EU LIFE Programme project
"Demonstration of climate change mitigation potential of nutrients rich organic soils in Baltic States and Finland"

REPORT

ON IMPLEMENTATION OF THE PROJECT

DEMONSTRATION OF CLIMATE CHANGE MITIGATION MEASURES IN NUTRIENTS RICH DRAINED ORGANIC SOILS IN BALTIC STATES AND FINLAND

WORK PACKAGE

FILLING KNOWLEDGE GAPS ABOUT GHG EMISSIONS FROM NUTRIENT-RICH ORGANIC SOILS (C1)

ACTIONS

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"LIFE OrgBalt compiled the first regional Baltic/ Finnish GHG emission factors for managed nutrient-rich organic soils (current and former peatlands), which have been made available for the customary scientific review and further verification for national GHG inventories in the hemiboreal region in Finland and the Baltic countries. While the project analysed selected CCM measures for drained organic soils in agriculture and forestry and developed spatial models and tools, it also identified remaining knowledge gaps. To bridge the remaining limitations and fill the gaps, it is essential to continue GHG measurements and model development, as well to broaden and complete the scope of the evaluated CCM measures in the after-LIFE-project period, notably by including rewetting and restoration of peatlands that are currently considered to be among the most recommended CCM measures on drained peatlands in the EU. In addition, the developed Simulation and PPC models still include limited macroeconomic considerations and lack assessment of all environmental impacts. For all these reasons, these models should be used carefully in CCM strategy development for identification of gaps in climate neutrality transition policy and funding frameworks and need further optimization for broader applicability as decision-making tools."

2024

SUMMARY

The Baltic region is characterized by a cool temperate climate with flat terrain and high precipitation, leading to the prevalence of organic soils formed after the glaciation period. Human activities like drainage, agriculture, and forestry impact terrestrial carbon sinks on organic soils and serve as a reason for major anthropogenic greenhouse gas (GHG) source formed from these soils. The Intergovernmental Panel on Climate Change (IPCC) provides guidelines to estimate GHG emissions from various land uses on drained organic soils, emphasizing factors like ecosystem type and management practices, and provides default emission (Tier 1 level). Using Tier 1 level emission factors (EFs) poses a risk of over- or underestimation due to averaged data from broad categories with potentially modest shared data characteristics.

National GHG Inventory Submissions in the Baltic States vary in methodology. Estonia and Lithuania follow combination of IPCC 2006 and 2014 Guidelines, while Latvia adheres to the guidance in IPCC 2014. As of 2019, CO_2 EFs in the region span Tier 1 and more specific data requiring Tier 2 levels. Estonia and Latvia typically employ Tier 2 EFs for forests, with Lithuania opting for default Tier 1 EFs. Improving EFs accuracy requires comprehensive data on soil dynamics and environmental conditions, an effort advanced by projects like Life OrgBalt in studying various land uses in the region.

In the Life OrgBalt project, data collection focused on temperate peatlands, encompassing forestland, grassland, and cropland sites on nutrient-rich organic soils. The monitoring setup included gaseous flux and mass-based data collection following IPCC guidance with additional insights ensuring comprehensive data collection. The key features included uniform data collection methods, spatially extensive GHG monitoring, and seasonal and interannual data collection periods. Environment parameters were studied by analyses made on peat samples and data loggers were applied for continuous water level and soil temperature monitoring. The Life OrgBalt expanded forest EF data by categorizing sites based on characteristics like draining status and dominant tree species. OrgBalt added new monitored sites in grasslands and croplands, considering diverse conditions and low organic carbon content. Through careful site selection and comprehensive monitoring, Life OrgBalt contributes to more robust emission factors and an enhanced understanding of emissions in forest land and agriculture systems in nutrient-rich organic soils in the Baltic region.

ABBREVIATIONS

AFOLU = agriculture, forestry and other land use

Basal area = tree trunk cross-section area per ha

C = carbon

CH_4 = methane

CO_2 = carbon dioxide

DBH = tree diameter at breast height

EF = emission factor

GHG = greenhouse gas

IPCC = Intergovernmental Panel on Climate Change

LIFE OrgBalt = EU-funded project "Demonstration of climate change mitigation potential of nutrients rich organic soils in Baltic States and Finland" (LIFE18 CCM/LV/001158)

LULUCF = land use, land-use change and forestry

N_2O = nitrous oxide

NFI = National Forest Inventory

UNFCCC = United Nations' Framework Convention on Climate Change

WL = water level below the soil surface

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1 INTRODUCTION

In Estonia, Latvia, and Lithuania, organic soils formed after the latest glaciation period. These cool temperate climate regions have flat terrain and higher precipitation than evaporation, making organic soils prevalent. Organic soils are formed over time as vegetation deposits decomposing litter into the soil, creating a partially decomposed organic substrate. These soils are commonly found in areas with high water levels (WL), which limit oxygen and slow down decomposition.

Human activities, particularly land use, land-use change, and forestry (LULUCF) activities, have a significant impact on terrestrial carbon sinks. Drainage for forestry, agriculture, and peat mining for energy production are common anthropogenic land uses in the Baltic region. Lowering the WL increases oxygen availability and enhances decomposition in the soil. Forests on drained organic soils are the main land use category in Latvia and Lithuania, while agriculture dominates in Estonia (LIFE OrgBalt, 2019a). The proportion of grasslands and cropping lands on organic soils in agriculture varies.

Drained organic soils are recognized as a substantial source of anthropogenic greenhouse gas (GHG) emissions, both in the European Union and globally. To report the annual GHG emissions and removals from soils under human land use, the Intergovernmental Panel on Climate Change (IPCC) provides guidelines, such as the AFOLU guidelines (IPCC, 2006) and the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (i.e. IPCC, 2014). These guidelines consider factors such as ecosystem type, land management practices, and environmental conditions to develop area-based emission factors (EFs) that reflect annual GHG emissions or removals from the soil.

The reduction of GHG emissions from drained organic soils is considered to be the most cost-effective option for mitigating climate change within the land-use and agricultural sectors. The Baltic States use IPCC guidance in their GHG inventories. They employ sampling-based National Forest Inventories (NFI) to estimate organic soil areas and apply classification to include site characteristics. Countries may opt for different methodological levels in their GHG reporting by applying the default IPCC EFs (Tier 1), EFs based on country-specific data (Tier 2), or repeated national inventories and/or advanced modelling (Tier 3). The Tier 1 EFs for drained organic soils are average emission values based on peer-reviewed studies covering a wide range of situations categorized by climatic zones.

Improving the accuracy of EFs and use of Tiers 2 and 3 require data on soil gas dynamics, soil and vegetation characteristics and environmental conditions. Studying litter production and decomposition dynamics can also enhance CO_2 EFs. Continued research and the availability of peer-reviewed data will contribute to more accurate and comprehensive EFs for specific management options and ecological conditions – Life OrgBalt (Demonstration of climate change mitigation potential of nutrients rich organic soils in Baltic States and Finland) project has taken an important role in improving the data pool by conducting research on multiple sites defined by typical conditions, and extend monitoring over two years on GHG and environment data collection. This work produces land use and site type specific EFs for nutrient-rich organic soils in forestry and agriculture outlined in this report. The focus of this report is on organic soil EFs in forestland and agriculture (cropland and grassland), land uses that form the most important anthropogenic land uses in the region studied in Life OrgBalt.

2 TIER 1 LEVEL DATA IN IPCC REPORTING

During the compilation of IPCC (2014) Wetlands assessment there was only a skeleton draft of the measures needed for forming soil C-balance and monitoring other GHGs, and the formed guidance, methods and database requirements were agreed by an expert team. Only a limited amount of data fulfilling the formed data requirements existed, and thus the data could be set in relatively broad top level categories, which included potentially wide range of site characteristics. The resulting data pool show considerable variation in the number of sites in each category and the width of confidence intervals (Table 1). Due to review type of data collection in IPCC 2014, it is likely that differences in spatial and temporal data collection and coefficients/literature values used in several studies contributed to the resulted uncertainty in the default EFs. Potential biases in data using literature-based data collection for drained forestlands were recently assessed in reports Jauhiainen et. al. (2019) and (2024).

The IPCC (2014) temperate zone Tier 1 EFs for forestland, grassland and cropland categories can be summarized as follows:

- Forestland data from drained organic soils has one category, which includes all tree-stand types, all organic soil types, all soil nutrient status conditions, and all WL regimes
    - CO_2; 5 studies, 8 sites in total
    - CH_4; 7 studies, 13 sites in total
    - N_2O; 5 studies, 13 sites in total
- Grassland data on nutrient rich organic soils has two categories (deep drained and shallow drained), and includes all organic soil types, and all soil nutrient status conditions
    - CO_2 deep drained; 18 studies, 39 sites in total
    - CO_2 shallow drained; 3 studies, 13 sites in total
    - CH_4 deep drained; 17 studies, 44 sites in total
    - CH_4 shallow drained; 4 studies, 16 sites in total
    - N_2O deep drained; 16 studies, 47 sites in total
    - N_2O shallow drained; 2 studies, 13 sites in total
- Cropland data on nutrient rich organic soils has one category, the studied sites are located at boreal and temperate climate zones, and it includes all organic soil types, all soil nutrient status conditions, and all WL regimes
    - CO_2; 8 studies from temperate zone and 4 studies from boreal zone, 39 sites in total
    - CH_4; 8 studies from temperate zone and 5 studies from boreal zone, 38 sites in total
    - N_2O; 7 studies from temperate zone and 5 studies from boreal zone, 36 sites in total

There is a potential risk of over- or underestimating soil CO_2, CH_4 and N_2O balances by using simple Tier 1 level EFs because these default EFs do not necessarily reflect sufficiently local site characteristics and environment conditions. The EF values provided by the IPCC (2014) are based on peer-reviewed literature, where the data averages represent broad categories with conditions that met the specified land use category criteria (Table 1).

Table 1. IPCC (2014) Wetlands supplement CO_2, CH_4 and N_2O emission factors (EF) for nutrient rich drained organic soils in temperate climate zone; average, Confidence limit range (95%), and number of sites in included data pool provided.

Defined category	CO_2 (t CO_2-C ha^{-1} yr^{-1})			CH_4 (kg CH_4 ha^{-1} yr^{-1})			N_2O (kg N_2O-N ha^{-1} yr^{-1})		
	EF	CI 95%	N sites	EF	CI95%	N sites	EF	CI95%	N sites
Forestland	2.6	2.0 – 3.3	8	2.5	-0.60 – 5.7	13	2.8	0.57 – 6.1	13
Grassland (deep dr.)	6.1	5.0 – 7.3	39	16	2.4 – 29	44	8.2	4.9 – 11	47
Grassland (shallow dr.)	3.6	1.8 – 5.4	13	39	-2.9 – 81	16	1.6	0.56 – 2.7	13
Cropland[1]	7.9	6.5 – 9.4	39	0	-2.8 – 2.8	38	13	8.2 – 18	36

[1] Data pooled from boreal and temperate climate zones

3 Emission factors applied in the Baltic states

The methodologies applied in the National Inventory Submissions differ in the Baltic States (LIFE OrgBalt, 2019a). While Estonia and Lithuania rely on combination of the IPCC 2006 and 2014 Guidelines, Latvia adhere to the IPCC (2014) Wetlands Supplement, Table 2. At the time of Life OrgBalt project commencement on the year 2019, the applied EFs in the Baltic States covered Tier 1 and Tier 2 levels:

- CO_2; Estonia and Latvia mainly used Tier 2 EFs for forests, while Lithuania used the default EF. In terms of CO_2 EFs for organic soils in agriculture, Estonia used Tiers 1 and 2, while Latvia and Lithuania used Tier 1 EFs.
- CH_4; EFs were reported using Tiers 1 and 2. Estonia considered forest soil nutrient characteristics. For agricultural soils, Estonia used Tier 2 EFs, while Latvia and Lithuania used Tier 1.
- N_2O; Forest emissions were reported at Tier 2 level in Estonia, as data on soil nutrient characteristics and country-specific or comparable condition GHG data were available. Latvia and Lithuania applied Tier 1 EFs for forests. For organic soils in agriculture, Estonia used Tier 2 EF for grasslands, Tier 1 for croplands, while all other countries used the default Tier 1 EF.

Table 2. Emission factor levels applied in forest and agriculture lands on nutrient rich organic soils in the Baltic states.

Country	Land use	EF level CO_2	EF level CH_4	EF level N_2O
Estonia	forestland	Tier 2	Tiers 1 – 2	Tier 2
	grassland	Tiers 1 – 2	Tier 2	Tier 2
	cropland	Tiers 1 – 2	Tier 2[1]	Tier 1
Latvia	forestland	Tier 2	Tier 1	Tier 1
	grassland	Tier 1	Tier 1	Tier 1
	cropland	Tier 1	Tier 1	Tier 1
Lithuania	forestland	Tier 1[2]	Tier 1[2]	Tier 1[2]
	grassland	Tier 1[2]	Tier 1[2]	Tier 1[2]
	cropland	Tier 1[2]	Tier 1[2]	Tier 1[2]

[1] Considered to be insignificant in the drained peatlands (IPCC, 2006, 2014).
[2] IPCC (2006) guideline EF-values applied.

3.1 Estonia

In Estonia, the methodology for calculating emissions and removals from the LULUCF sector was based on the IPCC 2006 Guidelines (IPCC, 2006). Estonia included using the six top-level land categories (Forest land, Cropland, Grassland, Wetlands, Settlements, Other land) and tracking land-use transitions between categories (Ministry of the Environment; 2019). The emissions from drained organic forest soils were reported for the first time in the 2019 submission, while previous submissions only estimated these emissions under the Wetlands category. Estonia did not have sufficient data regarding litter stocks; thus, under Forest land remaining forest land, the conservative Tier 1 method was implemented, assuming that carbon stocks were in equilibrium. Due to insufficient country-specific data regarding carbon stock changes in forest mineral soil, the EF from Sweden (0.175 t C ha^{-1} yr^{-1}) was implemented for remaining forest land. For estimating CO_2 emissions from cultivated organic soils in both remaining cropland and land converted to cropland subcategories, the Tier 2 method was applied. In this estimation, the emissions were calculated using EFs from Sweden, as Estonia lacked available country-specific data. Estonia took into account forest soil nutrient characteristics in the estimation of CH4 EF. In Estonia, N_2O emissions from cultivated organic soils were estimated using the IPCC 2006 Tier 1 method. Starting from the 2019 submission, emissions from drained grasslands were also included in the estimation of cultivated organic soils. The Tier 2 method was utilized to calculate the carbon loss from drained grassland soils. As there was insufficient country-specific data available for C-loss on grasslands, modified EF from Sweden was utilized (Estonia; 0.5 t C ha^{-1} y^{-1}, Sweden; 1.67 t C ha^{-1} y^{-1}).

3.2 Latvia

The land area was divided into six categories according to the 2006 IPCC Guidelines: Forest Land, Cropland, Grassland, Wetlands, Settlements, and Other Land. When calculating emissions from drained organic soils, default EFs from the IPCC (2014) were used, along with a country-specific approach based on scientific studies for forest land (Ministry of Environmental Protection and Regional Development, 2019). For forest land, changes in the soil organic carbon (SOC) stock and GHG emissions were estimated using the Tier 2 method with country-specific data. CO_2 emissions from drained soils were determined based on national research, which indicated that emissions from organic soils in forest land were 0.52 t C ha^{-1} annually (Lazdiņš & Lupiķis, 2017), along with 2.8 kg N_2O-N ha^{-1} (IPCC, 2014). To calculate CH_4 emissions from drained organic soils on forest land, country-specific equations and default EFs (IPCC, 2014) were used. N_2O emissions were based on Tier 1 (IPCC, 2014). Emissions from organic soils in afforested lands were calculated using the same approach as for emissions from drained organic soils in forests. For drained organic soils in croplands and grasslands, CO_2 emissions were calculated using the IPCC Wetlands Supplement Tier 1 method, while CH_4 and N_2O emissions were based on Tier 1 (IPCC, 2014) guidelines.

3.3 Lithuania

Lithuania estimated GHG emissions due to the drainage of organic soils in its annual GHG Inventory Report using Tier 1 EFs provided in the IPCC 2006 guidance (MoE/EPA/SFS, (2019). According to Martin and Couwenberg (2021), Lihuania has applied erroneously EFs for the boreal vegetation zone, as climatic conditions in Lithuania are temperate (IPCC 2006, Fig. 3.1.).

4 DATA COLLECTION AND LAND USES INCLUDED IN LIFE ORGBALT

In Life OrgBalt, data collection for temperate peatlands included forestland, grassland and cropland sites on nutrient rich organic soils. The selection of sites in each land use type was planned to address typical site type conditions, -management conditions and -environment parameter differences. In planning, guidance and approach available in IPCC (2006, 2014) was considered as the minimum for data collection in this project. Additional in-depth information to support spatio-temporal monitoring planning was sought from recent literature, e.g. Jauhiainen et al. (2019).

Table 3. Basic characteristics in forest sites included in Life OrgBalt monitoring in the Baltic States.

Country	Site ID	Dominant tree	WL regime	Organic layer (cm)	Stand age (years/ descrition)	Other info
Estonia	EEC106	Birch	Drained	70 – 80	35	Thinning in 2005
Estonia	EEC109	Birch	Drained	90 – 100	45	
Estonia	EEC108	Bl. alder	Drained	30 – 40	80	
Estonia	EEC105	Pine	Drained	90 – 100	60	Thinning in 2006
Estonia	EEC104	Spruce	Drained	80 – 90	60	Thinning in 2019
Latvia	LVC108	Birch	Drained	>50	24	Young birch stand
Latvia	LVC309	Birch and bl. alder	Wet	>50	81	
Latvia	LVC115	Birch	Drained	?	mature & young	Afforested
Latvia	LVC111	Birch	Wet	100+	mature	
Latvia	LVC311	Bl. alder	Wet	>50	81	Ditch reconstruction
Latvia	LVC109	Bl. alder	Wet	>50	mature	Protected, unmanaged
Latvia	LVC313	Pine	Drained	>100	141	Partial harvesting
Latvia	LVC107	Pine	Drained	>21	120	
Latvia	LVC116	Pine	Drained		141	
Latvia	LVC110	Pine	Wet	>21	mature	
Latvia	LVC113	Spruce	Drained	>50	48	Control for ash
Latvia	LVC307	Spruce	Drained	>50	48	Ash - done
Latvia	LVC104	Spruce	Drained	30+	mature	Mature forest stand
Latvia	LVC112	Spruce	Drained	30 – 40	162	Clearcut
Latvia	LVC105	Spruce	Drained	40	mature	Previous wood ash application
Latvia	LVC106	Spruce	Drained	40	mature	Control for LVC105
Latvia	LVC308	Spruce	Dry	>50	141	Partial harvesting
Latvia	LVC312	Spruce	Wet	>50	96	
Latvia	LVC310		drained	20 – 50	young	Fast growing tree species
Lithuania	LTC105	Birch	Drained	50 – 60	43	
Lithuania	LTC108	Birch	Undrained	150 – 250	45	Unmanaged forest
Lithuania	LTC106	Bl. alder	Drained	50 – 60	30	
Lithuania	LTC109	Bl. alder	Undrained	150 – 250	45	Unmanaged forest
Lithuania	LTC104	Spruce	Drained	50 – 60	70	

Especially in long rotation time ecosystems representing periods of decades to over a hundred years, i.e. forests, getting representative site combinations for monitoring can be hard. Challenges to get sites were set also by the willingness and possibilities of landowners and -managers to provide access to their land, logistics needed to access sites, and existing information on the site characteristics in the early project planning phase. Forest site selection in the planning phase shows variation in basic site characteristics, even if a relatively large selection of sites is included, see Table 3. Selection of sites in grasslands and croplands included in OrgBalt monitoring is shown in Table 4.

Table 4. Basic characteristics in Cropland and Grassland sites included in Life OrgBalt monitoring in the Baltic States.

Land use type	Country	Site ID	Management	Thickness of organic soil, mean (range), cm	WL mean and range, cm
Cropland	Latvia	CL_LV_1	Winter wheat	55	87.3 ± 3.9 (12 – 155)
		CL_LV_2	Maize	57	96.2 ± 2.8 (53 – 160)
		CL_LV_3	Winter wheat	45	41.7 ± 3.3 (-3 – 93)
		CL_LV_4	Maize	72	86.3 ± 2.3 (33 – 140)
		CL_LV_5	Winter wheat	18 (15 – 20)	59.1 ± 1.3 (30 – 100)
		CL_LV_6	Beans	16 (10 –21)	54.7 ± 3.4 (1 – 91)
	Estonia	CL_EE_1	Maize	33 (30 – 40)	46.7 ± 0.9 (29 – 78)
	Lithuania	CL_LT_1	Winter wheat	45 (45 – 45)	> 150 (110 – >150)
Grassland	Latvia	GL_LV_1	Perennial grass	42	91.1 ± 3.3 (1 – 150)
		GL_LV_2	Perennial grass	50	25.5 ± 2.9 (-2 - 98)
		GL_LV_3	Perennial grass	50	42.2 ± 3.1 (-4 – 110)
		GL_LV_4	Perennial grass	31 (30 – 32)	30.3 ± 2.7 (-3 – 91)
		GL_LV_5	Perennial grass	28 (20 – 35)	47.7 ± 2.1 (1 – 85)
		GL_LV_6	Perennial grass	22 (15 – 30)	94.2 ± 1.5 (47 – 127)
		GL_LV_7	Perennial grass	43 (20 – 70)	46.3 ± 2.1 (0 – 125)
		GL_LV_8	Perennial grass	17 (10 – 25)	83.0 ± 2.3 (0 – 146)
	Estonia	GL_EE_1	Perennial grass	37 (30 – 40)	22.6 ± 0.9 (-3 – 51)
		GL_EE_2	Perennial grass	47 (40 – 50)	58.4 ± 1.0 (32 – 84)
		GL_EE_3	Perennial grass	92 (75 – 100)	30.6 ± 1.4 (-1 – 96)
	Lithuania	GL_LT_1	Perennial grass	95 (78 – 120)	43.3 ± 3.7 (-3 – 150)

Some site characteristics could be revealed only by studies made on soil chemistry and environmental conditions (Table 5). Soil type characteristics were studied by peat samples collected from the surface to the organic layer bottom or down to 75 cm depth for soil physical and chemical analyses. Environment data, including soil WL data and temperature in the soil profile, was collected by setting data collection loggers at each site.

Monitoring setup for gaseous flux monitoring, spatial and temporal scales, was comparable at the sites. Mass based monitoring setup for monitoring litter deposition above- and belowground, above- and belowground biomass on different vegetation functional groups, litter decomposition on main litter types were planned in formed protocols before the start of implementation at field sites (Table 5).

The key features in Life OrgBalt data collection at field sites include;

- Harmonized methods in gaseous- and mass-based data collection at each site in the project
- GHG flux monitoring and mass-based data were collected at the same sites and time frames to complete soil C-balance.
- GHG monitoring spatially above the general average by including minimum of 5 total soil respiration monitoring points (CO_2, CH_4 and N_2O) at each site, and minimum of 9 CO_2 heterotrophic monitoring points at each site (based on information in IPCC (2014) and Jauhiainen et al., 2019).
- GHG monitoring spatially above the general average by extending over 2 years and including both warm- and cold season monitoring (based on guidance provided in IPCC, 2014).

The final grouping of sites in different soil type and drainage status categories for forestland, grassland and cropland could be done only after data analyses based on one-time sampling (soil samples) and monitoring data on WL were ready at the end of monitoring activity. A summary of measures quantified by one-time sampling or frequent monitoring is provided in Table 5.

Data collection on WL and soil temperature in soil are essential for modelling GHG fluxes over time, i.e. for work on achieving Tier 2 and Tier 3 EF levels. The accuracy of EFs can be improved as more peer-reviewed data become available and quantify a broader set of specific management options and ecological conditions for a given country or region. Methodologies implemented in Life OrgBalt are dealt in detail in reports LIFE OrgBalt (2019b , 2019c).

Table 5. Summary of measures quantified by one-time sampling or frequent monitoring from Life OrgBalt sites.

Parameter	Importance	Parameter/variable	Importance
Soil Temperature	GHG flux modelling	**GHGs** CO_{2aut}	Quantification of soil C loss in decomposition, component in soil carbon balance
WL over time	Site characteristics, GHG flux modelling	CO_{2tot}	Modelling
Bulk density	Soil C-pool estimation	CH_4	Quantification of soil CH4 balance
Peat depth	Site characteristics, soil C-pool estimation	N_2O	Quantification of soil N2O balance
C organic	Modelling, soil characteristics		
C tot.	-"-		
N tot.	-"-	**Biomass** Tree stand characteristics (species, age, DBH, basal area)	Site characterisation, modelling, upscaling
CN	-"-	Ground vegetation	Component in soil C balance

		aboveground biomass	
Ash	-"-	Herbaceous ground vegetation biomass production	-"-
K	-"-	Perennial ground vegetation biomass production	-"-
Ca	-"-	Moss cover and -production	-"-
Mg	-"-	Moss biomass	-"-
P	-"-	Ground vegetation belowground biomass and biomass production	-"-
		Fine root biomass	-"-
Water pH	Modelling	Fine-root production	-"-
Ntot	-"-		
N-NO_3^-	-"-	**Litter production and decomposition (forests)** Aboveground litter production	Component in soil C balance
DOC	-"-	Aboveground litter decomposition	-"-
NH_4^+	-"-	Belowground litter decomposition	-"-
PO_4^{3-}	-"-		
K	-"-		
Ca	-"-		
Mg	-"-		

5 EFS DEVELOPED IN LIFE ORGBALT

Data collection made over 2 years field work in each site produced a database which reflects uniform methods and spatio-temporal extent of data collection over warm- and cold seasons. This data pool was refined into EFs summarized in Table 6. The EFs formed in this project and potential impact are analysed in detail in LIFE OrgBalt (2024).

Table 6. Tentative soil carbon (CO_2-C), CH_4 and N_2O emission factors (EF) based on the data collection in Life OrgBalt project (Note; final values can be confirmed after approval of peer-reviewed publications).

Land use category	**CO_2 EF (t C ha^{-1} y^{-1})**	**CH_4 EF (kg CH_4 ha^{-1} y^{-1})**	**N_2O EF (kg N_2O ha^{-1} y^{-1})**
Cropland	7.5 [a]	-0.61	8.86
	6.6 [b]		
Grassland	6.2 [a]	4.94	1.84
	5.8 [b]		
Forest land, deciduous [e]	3.97 [d]	17.2	16.2
Forest land, coniferous [e]	3.79 [d]	-2.73	6.58
Forest land, drained deciduous	4.42 [d]	-4.81	22.7
Forest land, drained coniferous	4.07 [d]	-4.76	7.12
Forest land, undrained deciduous	3.09 [d]	61.2	3.29
Forest land, alder [e]	3.90 [d]	23.0	20.8
Forest land, birch [e]	4.03 [d]	14.3	13.9
Forest land, pine [e]	3.38 [d]	-4.25	2.52
Forest land, spruce [e]	4.19 [d]	-2.08	8.32
Forest land, drained	4.30 [d]	-4.78	13.9
Forest land, undrained	3.00 [d]	51.1	2.95
Forest land, drained alder	4.24 [d]	-4.11	34.3
Forest land, drained birch	4.60 [d]	-5.09	18.1
Forest land, drained pine	3.38 [d]	-4.25	2.52
Forest land, drained spruce	4.75 [d]	-5.01	9.42
Forest land, undrained alder	3.56 [d]	59.0	2.86
Forest land, undrained birch	2.61 [d]	62.8	3.61
Forest land, undrained spruce	2.89 [d]	15.5	1.76
Forest land, undrained pine	NE	NE	NE
Forest land, selective felling			

[a] Soil heterotrophic respiration (annual), all study sites combined.
[b] Soil heterotrophic respiration (annual), sites with mean OC content > 12% at 0 – 20 cm soil layer.
[c] Including above- and belowground vegetation of herbaceous plants and tree fine roots.
[d] Calculated by multiplying estimated soil total respiration by empirical factor characterising share of soil respiration in total respiration.
[e] Mean of drained and undrained site data.

6 COMPARISON BETWEEN DEFAULT EFS AND EFS BASED ON RECENTLY COLLECTED DATA

Data collected in this project has added tens of new data retrieval sites on different land use types in drained organic soils in the Baltic region if compared to the data pool available in IPCC (2014), see Table 7. The most notable increase is in the number of sites providing EF in drained forestland. On croplands, Life OrgBalt sites (N=8) in the Baltic States are sufficient for forming strictly temperate region data-based EF, and thus avoid the use of pooled data from two climate zones. On grasslands, Life OrgBalt data is mainly from deep drained sites with a notable number of sites (10 sites), which reflect typical draining conditions and site type commonness availability also in the IPCC (2014) data.

Table 7. Comparison of number of sites in IPCC (2014) reporting for drained forestland, grassland and cropland and number of sites providing EF in Life OrgBalt.

Land use	**GHG**	**N of sites in IPCC 2014**	**N of sites in Life OrgBalt**
Forestland	CO_2	8	29
	CH_4	13	29
	N_2O	13	29
Grassland			
• Deep drained	CO_2	39	10
• Shallow drained (2	CO_2	13	2
• Deep drained	CH_4	44	10
• Shallow drained (2	CH_4	16	2
• Deep drained	N_2O	47	10
• Shallow drained (2	N_2O	13	2
Cropland	CO_2	39 (1	8
	CH_4	38 (1	8
	N_2O	36 (1	8

(1 Boreal and temperate data combined
(2 Annual average WL max. 30 cm below the soil surface

The main improvements in EFs provided in Life OrgBalt arise from two key factors: research method implementation and characteristics of sites included in monitoring. By implementing harmonized methods across multiple sites, Life OrgBalt offers a significant advantage over the IPCC (2014) data used in Tier 1 EFs. In the IPCC (2014) dataset, data comes from various studies conducted in different projects and reported in separate publications. This inevitably leads to a database structure that contains differences in data collection, spatio-temporal coverage, variations in environment parameters monitored, superficial shared characteristics of sites studied, and a minimal and relatively random information structure in EFs contributing parameters in reporting.

The issues with data structure and EF-related considerations in peer-reviewed data-based EFs have been highlighted in reviews by Jauhiainen et al. (2019 and 2023). These reviews have pointed out the lack of uniformity in incorporating environmental data in research papers, which hampers the effective reuse and pooling of data. The scarcity of applicable data, primarily caused by a lack of environmental data, poses challenges in developing more dynamic EFs. Consequently, to develop higher Tier EFs for CO_2 in the temperate region, it is essential to conduct studies on aboveground litter production and decomposition dynamics.

In Life OrgBalt, harmonized methods included ambitious efforts to collect site-specific and at least site-type-specific data on gaseous fluxes, biomass and various dead organic matter based, and environment data (see Table 5). The outcome serve both as the best available original data for static EFs, but more importantly, enable effort to start testing dynamic modelling on soil C dynamics and on CH_4 and N_2O dynamics, which is a significant improvement compared to the use of simple EFs and limited categoriy selection available in IPCC reporting.

In addition to all inclusive pooling of all forest EF data from drained organic soils, as presented in IPCC (2014), Life OrgBalt new categories in forest data take in account draining status (drained vs. undrained), forest stand type (coniferous vs. deciduous), and dominant tree species (alder, birch, spruce, pine), and forms in total 18 categories (Table 6). Harmonized methods in data collection conducted both on GHG flux data monitoring mass-based data collection on biomass and litter enable possibilities to recombine sites in the different category sets. EF categories can further be defined by soil, ground vegetation and tree stand characteristics determined and measured at each site (Table 5). Harmonized environment data collection on WL and temperature provides possibilities to apply modelling based approach for estimation emissions in different conditions over seasons, and in some extent also interannually. Together, the measures included in this project monitoring are needed to enable improved forest soil carbon and other GHG (N2O and CH4) spatial upscaling in country specific and regional assessments. Data from forest lands in this project form the largest potential upgrade in EFs not only in the number of sites included in EF categories (from 8-13 sites in IPCC (2014) to 29 sites in Life OrgBalt, Table 2) and completeness of data collected. Due to long rotation time of trees and different management conditions, data collected in 2 years of monitoring can only provide a good starting point for further research on management impacts on GHG emissions over (usually) decades long life of tree generation.

In grasslands, Life OrgBalt contributed by adding 10 new monitored sites in deep drained (WL >30 cm below the soil surface) conditions (39 – 47 sites in IPCC, 2014), and 2 new sites in shallow drained conditions (13 – 16 sites in IPCC, 2014), see Table 7. Life OrgBalt provided 8 new cropland sites in the temperate climate zone, which is a major contribution considering that in IPCC (2014) data on Tier 1 EFs included data from 36 – 39 sites located in boreal and temperate zones. In grassland and cropland reporting Life OrgBalt project data considers also sites characterized by low organic carbon content (C organic max. 12% at 0 – 20 cm soil layer), which can be resulted from thin organic matter layer and management, e.g. tilling that reaches mineral soil and/or mineral substrates added in the past (Table 6). Croplands in monitoring were cultivated by winter wheat (4 sites), maize (3 sites), or beans (1 site) during the monitoring, which enhance the coverage and representation of different cropland systems. Harmonized environment data collection on WL and temperature provides possibilities to apply modelling based approach for estimation emissions in different conditions over seasons and assess production phase (annuals and perennial grasses produced) soil C balance and GHG balances (CH_4 and N_2O) based on the 12 grassland sites and 8 cropland sites included in the monitoring. This contributes to a more robust understanding of emissions and C-cycle in the two agriculture systems and facilitates the development of higher-tier emission factors.

For Estonia, immediate key benefits from the data collated in Life OrgBalt project include collectively large data pool from climatically comparable area (Estonia, Latvia, Lithuania) in comparison to previous years when supplementary data was modified from studies made in Sweden. In Latvia, data pool on soil C balance has increased markedly in this project and adds on the previous country specific data. For Lithuania, Life OrgBalt project launched country specific data collection altogether.

7 CONCLUSIONS

There have been challenges in developing dynamic EFs, particularly for CO_2 in temperate regions, due to a scarcity of applicable data, particularly environmental data. To address this, Life OrgBalt adopted ambitious efforts to collect a wide range of site-specific gaseous and mass-based environment data, enabling more robust dynamic modelling on soil carbon dynamics and gas emissions at Tier 2 and Tier 3 levels following the IPCC guidance. This marks a significant advancement over the simplistic Tier 1 EFs and categories available in IPCC reporting.

The main improvements in EFs provided in Life OrgBalt stem from two crucial factors: the implementation of harmonized research methods and the characteristics of the monitoring sites. Life OrgBalt offers a clear advantage over the previous IPCC (2014) data used in Tier 1 EFs by ensuring consistent methods across multiple sites. The previous dataset lacked uniformity due to data from various studies and projects, leading to inconsistencies in data collection and reporting parameters. In contrast, Life OrgBalt emphasizes site-specific data collection and aims to bridge the gaps in environment paprameters monitoring.

By adding new monitored sites across different conditions and types of land use, Life OrgBalt provides a more comprehensive understanding of GHG emissions and soil carbon dynamics in forestland, cropland and grassland ecosystems. Furthermore, the project's harmonized environment data collection allows for modelling-based estimations under varying conditions, further improving the accuracy and applicability of higher Tier EFs in the region.

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