Mapping of cultivated organic soils for targeting greenhouse gas mitigation

Hanna Kekkonen, Hannu Ojanen, Markus Haakanen, Arto Latukka and Kristiina Regina

ABSTRACT
Cultivated organic soils can be a major source of GHG emissions in countries with high coverage of peat soils. Targeting mitigation measures based on mapping of cultivated organic soils would reduce these emissions and increase sustainability of agriculture. Different georeferenced datasets were combined to study the area trend and describe current agricultural use of organic soils. The area was also mapped regionally into classes based on intensity of cultivation and organic layer depth, and an example allocation of potential mitigation measures was made at the country scale. The area and proportion of cultivated organic soils have increased in Finland since 1990 but the clearance rate has decreased in recent years. More than half of the area retains a peat layer deeper than 0.6 m indicating long-lasting mitigation potential with measures capable of slowing peat decomposition. Sixty-five percent of the cultivated organic soil area was not considered a priority area for radical management changes, for various reasons, but there are 85,000 ha of field with more realistic potential for GHG mitigation. The mapping method was found to be a practical tool for depicting the GHG mitigation potential of cultivated organic soils. Significant reductions in agricultural GHG emissions can be expected with implementation of the suggested mitigation measures.

KEYWORDS
Peat; greenhouse gas; agriculture; mitigation; climate change

Introduction
Peatlands cover about 3% of land area, store 30% of soil carbon and produce 6% of carbon dioxide (CO₂) emissions globally [1]. Waterlogging accumulates carbon and nitrogen in peat but when peatlands are drained and cultivated, the soil conditions change radically. Water level drawdown initiates microbial decomposition of the peat which is further enhanced by tillage, fertilization and liming. Compared to natural peatlands, drainage results in diminished methane (CH₄) emissions but also in increase of CO₂ and nitrous oxide (N₂O) emissions for which the losses can amount to tonnes of carbon and kilograms of nitrogen per hectare annually [2].

Cultivated organic soils are a significant source of greenhouse gas (GHG) emissions in countries with high proportion of peat soils. They are a major source of GHG emissions in the two reporting sectors Land Use and Land Use Change (LULUCF) and Agriculture in Finland [3]. Approximately 10% of croplands in Finland are classified as organic (≥ 12% carbon) but they produce 50–60% of total agricultural emissions interpreted as the sum of the Agriculture and Cropland and Grassland categories in LULUCF. As a high emission source they also provide a large mitigation potential in a relatively small area, which is worth exploring in detail. Compared to other options available for agriculture, mitigation measures targeted to cultivated organic soils are often found to be the most efficient but the full mitigation potential is not utilized [4]. In the rural development program there have already been environmental payments aiming at reducing the environmental impact of cultivated organic soils, but only a few thousand field hectares have been involved in the available measures under the program [5].

Targeting mitigation measures taking regional aspects into account would probably yield the best results nationwide, and actions based on peat quality and hydrology, for example, have been suggested [6]. Also, the regional significance of organic soils in farming affects the possibilities to change land use or management practices. The
higher the proportion of organic soils, the more difficult it is to avoid cultivating them. In Finland there are municipalities with > 60% of fields located on organic soils (www.luke.fi/economydoctor) and even farms with all of their fields on organic soils. However, the more southerly the location, the better the chances to remove these fields from production and gain benefits in GHG mitigation.

Peat depth partly determines the efficiency of mitigation, and especially methods involving raised groundwater level are efficient only when a deep layer of peat is rewetted [7]. The scarce resources available for mitigation activities are best used if targeted to fields with large quantities of organic matter still remaining. All fields are currently not in effective use but some extensive area exists for different reasons and this is the area most easily removed from agricultural use, at least from the viewpoint of maintaining food production. Identifying the extensively cultivated fields on deep organic soils is thus the natural first step in designing cost-effective regional mitigation measures [8].

For the fields potentially removable from cultivation, afforestation is a viable option from a life-cycle analysis viewpoint [9] but the emissions of N2O at least will continue at a rate similar to those of cultivated soils [10]. Afforestation involves drainage as well, and as long as there is peat above the groundwater level it will be prone to decomposition. The most efficient mitigation measure in these cases would thus be rewetting. It runs the risk of high CH4 emissions [11] and high nutrient losses to watercourses [12], but in some cases has been found to turn agricultural sites carbon neutral or to carbon sinks [13,14]. With the right crop selection, it may even be possible to continue cultivation in rewetted conditions (i.e. paludiculture) [15]. Suitable plant species for paludiculture in northern Europe could be plants which thrive in swamps such as sundews, berries or downy birch. Of course, the markets for paludiculture products are limited and developing the markets may require specific attention to, for example, launching a ‘low-carbon brand’ for such products. Also, raising the groundwater table for rewetting or paludiculture is only possible in sites with abundant water reserves and when the neighboring fields will no suffer from the management change.

A field that has been cultivated for decades may have lost most of the organic layer and it is hard to avoid losing the last remains of the peat. In this case it is probably wiser not to pay for mitigation but to recommend adapted cultivation practices to slow down the loss of organic matter and to retain the fertility of the soil. There is evidence that changing from annual to perennial cultivation can reduce the emissions significantly [16] although it is not clear from all datasets [10,17,18]. In the conditions of northern Europe, with a short growing season, other means of extending the vegetated period may be beneficial too but there is no research on the effects of, for example, cover crops or winter crops on organic soils. Reducing tillage may be an option to slow down peat mineralization but the evidence on its effects is scanty and varying [19,20].

It is not realistic to suggest a total ban on cultivating organic soils in a peat-rich country like Finland. However, considering the anticipated high emission reductions, their mitigation potential is worth exploring. Tailored mitigation measures would likely produce better results than the current ones. For this purpose, an approach is suggested based on readily available data that can be used to map different classes of cultivated organic soils. The aims of this study were to depict the area trend and current regional occurrence of cultivated peat soils in Finland, to test a method of mapping them according to cultivation intensity and field properties, and to estimate the mitigation potential of targeted measures. The possibilities of targeting GHG mitigation options based on the mapping approach are discussed.

**Material and methods**

**Datasets**

Detection of cropland area and conversions to cropland was based on national forest inventory (NFI) and datasets related to NFI such as thematic maps and stand attribute data (Table 1). In NFI, a ‘stand’ refers to both growing stock and land-use classification (e.g. agriculture or water bodies) [21]. To classify cultivated peat soil area on the basis of peat depth, two different datasets were used: a land parcel identifying system and the database on superficial deposits of Finland. For detecting peat covered areas and depth of peat layers for the database, the Geological Survey of Finland has used their own geophysical data and measurements in geological mapping, as well as data from the National Land Survey of Finland, Eurofins Viljavuuspalvelu, the National Forest Inventory and the Finnish Environment Institute [22,23]. The mapping scale of superficial deposits varies from 1:50,000 to 1:200,000 and the final database is at a
scale of 1:200,000. The geophysical data includes aerogeophysical low-altitude survey data: magnetic total field, electromagnetic and radiometric gamma-ray measurements. Estimates of peat depth are partly based on soil profile sampling and partly on the potassium content of the soil. Low potassium content indicates deep peat [22]. Airborne geophysical measurements have been made every 12.5/25 m at 34 m height with 200 m between flight lines, resulting in a database with 50-m pixel size. Combining all this geological data has resulted a database of sediment polygons with a minimum polygon size of 6 ha.

### Time series of the area of cultivated peat soils

The area of cropland was derived from the NFI [3]. Cropland comprises arable crops, rotational grass, set-aside, permanent horticultural crops, greenhouses and kitchen gardens. The land-use classification is the same as in the national inventory reporting of greenhouse gases under the UNFCCC and the Kyoto Protocol, where NFI land-use classes were reclassified into appropriate categories following the IPCC guidance [37]. Areas for each land-use category were calculated by multiplying the number of the NFI sample plot centers belonging to a particular land-use category with the area representative of a sampling density region [21]. The reasons for not using the land parcel identification system (LPIS) of the EU [38] for determining the total area of cultivated peat soils are that all fields are not in the register and that a unified method ensures consistent classification of the land area of different classes. However, the detailed analysis on crop species was constrained to the areas found in the LPIS (see below).

The information on land-use conversions between categories were obtained from NFI data. A subset of NFI data, selected by attributes such as stand age, was further analyzed to check the observations on previous land use or whether there are undetected changes. These data were complemented with other spatial datasets: remote sensing data (satellite images, aerial photographs), thematic maps of multi-source NFI, digital map data, and LPIS data on agricultural parcels. These datasets were utilized also in updating NFI land-use information which is derived from a 5-year inventory cycle. The results of image interpretation on land-use changes were updated to the NFI data for area estimation. In time-series over 1990–2016, a 5-year moving average method was applied for the area estimates of land-use changes to decrease the effect of sampling error related to rare occasions such as transitions between land-use categories [3].

When soil type was not available from the NFI, organic soils were identified using the Finnish georeferenced soil database. In the soil database, soil with an organic layer of \( \geq 30 \) cm is classified Histosol. Histosols and the most carbon-rich Gleysols (Umbric Gleysols) organic soils were considered organic soils.

### Mapping of fields based on peat depth and cultivation intensity

A geographical information system was used for analyzing spatial data at the level of the Centres for Economic Development, Transport and the Environment (ELY Centres) that divide Finland into 16 regions. One of the ELY Centres, Ahvenanmaa, located in the southwestern archipelago, was excluded from the study as there are no cultivated peat soils in this region. ArcGIS software was used for the mapping (ESRI ArcGIS ArcMap v. 10.3.1.).

Cultivated peat soil area was classified using LPIS and the dataset on superficial deposits. Peat-covered areas with deep peat (\( \geq 0.6 \) m of peat) were selected from the dataset on superficial deposits and made a new layer including only deep peat-layered areas. In the LPIS, every field parcel is one polygon and clipping this layer by the layer of deep peat resulted a layer of field parcel polygons including areas of deep peat. The same procedure was repeated to detect shallow-layered peat soils.
Based on the crop species registered in the LPIS in 2016, the area was divided into three classes: annual, perennial and extensive. Extensive use included areas such as temporarily uncultivated fields, biodiversity objects, managed uncultivated fields or perennial set-asides. As one reference parcel can include many agricultural parcels and therefore crop classes, as well as different soil types, the area of each field parcel can be divided into several classes. There were about 14,500 ha of fields for which there was no crop code because the owner had not applied for subsidies. This area was excluded from the analysis because it is not known how much of this area is in intensive use but not eligible for subsidies (e.g. fields cleared after 2004 are not) and how much is marginal area not in food production.

After summing the areas for ELY Centers, the final calculation includes the areas of deep peat-covered parts of field parcels for the three crop classes, annual, perennial and extensive. For final use, the classes annual and perennial were combined as ‘intensive’. In Finland, perennial grasses are mostly grown for 3–4 years as part of crop rotations and can be considered more intensive than extensive cultivation.

Selection of land use and management strategies

The above classification of fields was the basis for suggesting the best alternative management option for each field class in Finnish conditions (Figure 1). Extensive fields were considered available for mitigation actions regardless of the peat depth. Rewetting could be an option for deep organic soils when not restricted by scarcity of water or disturbance of neighboring fields. Estimating the hydrology was not part of this analysis, but should be investigated locally before starting rewetting. If a field is in intensive use it likely has more importance for food production than an extensive field and thus current intensive use indicates a higher mitigation cost. If the intensively managed field still has a deep organic layer, and mineral soils are available in the neighborhood, it may be worth looking for options to shift cultivation to mineral soils and rewet the organic soils. However, if the farm is located in a region with low availability of mineral soils, continuing cultivation with adapted practices may be the most realistic option also for deep peat soils. Afforestation may be the most suitable option for extensive fields on shallow organic soils as peat decomposition cannot be avoided in afforestation. If the intensively cultivated soil has already lost most of the organic layer and is currently shallow peat, it may be best to let cultivation continue but promote adapted practices such as continuous vegetation cover or reduced tillage.

Mineral soils were considered available in the region if less than 15% of the field area was on organic soil. As this is an arbitrary selection a cluster analysis was conducted to test whether it supported the authors’ intuitive idea of dividing Finland into two regions based on the availability of mineral soils for replacement. ELY Centres were grouped using the cluster procedure with average linkage method in the SAS Enterprise Guide software (v. 7.1). Variables in the analysis were percentage of organic soils of the total cultivated area, number of farms and average farm size in the region.

Estimation of the GHG mitigation potential

A rough estimate of the resulting reduction in GHG emissions in agriculture and land use was made based on the IPCC emission factors (Table 2). The difference in emission factors between cropland and grassland was used as the hectare-based estimate in

![Figure 1. Scheme of the classification of cultivated organic soils. Intensive cultivation includes food and feed production. Extensive cultivation includes temporarily uncultivated fields, biodiversity objects, managed uncultivated field and perennial set-asides. The depth dividing shallow and deep peat is 60 cm.](image-url)
cases when adjusted management was suggested. There are no emission factors available for other means of extending the growing period or reducing tillage in peat soils. For rewetting, the estimate of emission reduction per hectare was based on the difference of cropland and rewetted area or grassland and rewetted area, depending on the original status of the field. Intensively cultivated area was considered cropland and extensively cultivated grassland. The effect of afforestation was based on the difference in soil emissions of grassland and forest. Emissions from ditches and dissolved carbon were excluded as they do not vary much among the land-use types. Emissions of methane and nitrous oxide were converted to CO₂ equivalents using factors of 25 and 298, respectively.

**Results**

The total area of croplands has been quite stable since 1990 but the share of organic soils has increased (Table 3). The area of organic soils increased by 42,900 ha in 1990–2016. Clearance of new field area was most pronounced in 2000–2007 and has slowed down after that (Figure 2). Most new area taken for cultivation originates from forest areas, and minor areas were cleared from grasslands, abandoned peat extraction sites or other wetlands. In the most recent years, no pristine peatlands have been cleared for agriculture; the new area has been taken only from already drained sites such as forests and former peat extraction sites.

Half of the existing field area of organic soils is found in the area of three ELY Centres on the west coast, where also the number of farms is relatively high (11–13 in Table 4). Organic soils were most commonly cultivated in Pohjois-Pohjanmaa ELY Centre, where 64,000 field hectares were organic. The three northernmost ELY Centres had the largest share of croplands on organic soils (13–15 in Table 4). In these regions, the share of organic soils was from a quarter to a third of the total cultivated area, while in the southernmost ELY Centres the share was 2%.

At the country scale the majority (60%) of cultivated peat soils (166,000 ha) were those with more than 0.6 m of peat (Figure 3). The largest areas of deep organic soils were found in the ELY Centres Etelä-Pohjanmaa and Pohjois-Pohjanmaa (Figure 4). However, they are found in all parts of the country except the islands of Ahvenanmaa in the southwest.

The share of perennial cultivation increases toward the north of Finland (Table 5). There are no large differences in the share of extensive area between the regions. On average, about 13% of the total area of cultivated organic soils is in extensive use. Extensively used fields were slightly more common on deep- than shallow-layered organic

---

**Table 2.** Emission factors (t CO₂ eq. ha⁻¹) for estimating mitigation effects.

| Land use     | CO₂  | N₂O  | CH₄  |
|--------------|------|------|------|
| Cropland     | 28.97| 6.09 | 0    |
| Grassland    | 20.90| 4.45 | 0    |
| Forest land  | 3.41 | 1.50 | 0.05 |
| Rewetted     | −2.02| 0    | 3.43 |

Source: [39]

**Table 3.** Regional distribution of field area, cultivated organic soils and farm number and size.

| Region          | Total cultivated (ha) | Total organic (ha) | Share of organic (%) | Number of farms | Average size of farm (ha) |
|-----------------|-----------------------|--------------------|----------------------|----------------|--------------------------|
| 1 Uusimaa       | 191,506               | 3909               | 2                    | 3234           | 56                       |
| 2 Varsinais-Suomi | 303,289              | 5127               | 2                    | 5335           | 55                       |
| 3 Satakunta     | 147,700               | 12,184             | 8                    | 3042           | 46                       |
| 4 Hame          | 195,667               | 9660               | 5                    | 3570           | 52                       |
| 5 Pirkanmaa     | 172,926               | 10,744             | 6                    | 3855           | 43                       |
| 6 Kaakkoi-Suomi | 146,429               | 10,275             | 7                    | 3037           | 45                       |
| 7 Etelä-Savo    | 88,721                | 6292               | 7                    | 2401           | 30                       |
| 8 Pohjois-Savo  | 163,061               | 16,249             | 10                   | 3555           | 42                       |
| 9 Pohjois-Karjala | 97,653              | 11,593             | 12                   | 2043           | 42                       |
| 10 Keski-Suomi  | 107,298               | 8862               | 8                    | 2599           | 36                       |
| 11 Etelä-Pohjanmaa | 256,498           | 42,642             | 17                   | 5564           | 45                       |
| 12 Pohjanmaa    | 203,802               | 26,723             | 13                   | 4671           | 42                       |
| 13 Pohjois-Pohjanmaa | 245,911          | 64,025             | 26                   | 4359           | 54                       |
| 14 Kainuu       | 40,354                | 10,403             | 26                   | 666            | 39                       |
| 15 Lappi        | 56,147                | 17,547             | 31                   | 1366           | 33                       |
soils; 15% of the deep-layered soils were extensive (data not shown). In total, more than 23,000 hectares of deep-layered cultivated organic soils was in extensive use (Table 6). Most of this area was located in the ELY Centres Etelä-Pohjanmaa and Pohjois-Pohjanmaa (total approximately 8400 ha) but there its share of the total cultivated organic soils was relatively low.

In order to be able to consider also availability of mineral soils (see Figure 1) and to provide a simplified example of how the information from the mapping exercise can be used, Finland was divided into two regions: the southern part (ELY Centres 1–10) with relatively low density of organic soils, and the northern part (ELY Centres 11–15) having more than 15% of the field area on organic soils. This approach was supported by the cluster analysis as the combination of the two first clusters was close to the ‘northern’ region and the third cluster was very close to the selected ‘southern’ region (Figure 5). The cluster analysis allocated the two northernmost ELY Centres (low number of farms and high proportion of organic soils) as one cluster. The second cluster was formed of ELY Centres 2, 11, 12 and 13. These are regions with a high number of relatively large farms, on the west coast. The third cluster was formed of the regions of central and southern Finland with less significance in terms of agriculture or organic soils. This clustering explained 85% of the variation.

The most suitable mitigation options were allocated to the field groups described above. In northern Finland there is 13,000 ha of area suitable in principle for removal from production through rewetting, for example (i.e. extensive area on deep organic soils; Table 7). In addition, there is 5600 ha of extensive area on shallow organic soils for which the most suitable land use would be afforestation. The rest of the area is in intensive cultivation, and it is estimated that about 78,000 ha of this area is on deep organic soils and 56,000 ha on shallow organic soils. As the intensive area in these regions is most likely the property of active farms, and few mineral soil fields are available, only adapted cultivation methods are proposed to slow peat decomposition on this area.

In the southern regions, the area of extensive cultivation on deep organic soils was 10,000 ha and that on shallow organic soils 3000 ha, suggesting that in total 13,000 ha of cultivated peat soils is not in productive use in regions where its significance for production is relatively low and thus its GHG mitigation potential is high. There were 53,000 ha of field area in intensive cultivation on deep organic soils and this is also area for which alternatives should be sought. Part of the production in this area could possibly be gradually shifted to mineral soils, which would release peat area for rewetting or paludiculture. Maintaining the 23,000 ha of intensive cultivation on shallow organic soils would be acceptable in these regions if mitigation actions proceeded on the more potent fields.

If all suggested mitigation measures were implemented in the area estimated here, the resulting reduction in annual GHG emissions would be 4.6 Mt CO₂ eq. (Table 7). Almost half of this would result from rewetting intensively cultivated organic soils. Reducing soil emissions through afforestation would have a minor impact but converting intensively cultivated fields to perennial cultivation or rewetting extensive deep peat soils would cause a reasonably high reduction.

### Table 4. Regional distribution of field area, cultivated organic soils, and farm number and size.

| ELY Centre | Total cultivated (ha) | Total organic (ha) | Share of organic (%) | Number of farms | Average size of farm (ha) |
|------------|-----------------------|-------------------|----------------------|----------------|--------------------------|
| Uusimaa    | 191,506               | 3,909             | 2                    | 3234           | 56                       |
| Varsinais-Suomi | 303,289             | 5127              | 2                    | 5335           | 55                       |
| Satakunta  | 147,700               | 12,184            | 8                    | 3042           | 46                       |
| Häme       | 195,667               | 9660              | 5                    | 3570           | 52                       |
| Pirkanmaa  | 175,926               | 10,744            | 6                    | 3855           | 43                       |
| Kaakkiois-Suomi | 146,429             | 10,275            | 7                    | 3037           | 45                       |
| Etela-Savo | 88,721                | 6292              | 7                    | 2401           | 30                       |
| Pohjois-Savo | 163,061             | 16,249            | 10                   | 3555           | 42                       |
| Pohjois-Karjala | 97,653              | 11,593            | 12                   | 2043           | 42                       |
| Keski-Suomi | 107,398              | 8862              | 8                    | 2509           | 36                       |
| Etela-Pohjanmaa | 256,498           | 42,642            | 17                   | 5564           | 45                       |
| Pohjanmaa  | 203,802               | 26,723            | 13                   | 4671           | 42                       |
| Pohjois-Pohjanmaa | 245,911           | 64,025            | 26                   | 4359           | 54                       |
| Kainuu     | 40,354                | 10,403            | 26                   | 666            | 39                       |
| Lappl      | 56,147                | 17,547            | 31                   | 1366           | 33                       |

Figure 3. Share (%) of deep (black) and shallow (grey) cultivated organic soils by ELY Centre.
Figure 4. Hectares of deep-layered cultivated organic soils (peat layer ≥ 60 cm) by ELY Centre.
Discussion

The fact that the total cultivated area has remained constant since 1990 while the proportion of organic soils has increased indicates that the increase in the share of organic soils has mainly resulted from reallocation of production from mineral soils to organic soils. The number of farms has decreased by 46% but farm size increased by 95% in 1995–2016 [40], while there have not been radical changes in the total production volume [41].

The observed expansion in the area of cultivated organic soils can be explained by farm enlargement in the peat-rich areas while many farms have ceased production in the southern and central parts of the country. Animal production and farm enlargement are more common in the eastern and northern parts of the country where the occurrence of peat soils is also high. An enlarging animal farm needs new area for both feed production and manure spreading as the environmental permit defines the required field area based on quantity of nutrients in the manure. Since 2000, in 60% of cases the main reason to clear land for agricultural use has been the need for area for cattle fodder or manure spreading [42].

As the total cropland area has been stable, one can ask why new area was cleared instead of using the existing field area. The available fields may be too remote from the farm buildings, and as the prices are relatively high in intensive agricultural areas in many cases it is easier and cheaper to clear a new field than to buy or rent one. Sometimes the cleared forest has not been productive and the farm economy improves with converting it to agricultural use. As manure spreading is one driver for field clearance, an option would be to make arrangements with arable farms for manure transport, but this is still quite rare. The payments under CAP (the Common Agricultural Policy of the European Union) are not a direct driver as the cleared fields have not been eligible for payments after 2004. However, they are an

Table 5. Cultivated organic soils (ha) divided into intensive and extensive cultivation on shallow or deep peat.

| ELY Centre | Intensive Shallow | Intensive Deep | Extensive Shallow | Extensive Deep |
|------------|------------------|----------------|-------------------|----------------|
| 1 Uusimaa | 1038             | 2134           | 229               | 478            |
| 2 Varsinais-Suomi | 1943           | 2472           | 183               | 436            |
| 3 Satakunta | 4678             | 5224           | 522               | 1146           |
| 4 Häme | 1810             | 5725           | 242               | 1517           |
| 5 Pirkanmaa | 2638             | 5707           | 372               | 1353           |
| 6 Kaakkios-Suomi | 1478             | 6372           | 279               | 1494           |
| 7 Etela-Savo | 1277             | 3467           | 160               | 684            |
| 8 Pohjois-Savo | 3366             | 10,451         | 361               | 1248           |
| 9 Pohjois-Karjala | 2806             | 6386           | 320               | 936            |
| 10 Keski-Suomi | 1573             | 4984           | 271               | 1200           |
| 11 Etela-Pohjanmaa | 18,605          | 16,897         | 2189              | 3137           |
| 12 Pohjanmaa | 11,057           | 13,141         | 847               | 1298           |
| 13 Pohjois-Pohjanmaa | 22,678          | 34,053         | 1884              | 5296           |
| 14 Kainuu | 998              | 4113           | 114               | 953            |
| 15 Lappi | 2912             | 9901           | 558               | 2106           |

Figure 5. Results of the cluster analysis. The numbers represent regions as defined in Table 2.

Table 6. Cultivated organic soils divided into intensive and extensive cultivation on shallow or deep peat.

| ELY Centre | Intensive Shallow | Intensive Deep | Extensive Shallow | Extensive Deep |
|------------|------------------|----------------|-------------------|----------------|
| 1 Uusimaa | 1038             | 2134           | 229               | 478            |
| 2 Varsinais-Suomi | 1943           | 2472           | 183               | 436            |
| 3 Satakunta | 4678             | 5224           | 522               | 1146           |
| 4 Häme | 1810             | 5725           | 242               | 1517           |
| 5 Pirkanmaa | 2638             | 5707           | 372               | 1353           |
| 6 Kaakkios-Suomi | 1478             | 6372           | 279               | 1494           |
| 7 Etela-Savo | 1277             | 3467           | 160               | 684            |
| 8 Pohjois-Savo | 3366             | 10,451         | 361               | 1248           |
| 9 Pohjois-Karjala | 2806             | 6386           | 320               | 936            |
| 10 Keski-Suomi | 1573             | 4984           | 271               | 1200           |
| 11 Etela-Pohjanmaa | 18,605          | 16,897         | 2189              | 3137           |
| 12 Pohjanmaa | 11,057           | 13,141         | 847               | 1298           |
| 13 Pohjois-Pohjanmaa | 22,678          | 34,053         | 1884              | 5296           |
| 14 Kainuu | 998              | 4113           | 114               | 953            |
| 15 Lappi | 2912             | 9901           | 558               | 2106           |

Table 7. Example of mitigation measure allocation based on mapping of cultivated organic soils and estimate of the resulting reduction in annual GHG emissions.

| Cultivation | Peat depth | South | North | Total | Suggested management change | Estimated reduction in GHG emissions (Mt CO2 eq.) |
|-------------|------------|-------|-------|-------|-----------------------------|-----------------------------------------------|
| Intensive   | Shallow    | 22606 | 56,250 | 78,856 | Adapted cultivation practices | 0.77                                           |
|             | Deep       | 52,921| 78,106 | 131,027| North: adapted cultivation practices; south: shifting cultivation to mineral soils and rewetting organic soils | 3.14                                           |
| Extensive   | Shallow    | 2940  | 5591  | 8530  | Afforestation               | 0.17                                           |
|             | Deep       | 10,492| 12,791 | 23,283 | Rewetting or paludiculture  | 0.56                                           |
| Total       |            | 88960 | 152,737| 241,697|                             | 4.64                                           |
indirect driver that raises the value of agricultural land and drives the farms to enlarge in the less favorable regions with higher total payments.

The increase in the area of cultivated organic soils is shown in the GHG inventory as increased emissions of CO₂ and N₂O equal to one million tonnes CO₂ equivalent in 1990–2015, which is about 1.5% of the total emissions of Finland [3]. As the total cropland area or food production did not grow during the same period, the justification for this trend can be questioned. A positive aspect is that no pristine peatlands were drained for croplands recently. Since 2009 all new area has come from drained forest soils or former peat extraction sites where the peat is subject to decomposition as well. Thus, this is partly a question of reallocation of emissions from other land-use classes such as forest land or wetlands.

Depending on the viewpoint, cultivated peat soils can be seen either as a major source of GHG emissions in agriculture or as a ‘low-hanging fruit’ enabling efficient GHG emission mitigation. The currently continuing increase in the area of organic soils hampers any GHG mitigation actions on cultivated organic soils. Due to the high significance of organic soils in the northern regions, a total ban of organic soil cultivation is not a realistic option at the country level as it would put farmers in extremely unequal situations in different regions of the country. However, a ban on new clearance or a requirement for a clearance permit would likely not be a major problem as the rate of land conversion to agriculture is already decreasing.

In total, 157,000 ha (65%) of cultivated peat soils were classified as those where only adapted cultivation practices are feasible (Table 5). That leaves 85,000 ha of fields with considerable potential to mitigate GHG emissions. The intensity of cultivation is much higher in Finland compared to its neighbor Sweden, where two thirds of cultivated organic soils were extensively cultivated [43]. The fact that 13% of cultivated peat soil area is in extensive use in Finland suggests that at least this proportion could be relatively easily available for mitigation actions without endangering food production. While extensive use can be found beneficial for improving the cultivation properties of mineral soils, for example, this can be questioned in the case of peat soils. In some studies GHG emissions from abandoned fields on organic soils have been found to be relatively high compared to those from cultivated fields [10,44], indicating that carbon losses from peat decomposition can exceed the inputs from vegetation even in extensive use, and the result is a net loss of organic matter with no productive use of the area. Forty percent (10,000 ha) of extensively cultivated deep peat soils is located in the 10 southernmost ELY Centres. In these regions, many farmers would have the option to continue cultivation on mineral soils instead as the proportion of organic soils is less than 10% of the total field area. However, in the current agricultural policy scheme there are no incentives to reduce cultivated area. Taking this area out of cultivation would require totally new types of incentives.

Most fields on organic soils seem to have a relatively deep organic layer remaining, which may be an indication of their young age and originally deep peat layer. Directing mitigation measures such as rewetting or paludiculture to these fields would affect a large volume of peat and would yield long-lasting mitigation effects [15]. Extensive fields were more common on deep-layered peat soils than on shallow-layered soils, which may indicate that the cultivation properties of the likely less-humified deep peats are poorer, and this fact also encourages the finding of alternatives for their management.

Most of the suggested alternative management options would reduce but not cease peat decomposition or GHG emissions. Rewetting is likely the most effective way to cut emissions of CO₂ but there is a risk of increased CH₄ emissions [7] or high nutrient losses in runoff and leaching [12]. However, two recent examples show that rewetted croplands can be emission neutral or even sinks of carbon [13,14]. High CH₄ emissions could be likely avoided in paludiculture when maintaining the groundwater level at 20 cm at maximum, but in practice regulating the groundwater level is difficult and occasional CH₄ emissions cannot be avoided [45]. As crop residues can be the major source of CH₄, selecting crop species with modest amounts of residues for paludicultural production could reduce the risk of high CH₄ emissions [46,47]. Afforestation has a much better GHG balance than cultivation [10] but the organic layer is likely well aerated also in an afforested field, resulting in continuation of peat decomposition. Modest mitigation rates can be expected also from adapted management, such as simply maintaining the fields covered by perennial cropping or cover crops [48], or reducing the tillage intensity [19].

The practices suggested here as the most appropriate for each field class are of course not the only option or even possible everywhere.
For example, rewetting can only be done if the hydrology of the surroundings allows for it and if the neighboring fields are not affected. However, this supports the idea that regional planning with the cooperation of farmers would be beneficial to find the most suitable options for each region.

It is clear that the limited accuracy of the materials used causes high uncertainties in the results. However, Finland’s soil mapping is relatively well developed and will improve further in the future. These were the first results estimating the mitigation potential at this level of precision, but it is foreseen that the targeting of mitigation measures can be eventually made using even better methods such as combining information on topography with the decision-making to aid in finding sites suitable for rewetting. The analysis was based on only 1 year of data on crop species and thus the interpretation of extensiveness is not necessarily valid at the field scale or across years. However, it illustrates the situation in 2016 and can motivate a more thorough analysis of the land use on cultivated organic soils. Sustainable intensification has the potential to release agricultural area for other land uses and this work should involve consideration of soil types [49]. Ways to promote sustainable intensification in agriculture demand understanding the reasons for yield gaps and farmers’ decisions, for example; also, work to guide optimal land use by taking soil type as a criterion in land-use planning is ongoing in Finland [50].

The criterion for allocating the management options after the first classification (intensity/depth) was simply a subjective decision based on the proportion of organic soils in the regions. In the present approach, a different criterion would mainly reallocate intensively cultivated deep peat soils among the regions as the mitigation measures suggested for the other classes did not depend on availability of mineral soils. Different criteria for regionalization may be applicable in other countries and the process could be more detailed (e.g. if applied within one ELY Centre or municipality). Of course, the options for mitigation measures may also differ between countries.

The estimated reduction in GHG emissions was extremely high, more than half of the reported emissions from cultivated organic soils (1.5 Mt N₂O and 6.3 Mt CO₂ in the latest submission). There are, of course, practical constraints in implementing these mitigation measures, such as the fact that rewetting is feasible only in favorable hydrological conditions. It must be considered also that the reduction in reporting agriculture sector and cropland class is higher than indicated in Table 7, as the calculation was based on differences in emission factors. When the field area changes to a different reporting sector or class, emissions are allocated to the new class and thus, for example, emissions from afforested fields are nullified in agriculture and cropland but added to the emission sum of forest land.

Conclusions

We tested a method of mapping cultivated organic soils based on the cultivation intensity and depth of the peat layer. A proportion of 65% of cultivated organic soils in Finland was not considered priority area for radical management changes, for various reasons, but there remains 85,000 ha of field with more realistic potential for greenhouse gas mitigation. The mapping method was found to be a practical tool for making a rough estimate of areas available for different types of greenhouse gas mitigation measures, and it can be applied anywhere if suitable georeferenced data is available. Significant reductions in agricultural GHG emissions can be expected from a relatively small area if the suggested mitigation measures are implemented.

Acknowledgements

The authors are grateful to Maisa Tapio-Biström from the Ministry of agriculture and forestry for the idea of using peat depth as a criterion for selecting mitigation measures and to an anonymous reviewer who gave excellent ideas for the revision of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was funded by the Finnish Academy (project Novel management practices – key for sustainable bioeconomy and climate change mitigation - SOMPA) and Natural Resources Institute Finland (Luke).

ORCID

Hanna Kekkonen [http://orcid.org/0000-0002-9041-6899]
Hannu Ojanen [https://orcid.org/0000-0003-3758-353X]
Kristiina Regina [http://orcid.org/0000-0001-9080-7956]

References

1. Joosten H, Tapio-Biström M, Tol S. Peatlands: guidance for climate change mitigation by conservation, rehabilitation and sustainable use. 2nd ed. Rome, Italy:
Food and Agriculture Organization of the United Nations (FAO) and Wetlands International; 2012.}

2. Frolking S, Talbot J, Jones MC, et al. Peatlands in the earth’s 21st century climate system. *Environ Rev.* 2011;19:371–396.

3. Statistics Finland. Greenhouse gas emissions in Finland 1990–2015. National Inventory Report Under the UNFCCC and the Kyoto Protocol; 2017.

4. Regina K, Budiman A, Greve MH, et al. GHG mitigation of agricultural peatlands requires coherent policies. *Climate Policy.* 2016;16:522–541.

5. Regina K, Heikkinen J, Hillen Sitominen JA, Talteenotto Maataloudessa. In: Yi-Vilkari A, Aakkula J, editors, *Maaseutuohjelman ympäristöarviointi.* Vol. 54/2017. Helsinki: Natural Resources Institute Finland; 2017. [in Finnish, Abstract in English]

6. Klove B, Berglund K, Berglund O, et al. Future options for cultivated nordic peat soils: can land management and rewetting control greenhouse gas emissions? *Environ Sci Policy.* 2017;69:85–93.

7. Couwenberg J, Thiele A, Tanneberger F, et al. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. *Hydrobiologia.* 2011;674:67–89.

8. Roeder N, Osterburg B. The impact of map and data resolution on the determination of the agricultural utilisation of organic soils in Germany. *Environ Manage.* 2012;49:1150–1162.

9. Sarkkola S. Greenhouse impacts of the use of peat and peatlands in Finland. Report no. 2007–11a, Helsinki: Ministry of Agriculture and Forestry; 2007.

10. Maljanen M, Sigurdsson BD, Guðmundsson J, et al. Greenhouse gas balances of managed peatlands in the Nordic countries: present knowledge and gaps. *Biogeoosciences.* 2010;7:2711–2738.

11. Schafer C, Elsgaard L, Hoffmann CC, et al. Seasonal methane dynamics in three temperate grasslands on peat. *Plant Soil.* 2012;357:339–353.

12. Kieckbusch J, Schrautzer J. Nitrogen and phosphorus dynamics of a re-wetted shallow-flooded peatland. *Sci Total Environ.* 2007;380:3–12.

13. Herbst M, Friborg T, Schelde K, et al. Climate and site management as driving factors for the atmospheric greenhouse gas exchange of a restored wetland. *Biogeoosciences.* 2013;10:39–52.

14. Schriever-Uijl AP, Kroon PS, Hendriks DMD, et al. Agricultural peatlands: towards a greenhouse gas sink—a synthesis of a Dutch landscape study. *Biogeoosciences.* 2014;11:4559–4576.

15. Wichtmann W, Schröder C, Joosten H. (eds), *Paludiculture: productive use of wet peatlands—climate protection - biodiversity - regional economic benefits.* Stuttgart (Germany): Schweizerbart Science Publishers; 2016.

16. Maljanen M, Hytonen J, Makiranta P, et al. Greenhouse gas emissions from cultivated and abandoned organic croplands in Finland. *Boreal Environ Res.* 2007;12:133–140.

17. Norberg L, Berglund Ö, Berglund K. Seasonal CO2 emission under different cropping systems on histosols in Southern Sweden. *Geoderma Region.* 2016;7:338–345.
35. Lilja H, Uusitalo R, Yli-Halla M, et al. Suomen Maannostietokanta. Käyttöopas Versio 1.0. [Finnish Soil Database User’s Guide 1.0.], 6, 2009.

36. Interface services [Internet]. Geological Survey of Finland; [cited 2018 Nov 28]. Available from: http://en.gtk.fi/informationservices/interface_services/

37. Eggleston HS, Buendia L, Miwa K, et al. (eds). IPCC 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme (IGRS, Japan); 2006.

38. European Union (EU). EU Council Reg. 3508/92 (1992); 1992.

39. IPCC 2014, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Switzerland: IPCC; 2014.

40. Jansik C, Karhula T, Knutttila M, et al. Finnish agriculture and food sector 2016/17. Natural Resources and Bioeconomy Studies, 49/2017. Helsinki: Natural Resources Institute Finland; 2017.

41. Luke. Ruoka- Ja Luonnonvaratilastojen E-Vuosikirja 2017: Tilastojen Maataloudesta, Metsäsektorilta Sekä Kala: Ja Riistataloudesta. 2017. [in Finnish]

42. Niskanen O, Lehtonen E. Maatilojen Tilusrakenne Ja Raivaus Suomessa 2000-Luvulla. Esitelma- ja posteritiivistelmät Maataloustieteen päivät 2014, Helsinki; 2014. [in Finnish]

43. Berglund O, Berglund K. Distribution and cultivation intensity of agricultural peat and Gytija soils in Sweden and estimation of greenhouse gas emissions from cultivated peat soils. Geoderma. 2010;154: 173–180.

44. Hadden D, Grelle A. The impact of cultivation on CO2 and CH4 fluxes over organic soils in Sweden. Agric For Meteorol. 2017;243:1–8.

45. Karki S, Elsgaard L, Audet J, et al. Mitigation of greenhouse gas emissions from reed canary grass in paludiculture: effect of groundwater level. Plant Soil. 2014;383:217–230.

46. Hahn-Scheufl M, Zak D, Minke M, et al. Organic sediment formed during inundation of a degraded fen grassland emits large fluxes of CH4 and CO2. Biogeoosciences. 2011;8:1539–1550.

47. Karki S, Elsgaard L, Laerke PE. Effect of reed canary grass cultivation on greenhouse gas emission from peat soil at controlled rewetting. Biogeoosciences. 2015;12:595–606.

48. Leppelt T, Dechow R, Gebbert S, et al. Nitrous oxide emission budgets and land-use-driven hotspots for organic soils in Europe. Biogeoosciences. 2014;11: 6595–6612.

49. Coyle C, Creamer RE, Schulte RPO, et al. A functional land management conceptual framework under soil drainage and land use scenarios. Environ Sci Policy. 2016;56:39–48.

50. Peltonen-Sainio P, Jauhiainen L, Sorvali J. Diversity of high-latitude agricultural landscapes and crop rotations: increased, decreased or back and forth? Agri Syst. 2017;154:25–33.