying organisms are also known to be sensitive to pH, with lower nitrification rates occurring in more acid soils (Hynes and Knowles, 1984; Baggs *et al.,* 2010).

Denitrification is most likely to occur when soils containing nitrate and an adequate supply of organic matter become wet and anaerobic. Soil wetness plays an important role in controlling the aeration of a soil. As a soil becomes wetter, less of the soil's pore spaces are occupied by air, which in turn reduces rates of gaseous diffusion. The remaining oxygen is consumed by microbial respiration resulting in the development of anaerobic soil conditions (indicated by low redox potentials (redox potential is a measure of the tendency of a chemical to acquire electrons and thereby be reduced)). It is under these conditions where water filled pore space occupies more than 80% of the total that denitrification rates are highest (Dobbie and Smith, 2001). Soil pH also influences the amount of N_2O released from denitrification, as acid soils have been shown to increase the ratio of N_2O:N_2 produced (Simek *et al.,* 2002).

The soil conditions promoting nitrification and denitrification are quite different, and yet the heterogeneity of the soil environment can allow both processes to occur simultaneously. Most soils are formed from structural units or aggregates, which define the physical architecture of the soil. Aggregates are separated by pores which allow the transport of the errant water (interpore water). This means that the physical, chemical and biological environment within aggregates can be very different to that in the pore space. Consumption of oxygen within a soil aggregate can lead to large gradients in oxygen availability across the aggregate, and allow the development of an anaerobic aggregate centre to coexist with an aerated peripheral region (Arah and Ball, 1994). These contrasting conditions therefore allow the processes of nitrification and denitrification to take place simultaneously at different microsites (small individual locations in a soil) within the same soil. Soil conditions also respond very rapidly to changes in the external environment. Thus changes in temperature, rainfall, crop growth, fertiliser addition and tillage fundamentally affect the drivers of nitrification and denitrification.

The effect of drainage on net greenhouse gas emissions is complex. When fertiliser nitrogen is applied to wet soils, it can be expected that nitrous oxide emissions will be increased relative to those in well drained soils. However wetter soils can also inhibit soil respiration and so lead to decreased CO_2 emissions. Whether or not this leads to an increase in soil organic matter depends upon the balance of CO_2 release and carbon input through photosynthesis. The overall effect on greenhouse gas balances is thus difficult to predict. This will be achieved by using a review of literature to understand how changes in drainage status influences individual greenhouse gas emissions, and then bring this together within the context of the overall system.

The release of N_2O to the atmosphere from soils depends mainly on the microbiological production processes of nitrification and denitrification. In cultivated soils, at a field or landscape scale, these processes are driven by soil temperature, soil wetness (Smith *et al.,* 1998), the addition of N fertilisers and land management (Dobbie *et al.,* 1999). Therefore, the emissions are neither spatially nor temporally uniform and will vary with climate and farm type/enterprise. One key aspect for mitigation is the control of soil moisture content through land drainage. Land drainage has been used to improve cultivation in Scotland probably since Roman times. Medieval rig and furrow helped to improve aeration in at least part of the field (rig) while modern under-drainage techniques also increase accessibility for farm machinery.

The magnitude of emissions reductions provided by this measure is likely to be significant, but would vary according to the current state of drainage systems. It was estimated by MacLeod *et al.,* (2010) that the annual UK abatement potential by 2022 would be 5.84 kt N_2O.

Land Management and Environmental Controls

There are a number of studies undertaken both in Scotland and elsewhere that show the relationship between N_2O emissions and anaerobic conditions induced by soil wetness.

Anaerobic conditions promote the release of N_2O by incomplete denitrification (Dobbie and Smith, 2006; Kliewer and Gilliam, 1995) and can be caused by rises in the water table; restricted downward drainage due to natural; and anthropogenic compaction and transient water-logging due to prolonged or heavy rainfall. Reiners *et al.,* (1998), working in Costa Rica, noted that the indirect effect of topography on N_2O fluxes was primarily due to topographic influences on soil moisture contents. This relationship between topography, soil moisture content and N_2O flux was also found by Corre *et al.,* (1999) in Saskatchewan. In an earlier study, Corre *et al.,* (1996) reported that the role of topography in controlling N_2O fluxes was primarily due to its influence on hydrologic and pedologic (*i.e.* soil related) processes in the landscape. Working in eastern Scotland, Ball *et al.,* (1997) found increased N_2O emissions associated with micro-topographic hollows. In studying the influence of drainage and texture on N_2O fluxes, Skiba and Ball (2002) reported the greatest fluxes from a sandy loam located in a valley bottom and from imperfectly drained clay loams and sandy clay loams located on level sites.

Using soil cores in the laboratory, Akiyama *et al.,* (2004) and Yanai *et al.,* (2007) found N_2O emissions to increase with increasing soil wetness. Andersen and Petersen (2009) found similar results using repacked soil cores. Bollman and Conrad (1998) reported increases in N_2O emissions from air-dried top-soils in response to increases in water content and, like Andersen and Petersen (2009), found little N_2O emission from the drier soil samples. McTaggart *et al.,* (2002) extracted soil cores from 4 Japanese upland soils. These cores were taken to a laboratory, partially dried using tension tables, fertilised and rewetted. They found that emissions of N_2O increased at higher moisture contents in all four soils, but the magnitude of increase was much greater in fine textured soils. This indicated that the pore size distribution in soils is of importance in N_2O emissions. Soils with limited pore space will reach saturation earlier in any rainfall event compared to soils with greater pore space. In Maryland, USA, Castellano *et al.,* (2010) took intact cores from the field into the laboratory and subjected them to the same responses in water content that they had observed in the field (rising water tables leading to saturation). They found that both water-filled pore space and matric potential were related to N_2O emissions with matric potential being the better predictor. The main conclusion though, is that soil water content drives N_2O emissions from these soils. Although it is clear that increased soil wetness induces N_2O emissions in laboratory samples it is difficult to relate the water contents of these soils to field soils as they are often repacked or otherwise disturbed. The nature of the relationship between soil water content and N_2O emissions can only be determined by examining field-based experiments such that potential mitigation strategies can be put in place.

Livesley *et al.,* (2008) reported a weak but significant increase in N_2O emissions in response to rainfall in sheep pastures of Victoria, Australia while Webb *et al.,* (2000) reported increases in N_2O emissions after rainfall events for soils in England. The greatest emissions were reported the day after rainfall indicating that denitrification was occurring in response to the wetter conditions but that the resulting N_2O was trapped in the soil pores until such times as the soil dried sufficiently to allow it to escape. Henault *et al.,* (1998) examined N_2O emissions from 3 contrasting soil types in, what they considered a uniform climatic zone in northwest France. The soil that gave the greatest emissions was the one with inhibited drainage and exhibiting hydromorphism (gleying *i.e.* the process of water-logging and reduction in soils). However, short-term fluctuations in near-surface moisture conditions during rainfall events can have a major effect on emissions even on well-drained soils, particularly if high mineral N is present, these effects are nevertheless temporary (Dobbie *et al*.,1999).

With respect to N_2O emissions in Scotland, there has been much work by Smith *et al.,* (1998); Clayton (1997); Dobbie and Smith (2006); Dobbie and Smith (2003); Dobbie and Smith (2001) and Dobbie *et al.,* (1999). All report increases in N_2O emissions with increases in soil wetness from field-based experiments over a long period of time which gives the opportunity to examine the effect of climate (in particular, rainfall) on emissions of N_2O from Scottish agricultural systems. Both Clayton *et al.,* (1997) and Smith *et al.,* (1998b) reported increases in N_2O emissions from the same soils but over two different years. The greatest emissions were recorded during the wetter of the two years. Dobbie and Smith (2006) found a direct relationship between the height of a perched water table and an increase in N_2O emissions (Figure 12). The perched water table lead to an increase in water filled pore space (increased water contents) within the topsoil above the zone of saturation. The N_2O emissions fell when the water table retreated to below 40cm allowing the topsoil to dry. Somewhat contradictory, Smith *et al.,* (1998a) found that N_2O emissions declined when the soils were almost saturated. However, it is likely that increased water contents stimulate denitrification in soils that are near to saturation but, as the soil becomes wetter, this process either declines, the soil water physically prevents the gas from escaping (Webb *et al*., 2000) or the denitrification process produces gaseous N_2.

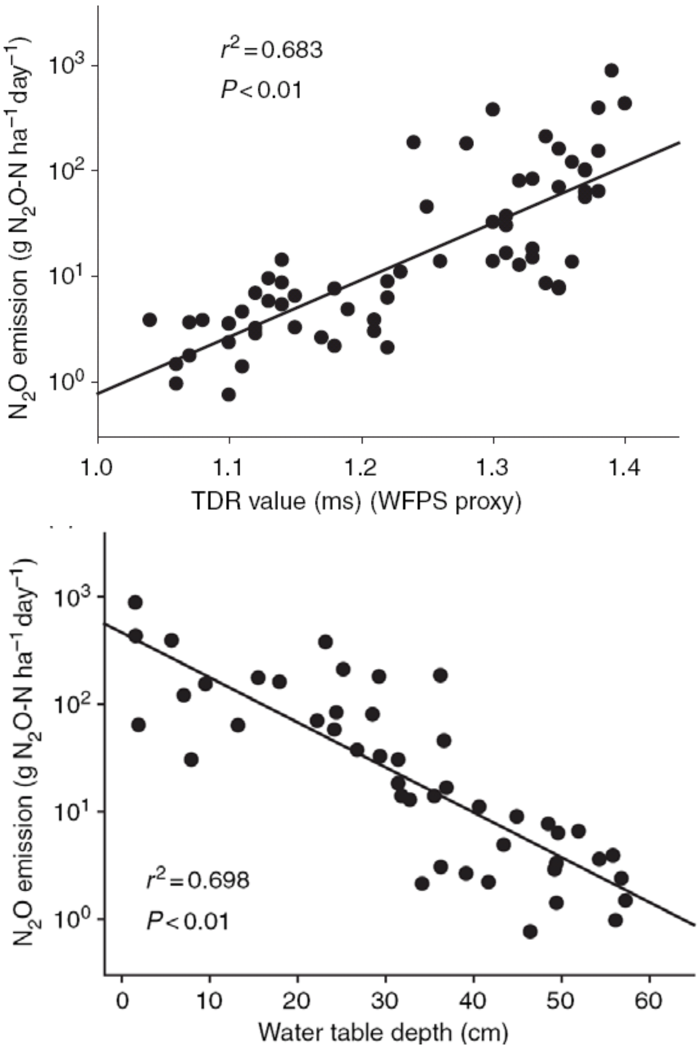


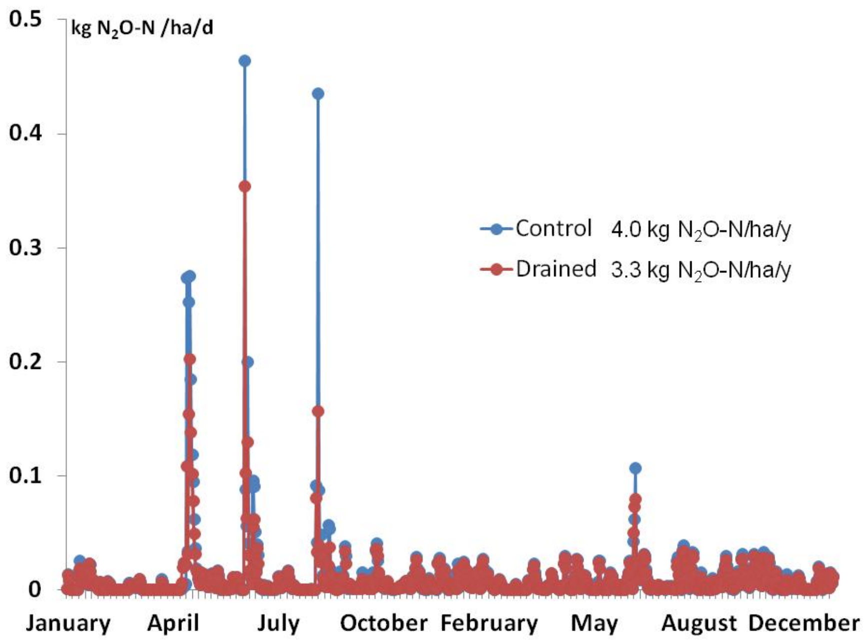
Figure 12: The relationship between soil wetness and N_2O emissions (Dobbie and Smith 2006).

Given that one of the main drivers of N_2O emissions seems to be soil wetness it would seem appropriate to attempt to mitigate losses by improving soil drainage. As Dobbie and Smith (2006) showed that if the water table could be kept to no less than 35 cm below the ground surface, fluxes during the growing season would be reduced by 50%. A reduction in the height of the perched water table to 45cm below the soil surface could result in an 80% reduction. However, even in well drained soils, transient wetness due to heavy or prolonged rainfall could still lead to increases in N_2O emissions, albeit temporarily (Dobbie *et al.*,1999).

Unpublished work (Lilly, 1995) suggests that artificial drainage systems can reduce perched water tables in a Scottish soil by an average of 18cm and could be up to 60cm, well within the range suggested by Dobbie and Smith (2006). Once excess soil water has been removed by artificial drainage systems it is often discharged to a ditch or stream. Reay (2009) found that up to 25% of the total N_2O emissions from a farm could be from degassing of drainage water, highlighting the importance of N management in addition to soil drainage in the mitigation of GHG emissions.

Hopkins and del Prado (2007) in their review of implications of climate change for European grasslands also suggest increasing aeration through drainage and avoiding compaction as potential mitigation strategies. In New Zealand, de Klein and Legard (2005); Luo *et al.,* (2010) also suggested that improving soil drainage may help mitigate N_2O emissions to the atmosphere as well as reducing compaction. Compacted soils have less macropore (*i.e.* cavities larger than 50µm) space and will reach anaerobic conditions more readily than non-compacted, porous soils. However, de Klein and Legard (2005) caution that increased drainage may cause N losses in the form of dissolved nitrate. This is possible, particularly in more permeable soils affected by high water tables but less likely where the cause of the wetness, like in much of the Scottish agricultural lowlands, is due to a perched water table on slowly permeable subsoil.

Integrated studies of the effects of drainage on emissions of N_2O and tradeoffs with other pollutants are lacking. However, such interactions can be analysed by using ecosystem models such as DNDC. A simulation of the response of a grassland soil with and without drainage was undertaken at a grassland site in SE Scotland. The simulation indicated that while drainage reduced N_2O emissions (particularly during periods of high soil wetness), there were relatively small changes in nitrate leaching (Figure13)



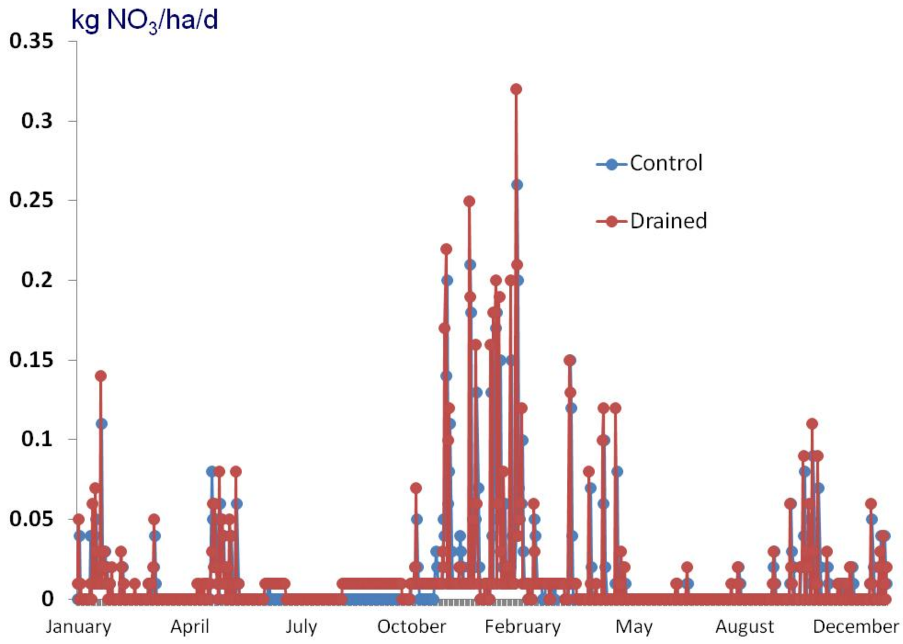


Figure 13: Modelled effects of drainage on N_2O emissions and nitrate leaching at Easter Bush, a permanent grassland in the SE of Scotland. Emissions were modelled using input data (including met data) collected from the site using DNDC (v94).

Regional Variation

Lilly *et al.,* (2003; 2009) made use of this relationship between soil wetness and N_2O emissions to spatially scale field-based data (Clayton *et al.,* 1997; McTaggart *et al.,* 1997; Dobbie *et al.,* 1999) to derive maps of N_2O emissions throughout Scotland. This scaling framework took account of soil wetness (Lilly and Matthews, 1994) and calculated annual emissions based on land management and farm type. Lilly *et al.,* (2009) found that the greatest N_2O emissions from the Scottish agricultural sector were from dairy production on grazed grass with wet soils (predominantly in the south and west). Cereal production produced the least N_2O emissions from the Scottish agricultural sector (broadly distributed in the east of the country. Thus, it is not only the degree of wetness of the soil that will affect the likelihood of N_2O emissions but the soil/land use combination.

4. Impacts or benefits of installing field drainage for other climate change mitigation policies, and other environmental priorities and regulations

Drainage represents a significant land management intervention and has the potential to impact on a range of functions both directly and indirectly in ways that are not always intended. For example the installation of artificial drainage systems into cultivated and fertilised land can increase nitrate and phosphorus leaching to surface waters by increasing the rate of runoff. This will also have the potential to alter river flows which will be more marked in those catchments with a high proportion of cultivated land and soils with inhibited drainage. Conversely, nitrate leaching to groundwater may be reduced as soil hydraulic conductivity is greatest when the soil is saturated; artificial drainage schemes will reduce length of time a soil is saturated.

The influence of policies on drainage system installation and maintenance can therefore have wide ranging system wide effects. Although grant schemes supporting the installation of drains are no longer available, a number of current policies have an impact on decisions regarding drainage installation. These are described below.

Common Agricultural Policy

The Common Agricultural Policy (CAP) plays a significant role in the overall management of agricultural land. The policy has led to a number of negative effects on the environment, while successfully increasing production. The reforms of 2003 (Fischler Reforms) have led to the removal of production-related payments[1], and there is some indication that this has led to reduction in stocking densities for livestock (SAC, 2009; Thomson et al*,* (2011).

Since decoupling of CAP payments, farmers have received a Single Farm Payment (SFP) based on historic payments received between 2000-02[2]. These support payments are subject to conditions, to meet Good Agricultural and Environmental Conditions (GAEC) and adherence to environmental, food safety, animal and plant health and animal welfare legislation known as Statutory Management Requirements (SMRs)[3]. These standards are referred to as cross-compliance (CC) and farmers can have their SFP reduced for any breaches in these conditions, meaning there is a financial incentive for farmers in receipt of SFP to comply with the CC standards. Devolved authorities use a number of the CC measures that may impact (indirectly) on the condition of drainage systems. Regional CC variants are primarily based on EU Regulation 1782/2003 (as amended).

Maintaining functioning field drainage systems is a requirement under the Common Agricultural Policy Schemes (Cross-Compliance) (Scotland) Regulations 2004, and has been transposed into a criterion for GAEC (GAEC 5: Maintenance of functional field drainage systems; see also PEPFAA Code). The clearing of ditches is subject to the Controlled Activities (Scotland) Regulations 2006. Effective land drainage can reduce peak flows, which has a bearing on (sustainable) flood management and associated regulation and guidance (Flood Risk Management (Scotland) Act 2009).

Codes of Good Agricultural Practice

---

[1] So-called decoupling

[2] Scotland and Wales maintain a fully historic SFP, Northern Ireland has a static hybrid model where the payment is largely determined by historic CAP payments and an area payment of €68 per hectare also paid. In England a "dynamic hybrid" was adopted and the SFP has been moving from having primarily a historic basis in 2005 to being entirely based on the farmed area in 2012.

[3] See Annex I to Council Regulation (EC) No 1782/2003.

In addition to standard CC measures, devolved administrations also have their own "Codes of Good Agricultural Practice" for the protection of air, water and soil. In Scotland this takes the form of the PEPFAA Code and the 4 Point Plan. The Scottish Rural Development Programme (SRDP) has a number of voluntary options open to eligible land mangers. The majority are under Axis 2 funding, associated with protection of the environment, although these do not directly support the installation of drainage systems.

Other voluntary guidelines supporting the maintenance of field drainage systems include Scottish Best Management Practice Handbook and Farm Soils Plan.

Although there is recognition that drainage provides a range of benefits in agricultural soils, there is also increasing concern that drainage of organic rich soils can have deleterious effects on a range of ecosystem services including carbon storage and biodiversity. There are an increasing number of policies and guidelines that therefore support the avoidance of drainage of organic rich soils and wetlands. These include the Scotland Rural Development Programme, Farming for a Better Climate and Flood Risk Management (Scotland) Act 2009

While it is normally assumed that 'wet' soil will tend to store more carbon than 'dry' soils due to a lowering of biological activity when anaerobic, an analysis of 2,464 topsoil samples from the Scottish Soils Database (held at JHI) does not substantiate this assumption.

The median carbon contents were calculated for 1,960 topsoils samples described as having arable crops and stratified into Brown earths, Podzolic soils (both freely draining soils) and into Noncalcareous gleys and Brown earths with gleying (both with some level of inhibited drainage). The median carbon contents of the Brown earths was the greatest followed by Noncalcareous gleys, Podzolic soils and finally, Brown earths with gleying.

For 303 soils under rotational grass, the sequence was Brown earths and Podzolic soils followed by Noncalcareous gleys and Brown earths with gleying and for the remaining 201 soils under permanent, improved grass, the soils with the greatest median carbon contents were Noncalcareous gleys, podzolic soils, Brown earths and then Brown earths with gleying (Table 5)

Land Use	Greatest C content			Least C content
Arable	Brown earths	Noncalcareous gleys	Podzolic soils	Brown earths with gleying
Rotational grass	Brown earths and Podzolic soils		Noncalcareous gleys	Brown earths with gleying
Permanent (improved) grass	Noncalcareous gleys	podzolic soils	Brown earths	Brown earths with gleying

Table 5: sequence of carbon concentrations by soil type under arable, rotational or improved permanent grass pasture

Clearly there are other factors besides wetness that are influencing the carbon contents of these soils otherwise the expected sequence would be Noncalcareous gleys> Brown earths with gleying> Brown earths> podzolic soils. Therefore, it is difficult from these data to state whether improved drainage would have an effect on the ability of Scotland's soils to store carbon.

Conclusions

Land drainage is an essential component of Scottish agriculture as approximately half of the cultivated land (arable and improved grassand) in Scotland has soils with some degree of seasonal waterlogging. Unless these soils are drained, their ability to sustain agricultural production at current levels would be compromised.

Evidence suggests that the condition of drainage systems in Scotland has deteriorated in the past 50 years with little investment currently taking place. However this conclusion is based upon a very limited survey and more research is necessary to provide a comprehensive assessment. It does however seem likely that many farm drainage systems are currently in a sub optimal condition.

Drainage has a significant environmental impact. Improved drainage can increase productivity and reduce emissions of N_2O (expressed on a unit area and unit product basis). There is however a need for direct experimental evidence to quantify the magnitude of drainage effects. The improvement of soil drainage could however be seen as a cost effective mitigation measure to reduce emissions, and a sensible climate adaptation.

These recommendations do not apply to semi-natural, organic rich and wetland soils as there are many environmental benefits including those related to carbon storage and natural flood management provided by the avoidance of drainage in these systems. However, there is currently insufficient evidence to suggest that wet, cultivated mineral soils would lose more carbon if the soil were drained.

References

Akiyama, H., McTaggart, I.P., Ball, B.C., Scott, A., 2004. N_2O, NO, and NH3 emissions from soil after the application of organic fertilizers, urea and water. Water Air and Soil Pollution 156, 113-129.

Andersen, A.J., Petersen, S.O., 2009. Effects of C and N availability and soil-water potential interactions on N_2O evolution and PLFA composition. Soil Biology and Biochemistry 41, 1726-1733.

Anthony, S., Wilson, L., Hodgkinson, R., Jordan, C., Higgins, A., Lilly, A., Baggaley N. and Farewell. T. 2012. Agricultural field under Drainage installation in the United Kingdom. Report to DEFRA: Project AC0114.

Arah,J.R.M., Smith,K.A., Crichton,I.J. and Li,H.S. 1991. Nitrous-Oxide Production and Denitrification in Scottish Arable Soils. Journal of Soil Science, 42, 351-367.

Arah,J.R.M.and Ball,B.C. 1994. A functional-model of soil porosity used to interpret measurements of gas-diffusion. European Journal of Soil Science, 45, 135-144.

Baggs, E. M., Smales, C. L., and Bateman, E. J. 2010. Changing pH shifts the microbial source as well as the magnitude of N_2O emission from soil. Biology and Fertility of Soils, 46, 793-805.

Baggs,E.M. 2008. A review of stable isotopes techniques for N_2O source partitioning in soils: Recent progress, remaining challenges and future considerations. Rapid Commun.Mass Spectrom., 22, 1664-1672.

Ball, B.C., Horgan, G.W., Clayton, H. and Parker, J.P. 1997. Spatial variability of nitrous oxide fluxes and controlling soil and topographic properties. Journal of Environmental Quality, 26, 1399-1409.

Clayton, H., McTaggart, I.P., Parker, J., Swan, L. and Smith, K.A. 1997. Nitrous oxide emission from fertilised grassland: A two-year study of the effects of N fertiliser form and environmental conditions. *Biology and Fertility of Soils,* 25, 252-260.

Corre, M.D., Pennock, D.J., Van Kessel, C. and Elliott, D.K. (1999) Estimation of annual nitrous oxide emissions from a transitional grassland-forest region in Saskatchewan, Canada. Biogeochemistry, 44, 29-49.

Corre, M.D., van Kessel, C. and Pennock, D.J. (1996) Landscape and seasonal patterns of nitrous oxide emissions in a semiarid region. Soil Sci Soc Amer J*,* 60, 1806-1815.

de Klein, C.A.M., Ledgard, S.F., 2005. Nitrous oxide emissions from New Zealand agriculture - key sources and mitigation strategies. Nutrient Cycling in Agroecosystems 72, 77-85.

Dobbie, K.E. and Smith, K.A. 2001. The effects of temperature, water-filled pore space and

Dobbie, K.E. and Smith, K.A. 2003. Nitrous oxide emission factors for agricultural soil in Great Britain: the impact of soil water-filled pore space and other controlling factors. *Global Change Biology*, 9, 204-218.

Dobbie, K.E. and Smith, K.A. 2006. The effect of water table depth on emissions of N_2O from a grassland soil. *Soil Use and Management*, 22, 22-28.

Dobbie, K.E., McTaggart, I.P. and Smith, K.A. (1999) Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables, and mean emission factors. Journal of Geophysical Research-Atmosphere, 104, 26891-26899.

Green, F.H.W. 1979a. Field drainage in Europe: a quantitative study. *Institute of Hydrology report 57*.

Green, F.H.W. 1979b. Field , forest and hill drainage in Scotland. *Scottish Geographical Journal*, 95, 159-164.

Green, F.H.W. 1980. Field under-drainage before and after 1940. *The Agricultural History Review*, 28, 120-123.

Groffman,P.M., Altabet,M.A., Bohlke,J.K., Butterbach-Bahl,K., David,M.B., Firestone,M.K., Giblin,A.E., Kana,T.M., Nielsen,L.P. and Voytek,M.A. 2006. Methods for measuring denitrification: Diverse approaches to a difficult problem. Ecological Applications, 16, 2091-2122.

Henault, C., Devis, X., Page, S., Justes, E., Reau, R. and Germon, J.C. 1998. Nitrous oxide emissions under different soil and land management conditions. Biology and Fertility of Soils 26, 199-207.

Howat, D., McCombie, C.M., McGregor, A.J. and Shipley, B.M. 1978. Drainage of soils of low permeability: The Slamannan Project. Research and Development Publication 8. The West of Scotland Agricultural College. Auchincruive.

Hynes, R. K and Knowles, R. Production of nitrous oxide by Nitrosomanas europea: effects of acetylene, pH and oxygen. Canadian Journal of Microbiology 30, 1397-1404. 1984.

IPCC 2006. *IPCC Guidelines for National Greenhouse Gas Inventories; 2006. Prepared by the National Greenhouse Gas Inventories Programme*. IPCC, Japan.

Kliewer, B.A. and Gilliam, J.W. 1995. Water table management effects on denitrification and nitrous oxide evolution. *Soil Science Society of America Journal*, 59, 1694-1701.

Laird, P.R. 1946. Agricultural Survey of Scotland. Department of Agriculture for Scotland. HMSO.Edinburgh

land use on N_2O emissions from an imperfectly drained gleysol. *European Journal of Soil Science*, 52, 667-673.

Lilly, A and Matthews, K B. 1994. A Soil Wetness Class map for Scotland: new assessments of soil and climate data for land evaluation. Geoforum, 25, 371-379.

Lilly, A. 1995. Simulating the water regime of some Scottish soils: implications for land evaluation. PhD Thesis. University of Stirling.

Lilly, A. 1999. The use of inverse modelling and dipwell data in the calibration and evaluation of a soil water simulation model. *Geoderma*, 90, 203-227

Lilly, A., Ball, B.C., McTaggart, I.A. and DeGroote, J. 2009. Spatial modelling of nitrous oxide emissions at the national scale using soil, climate and land use information. Global Change Biology, 15, 2321–2332

Lilly, A., Ball, B.C., McTaggart, I.P. and Horne, P.L. 2003. Spatial and temporal scaling of nitrous oxide emissions from the field to the regional scale in Scotland. *Nutrient Cycling in Agroecosystems,* 66, 241-257.

Livesley S.J., Kiese, R., Graham, J., Weston, C.J. Butterbach-Bahl, K. and Arndt, S.K. Trace gas flux and the influence of short-term soil water and temperature dynamics in Australian sheep grazed pastures of differing productivity. Plant Soil (2008) 309:89–103.

Livesley, M.C. Field Drainage. 1960. Spon Agricultural Books. London

Luo, J., de Klein, C.A.M., Ledgard, S.F., Saggar, S., 2010. Management options to reduce nitrous oxide emissions from intensively grazed pastures: A review. Agriculture, Ecosystems and Environment 136, 282-291.

Maag,M.and Vinther,F.P. 1996. Nitrous oxide emission by nitrification and denitrification in different soil types and at different soil moisture contents and temperatures. Applied Soil Ecology, 4, 5-14.

MacCarthy, J., Brown, K., Webb, N., Passant, N., Thistlewaite, G., Murrels, T., Watterson, J., Cardenas, L., Thomson, A., and Pang, Y. UK Greenhouse Gas Inventory, 1990 to 2009; Annual Report for Submission under the Framework Convention on Climate Change. 2011. Department of Energy and Climate Change.

MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Smith, P. and Moxey, A. 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. *Agricultural Systems*, 103, 198-209.

MacKay, C. 1973. Drainage of Agricultural Land in Scotland; a report by a working group set up by the Department of Agriculture and Fisheries for Scotland.

McTaggart IP, Clayton H, Parker J, Swan L and Smith KA (1997) Nitrous oxide emissions from grassland and spring barley, following N fertiliser addition with and without nitrification inhibitors. *Biology and Fertility of Soils,* 25, 261-268.

MLURI, 1993. Land Cover of Scotland, 1988. Macaulay Land Use Research Institute. Aberdeen. http://www.macaulay.ac.uk/explorescotland/lcs_mapformat.html

Moran, D., MacLeod, M., Wall E., Eory V., Pajot, G., Matthews, R., McVittie, A., Barnes, A., Rees, R., Moxey, A.,Williams, A. and Smith,P. (2008). UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with Qualitative Analysis of Options to 2050. *Final Report to the Committee on Climate Change.* Project RMP 4950

Morris, R.J.F and Shipley, B.M. 1986. Drainage guidelines for the soils of Scotland. Soil Use and Management, 2, 109-114.

Neftel,A., Flechard,C., Ammann,C., Conen,F., Emmenegger,L. and Zeyer,K. 2007. Experimental assessment of N_2O background fluxes in grassland systems. Tellus Series B-Chemical and Physical Meteorology, 59, 470-482.

Philippot,L., Hallin,S., Borjesson,G. and Baggs,E.M. 2009. Biochemical cycling in the rhizosphere having an impact on global change. Plant and Soil, 321, 61-81.

Pihlatie,M., Ambus,P., Rinne,J., Pilegaard,K. and Vesala,T. 2005. Plant-mediated nitrous oxide emissions from beech (Fagus sylvatica) leaves. New Phytologist, 168, 93-98.

RCAHMS. http://sites.scran.ac.uk/kestrel3d/flooding/flooding.pdf. Accessed 30 Nov 2012.

Reay DS, Edwards AC and Smith KA (2009) Importance of indirect nitrous oxide emissions at the field, farm and catchment scale. Agriculture, Ecosystems and Environment. 133, 163-169

Reiners, W.A., Keller, M. and Gerow, K.G. (1998) Estimating rainy season nitrous oxide and methane fluxes across forest and pasture landscapes in Costa Rica. Water Air and Soil Pollution*,* 105, 117-130.

Report of the Land Drainage Committee (Cmd 7948). 1950. Department of Agriculture for Scotland. HMSO.

Robertson, G. P. and Tiedje, J. Nitrous oxide sources in aerobic soils: Nitrification, denitrification and other biological sources. Soil Biology and Biochemistry 19, 187-193. 1987.

Robinson, M. 1990. Impact of improved land drainage on river flows. Report no. 113. Institute of hydrology. Wallingford. England.

Robinson, M., Clayton, M.C. and Henderson, W.C. 1990. The extent of agricultural field drainage in Scotland, 1983-6. Scottish Geographical Magazine, 106, 141-147.

Robinson, M., Clayton, M.C. and Henderson, W.C. 1990. The extent of agricultural field drainage in Scotland, 1983-6. Scottish Geographical Magazine, 106, 141-147.

Simek,M., Jisova,L. and Hopkins,D.W. 2002. What is the so-called optimum pH for denitrification in soil? Soil Biology and Biochemistry, 34, 1227-1234.

Skiba, U. and Ball, B.C. 2002. The effect of soil texture and soil drainage on the emissions of nitric oxide and nitrous oxide. *Soil Use and Management*, 18, 56-60.

Skiba,U., Drewer,J., Tang,Y.S., van Dijk,N., Helfter,C., Nemitz,E., Famulari,D., Cape,J.N., Jones,S.K., Twigg,M., Pihlatie,M., Vesala,T., Larsen,K.S., Carter,M.S., Ambus,P., Ibrom,A., Beier,C., Hensen,A., Frumau,A., Erisman,J.W., Br³ggemann,N., Gasche,R., Butterbach-Bahl,K., Neftel,A., Spirig,C., Horvath,L., Freibauer,A., Cellier,P., Laville,P., Loubet,B., Magliulo,E., Bertolini,T., Seufert,G., Andersson,M., Manca,G., Laurila,T., Aurela,M., Lohila,A., Zechmeister-Boltenstern,S., Kitzler,B., Schaufler,G., Siemens,J., Kindler,R., Flechard,C. and Sutton,M.A. 2009. Biosphere-atmosphere exchange of reactive nitrogen and greenhouse gases at the NitroEurope core flux measurement sites: Measurement strategy and first data sets. Agriculture, Ecosystems and Environment, 133, 139-149.

Smith, K.A., McTaggart, I.P., Dobbie, K.E. and Conen, F. 1998b. Emissions of N_2O from Scottish agricultural soils, as a function of fertilizer N. *Nutrient Cycling in Agroecosystems* 52: 123–130.

Smith, K.A., Thomson, P.E., Clayton, H., McTaggart, I.P. and Conen, H. 1998a. Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils. Atmospheric Environment, 32, 3301-3309.

Soil Survey of Scotland Staff. (1981). Soil maps of Scotland at a scale of 1:250 000. Macaulay Institute for Soil Research, Aberdeen

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M, Averyt, K. B., Tignor, M., and Miller, H. L. IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth AssessmentReport of the Intergovernmental Panel on Climate Change . 2007. Cambridge, Cambridge University Press.

Sutton,M.A., Howard,C.M., Erisman,J.W., Billen,G., Bleeker,A., Grennfelt,P., Grinsven,H.V. & Grizzetti,B. 2011. *The European nitrogen assessment;Sources, effects and policy perspectives*. Cambridge University Press.

Sutton,M.A., Nemitz,E., Erisman,J.W., Beier,C., Bahl,K.B., Cellier,P., de Vries,W., Cotrufo,F., Skiba,U., Di Marco,C., Jones,S., Laville,P., Soussana,J.F., Loubet,B., Twigg,M., Famulari,D., Whitehead,J., Gallagher,M.W., Neftel,A., Flechard,C.R., Herrmann,B., Calanca,P.L., Schjoerring,J.K., Daemmgen,U., Horvath,L., Tang,Y.S., Emmett,B.A., Tietema,A., Penuelas,J., Kesik,M., Brueggemann,N., Pilegaard,K., Vesala,T., Campbell,C.L., Olesen,J.E., Dragosits,U., Theobald,M.R., Levy,P., Mobbs,D.C., Milne,R., Viovy,N., Vuichard,N., Smith,J.U., Smith,P., Bergamaschi,P., Fowler,D. and Reis,S. 2007. Challenges in quantifying biosphere-atmosphere exchange of nitrogen species. Environmental Pollution, 150, 125-139.

Van Cleemput, O. and Baert, L. Nitrite: a key compound in N loss processesunder acid conditions? Plant and Soil 76, 233-241. 1984.

Webb, J., Harrison, R., Ellis, S., 2000. Nitrogen fluxes in three arable soils in the UK. European Journal of Agronomy 13, 207-223.

Wrage,N., Velthof,G.L., van Beusichem,M.L. and Oenema,O. 2001. Role of nitrifier denitrification in the production of nitrous oxide. Soil Biology and Biochemistry, 33, 1723-1732.

Yanai, Y., Toyota, K., Okazaki, M., 2007. Effects of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. Soil Science and Plant Nutrition 53, 181-188.

Appendix 1
Farmer survey

Land drainage Survey

Land drainage plays a critical role in supporting the productivity of many Scottish farms. Much of the current drainage network was installed during the 1970s and 80s when generous subsidies were available. There is anecdotal evidence to suggest that since that time, the performance of drainage systems has deteriorated. SAC is now assessing evidence for the current status of drainage in Scottish farmlands and would warmly welcome your participation in this survey. Any data collected during this survey will be reported anonymously. Please circle the most accurate answer or answers.

Name ______________________ Farm __________________________

Area ______________ Hectares/acres*

Location and postcode ______________________________________

Primary enterprise	Arable	Beef	Sheep	Dairy	Other (specify)
Proportion of farm that is drained?	<20%	20-40%	40-80%	80-100%	Don't know
How old is the current drainage system?	>100 y	50-100y	20-50y	<20y	Don't know
What is the current status of the drainage system?	Excellent	Good	Moderate	Poor	Don't know
How often is your drainage system maintained/repaired?	Every year	Every 2 years	2-5years	5-10 years	More than 10 years
What type of wetness does your drainage system address?	Surface wetness	Ground water	Spring water		
Have you installed new drainage within the last 5 years?	Yes / No				
Are you considering installing drainage in the next 5 years?	Yes / No				
What do you consider to be the main benefits of improved drainage?	Increased production	Improved accessibility	Animal welfare	Greenhouse gas mitigation	Other (specify)
What would be the main constraints in installing new drainage?	Cost	Availability of contractors	Lack of any perceived benefit	Lack of reliable advice	Other (specify)
Have you left any areas of fields undrained to provide conservation benefits?	Yes / No				

Any other comments

Contractor survey

Land drainage Survey

Land drainage plays a critical role in supporting the productivity of many Scottish farms. Much of the current drainage network was installed during the 1970s and 80s when generous subsidies were available. There is anecdotal evidence to suggest that since that time, the performance of drainage systems has deteriorated. SAC is now assessing evidence for the current status of drainage in Scottish farmlands and would warmly welcome your participation in this survey. Any data collected during this survey will be reported anonymously. Please circle the most accurate answer or answers.

Name ______________________________ Business ____________________________________

Location and postcode ____

Primary farm work	Arable	Beef	Sheep	Dairy	Other (specify)
Amount of new land drainage undertaken in the past 5 y (ha)	<100	100-500	500-5000	>5000	Other (specify)
Amount of land drainage work anticipated in the next year (ha)	<100	100-500	500-5000	>5000	Other (specify)
In your experience, what is the current status of most Scottish land drainage systems?	Excellent	Good	Moderate	Poor	Don’t know
Has income from installing new drainage systems increased within the last 5 years?	Increased/ constant/ decreased				
Do you expect income from new drainage work to increase in the next 5 years?	Increased/ constant/ decreased				
What do you consider to be the main benefits of improved drainage?	Increased production	Improved accessibility	Animal welfare	Greenhouse gas mitigation	Other (specify)
What would be the main constraints in installing new drainage?	Cost	Availability of contractors	Lack of any perceived benefit	Lack of reliable advice	Other (specify)

Any other comments (continue overleaf)