2.3 Greenhouse Gas Fluxes from Agricultural Soils

2.3.1 Mineral Soils

2.3.1.1 Carbon Dioxide

The balance between carbon input and decomposition of organic matter determines if a field is a source or a sink of carbon. There is only one study that reports net ecosystem exchange of a field on mineral soil (Lind et al. 2016) and that represents cultivation of reed canary grass which is not an especially common crop. Thus, the available data does not allow for estimation of a full carbon balance of a typical field based on measurements (Table 2.2). Evidence from a 35-year field monitoring points to the direction that cultivated mineral soils on the average lose carbon at an annual rate about 200 kg/ha (Heikkinen et al. 2013). The estimate was based on monitoring of about 500 fields and soil sampling only to 15 cm; thus, it represents changes in the topsoil only. The authors deduced that the declining trend is related to warming climate, changes in cropping (less annual crops and varieties with less crop residues) and the young age of fields that may be still losing carbon from the phase of the preceding land use (forest).

The amount of carbon input depends on choices made in cultivation practices. Decomposition is mainly driven by the climatic conditions although, e.g. tillage practices have a role in that as well. Despite the cool climate restricting decomposition of organic matter, it is likely that conventional agricultural practices result in loss of carbon from soil in Finnish conditions. A long-term field experiment in the neighbouring country, Sweden, showed that returning only crop residues with

Table 2.2 Annual greenhouse gas fluxes of cultivated mineral soils

	Mean (g m^2 $year^{-1}$)	Min	Max	n	Refs.
Annual crop					
Net CO_2 exchange	–	–	–		
C loss as yield (CO_2)	–	–	–		
CH_4 flux	−0.04 ± 0.07	−0.12	0.06	7	1; 2
N_2O flux	0.57 ± 0.23	0.20	1.02	31	1; 3; 4; 5
Perennial crop					
Net CO_2 exchange[a]	−950	−961	−939	2	6
C loss as yield (CO_2)	1183	1228	1137	2	6
CH_4 flux	−0.05 ± 0.03	−0.09	0.03	14	1; 2; 10
N_2O flux	0.43 ± 0.31	0.06	1.13	20	1; 3; 4; 7; 8; 9

n = number of annual flux estimates

[a]Negative value = carbon sequestration, positive value = carbon loss

References: 1 (Syvasalo et al. 2006); 2 (Regina et al. 2007); 3 (Syvasalo et al. 2004); 4 (Petersen et al. 2006); 5 (Sheehy et al. 2013); 6 (Lind et al. 2016); 7 (Regina et al. 2006); 8 (Maljanen et al. 2009); 9 (Virkajarvi et al. 2010); 10 (Maljanen et al. 2012b) no other amendments usually results in the decline of the carbon stock (Katterer et al. 2011). Plant breeding tends to develop varieties with less and less crop residues, which may also complicate maintaining the carbon content of cultivated soils. However, the amount of above-ground plant litter does not seem to be crucial for maintaining the carbon stocks of cultivated soils as the removal or burning of straw did not have an effect in a 30-year field experiment in Southern Finland (Singh et al. 2015).

Converting native ecosystems to agricultural use typically reduces the carbon stock by 20–40%, and the loss of carbon from the soil profile is fastest during the first decades (Guo and Gifford 2002; Karhu et al. 2011). Reaching a new steady state where the carbon input and its loss are in balance may take several decades, and thus it is impossible to say how much of the observed carbon loss is due to the land use change and how much is caused by agricultural management.

2.3.1.2 Methane

Methane is produced microbially in anaerobic conditions and consumed in aerobic conditions. In soils, the conditions can vary from anaerobic to aerobic in time or space. The sites of CH_4 production are the lower soil layers with low oxygen content or soil aggregates favouring anaerobic bacteria. Sites of CH_4 consumption are the topsoil or macropores of the soil. Soil micro- or macroporosity was found to affect the observed rates of CH_4 flux in Finnish clay and sandy soils (Regina et al. 2007). In cultivated soils, the annual balance of CH_4 is usually close to zero most often resulting in more CH_4 being consumed than produced. Emissions of CH_4 have been reported to occur occasionally in wet conditions (Regina et al. 2007), but even then, the annual balance typically indicates net consumption of CH_4. Compared to CO_2, the carbon flows related to CH_4 are minor (Table 2.2). The annual fluxes have ranged from -0.12 to 0.06 g m^{-2} with no clear differences between annual and perennial cropping can be seen. Grazing has been found to change pastures from sink to source of CH_4 emissions due to CH_4 released from the deposited dung (Maljanen et al. 2012b).

2.3.1.3 Nitrous Oxide

In cultivated mineral soils, the most significant gas in the total greenhouse gas budget is N_2O. Average annual emissions of N_2O have been 0.6 g m^{-2} for annual crops and 0.4 g m^{-2} for perennial crops including mostly grass leys (Table 2.2). Annual emissions of N_2O are typically slightly higher from annual cultivation compared to perennial despite the higher fertilization rates on perennial ley production (Regina et al. 2013).

Perennial crops take up nutrients clearly for a longer period annually compared to annual crops and that reduces the amount of nitrogen available for the microbes during the non-vegetated period. The emissions during the period between harvest and sowing represent about 40% of the annual budget of N_2O (Regina et al. 2013) which highlights the importance of the residual nitrogen after harvest in the absence of nutrient uptake of plants. The difference between perennial and annual crops may thus be emphasized in the northern conditions with short growing season of cash crops.

It has been found in many studies that emissions of N_2O are not ceased in the winter time even when the soil is frozen. Availability of nitrate is always good in cultivated soils, and the low oxygen content favours denitrifying bacteria that can be active in microsites with unfrozen water of frozen soil (Teepe et al. 2004). One reason for the high N_2O production at low temperatures can be that N_2O reductase enzymatic activity is inhibited (Muller et al. 2003), and therefore the end product of denitrification is N_2O instead of N_2.

The timing of freezing and soil water content have important effects on the emission of N_2O (Maljanen et al. 2009; Teepe et al. 2004). Also the depth and timing of snow cover can affect N_2O emissions. Snow manipulation experiments have shown that thinner snow cover can lower soil temperatures and increase the extent and duration of soil frost (Maljanen et al. 2009). In frozen soil, N_2O is still produced and accumulated in soil, and it is then rapidly released during thawing (Koponen and Martikainen 2004; Maljanen et al. 2007a, 2009). The N_2O production in frozen soil does not correlate well with the N_2O emitted from soil as a result of the low gas diffusion rate. Therefore, the release of N_2O during winter does not give the correct estimate of N_2O production activity during the winter.

Fertilization rate, especially the amount of mineral nitrogen, has been found to affect the annual emissions when studied in subsets of annual and perennial cropping (Regina et al. 2013). The available data does not allow reliable estimates of the effects of fertilizer type (mineral/organic) on N_2O emissions. Recent evidence shows that external nitrogen inputs induce also emissions of nitric oxide (NO) and gaseous nitrous acid (HONO) that are not greenhouse gases but reactive in the atmosphere (Bhattarai et al. 2018; Maljanen et al. 2007b).

There is some evidence that no-till management increases N_2O emissions from cultivated soils (Sheehy et al. 2013). The increase is related to the more dense structure of the soil and thus higher soil moisture favouring denitrification.

A probable but poorly known hotspot of N_2O emissions are fields on acid sulphate soils. They are located on the former sea bottom of the coastal regions and have large amounts of organic matter in the subsoil due to sedimented materials. The field area on acid sulphate soils is in the range of 43 000–130 000 ha (Yli-Halla et al. 1999). They are characterized by a large stock of nitrogen and high microbial activity that may induce extremely high emissions of N_2O, even of the magnitude of tens of kilograms per hectare when drained for agriculture (Simek et al. 2011, 2014; Petersen et al. 2012; Denmead et al. 2010).

2.3.2 Organic Soils

2.3.2.1 Carbon Dioxide

Losses of carbon from organic soils are typically several folds compared to carbon stock changes in mineral soils. Typically 0.5–2 cm of peat is lost from the topsoil of cultivated soils due to peat decomposition annually (Gronlund et al. 2008) and that represents carbon loss of several tonnes per hectare. Although carbon exchange between the soil and atmosphere forms the majority of the climatic impact of cultivated organic soils, full carbon balance estimates are still rare. The annual net ecosystem exchange has varied between −800 and 3000 g m^{-2} in Finnish studies (Table 2.3). As the reported values show, even in organic soils photosynthesis may sometimes exceed carbon loss from the soil, at least in the case of crops with large biomass. The consideration of the climatic impact must, however, include the biomass transported from the field, and in most cases, this turns the field to net source of carbon even if photosynthesis was able to counteract peat decomposition.

Table 2.3 Annual greenhouse gas fluxes of cultivated organic soils

	Mean (g m^2 $year^{-1}$)	Min	Max	n	GWP (t CO_2 eq. ha^{-1} $year^{-1}$)	Refs.
Annual crop						
Net CO_2 exchange*	2080 ± 1150	770	3040	4	20.8	1, 2, 3
C loss as yield (CO_2)	600 ± 180	460	855	4	6.0	1, 2, 3
CH_4 flux	−0.06 ± 0.24	−0.49	0.51	10	−0.02	3, 4, 5
N_2O flux	1.74 ± 0.92	0.84	3.79	11	5.2	3, 6, 7
Total					32.0	
Perennial crop						
Net CO_2 exchange*	560 ± 1210	−780	2750	8	5.6	1, 2, 3
C loss as yield (CO_2)	920 ± 400	280	1570	8	9.2	1, 2, 3
CH_4 flux	0.15 ± 0.34	−0.25	0.91	14	0.05	3, 4, 5, 8
N_2O flux	1.14 ± 1.47	0.04	5.47	19	3.4	3, 6, 7, 8, 9, 10
Total					18.3	

n = number of annual flux estimates
GWP = global warming potential
*Negative value = carbon sequestration, positive value = carbon loss
References: 1 (Maljanen et al. 2001); 2 (Lohila et al. 2004); 3 (Maljanen et al. 2004); 4 (Maljanen et al. 2003a); 5 (Regina et al. 2007); 6 (Maljanen et al. 2003b); 7 (Regina et al. 2004); 8 (Maljanen et al. 2009); 9 (Maljanen et al. 2010b); 10 (Shurpali et al. 2009)