Environmental and Climate Technologies
2024, vol. 28, no. 1, pp. 527–539
https://doi.org/10.2478/rtuect-2024-0041
https://content.sciendo.com

Which EU Country Contributes Most to GHG Emissions in the LULUCF Sector Relative to Population and GDP?

Valerija KOSTEVICA[1*], Dagnija BLUMBERGA[2]

[1,2]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia*

Received 30.04.2024; accepted 12.09.2024

***Abstract* – In pursuit of climate neutrality, EU nations must collectively address the problem of greenhouse gas (GHG) emissions and air pollutants, which necessitates equitable economic strategies. However, the heterogeneous economic, social, and geographical profiles present hurdles in enacting a cohesive policy framework and realizing shared goals. Land use, land use change and forestry (LULUCF) sector play a crucial role in achieving the EU 2050 climate neutrality goal, as LULUCF is both a source and a sink for GHG emissions, it provides products like wood and biomass that help to reduce emissions in other sectors. This paper aims to compare GHG emissions of different EU countries by using targeted indicators related to per capita and to GDP per capita to enhance the analysis. The results reveal substantial differences in emissions in relation to population and GDP per capita between selected EU countries, even among countries with similar profiles, such as Estonia, Latvia, Lithuania. Notably, countries with lower GDP per capita and smaller population tend to have higher emission values, suggesting less efficiency in managing land use and forestry. The study highlights the need for multi-year data analysis to identify trends in emissions and removals within the LULUCF sector, considering the impacts of natural disasters and economic activities such as bark beetle outbreak or wood harvesting.**

***Keywords* – Air pollutants; GHG; land use; land-use change and forestry; national inventory reports.**

1. Introduction

In November 2018, the European Commission unveiled an ambitious long-term strategy aimed at mitigating GHG emissions, by investing in viable technological solutions and by synchronizing efforts in essential areas such as industrial policy, finance, and research to lead as the first climate-neutral continent by 2050 [1]. Achieving this goal requires significant reductions in emissions across all EU countries, coupled with enhanced efforts to capture GHG from the atmosphere [2]. In comparison to the National Determined Contribution goal established in 1990, which aimed for a 40 % reduction in emissions by 2030, the EU raised its target to 55 % in 2023. This adjustment reflects the recognition that EU policy frameworks alone may not be sufficient to achieve the 2050 objectives. Consequently, the less action the EU takes in the coming decade, the more rapid emissions reductions will be required after 2030 [3].

* Corresponding author.
E-mail address: valerija.kostevica@rtu.lv

In pursuit of climate neutrality, EU nations must collectively address the GHG emissions and air pollutants problem, necessitating equitable economic strategies [4]. Nonetheless, the heterogeneous economic, social, and geographical profiles present hurdles in enacting a cohesive policy framework and realizing shared goals [5], [6]. Ascertaining comparability necessitates the standardization of reporting protocols, enhancement of data precision, and alignment of emission calculation methodologies across EU member states [7].

To systematize the GHG emissions accounting, EU member states annually prepare national emission inventory reports (NIR) for United Nations Framework Convention on Climate Change (UNFCCC). This report includes detailed information about GHG and air pollutant emissions. They help monitor emission trends, inform policy decisions, fulfil international reporting obligations, and promote transparency and accountability in addressing climate change [8]. To ensure consistency in these reports Intergovernmental Panel on Climate Change (IPCC) provides standardized guidance and methodologies for estimating GHG at three level of detail, from default to most detailed method (Tier 1, Tier 2 or Tier 3). Based on available information and research carried by country, the method for emission calculation for different activity can be chosen [9].

Precise and consistently formatted emission inventories are crucial for understanding a country's emission patterns and assessing its environmental responsibilities [10]. Knowing only direct emissions from each country an unfair distribution of responsibilities may occur if countries with different economic, social and geographical profiles are compared [11]. To address this issue Brodny and Tutak [7] suggested to consider three additional factors to analyse GHG emissions – a comparison between the volume of emissions to the number of inhabitants of a given country, the value of gross domestic product (GDP) and surface area.

All countries, when reporting emissions in NIR emissions, divide emissions by economic sectors – energy, industrial processes and product use (IPPU), agriculture, land use, land-use change and forestry (LULUCF), waste and other [9]. It was decided to analyse emissions within the framework of one sector – LULUCF, considering that national inventory reports (NIR) contain information on calculated emissions from 6 sectors and are very broad, it would be difficult to analyse each sector separately within the framework of the study, while analysing all the emissions together would provide overly generalized information. The LULUCF sector was chosen, because analysing it is important for understanding its significant role in GHG emissions and carbon sequestration [12], [13]. Unlike other sectors, LULUCF encompasses both carbon dioxide (CO_2) emissions and removals, due to its diverse land management practices [14]. This sector includes land use categories such as croplands, grasslands, wetlands, forests, and settlements, each influencing carbon dynamics differently [15]. For instance, some land use types act as carbon sinks, sequestering CO_2 from the atmosphere, while others, like deforestation or peatland drainage, serve as sources of CO_2 emissions [16]. The importance of focusing on LULUCF arises from its substantial potential for mitigating climate change [17]. Effective management of land use can lead to significant reductions in GHG emissions and enhanced carbon sequestration. This is particularly relevant in the context of the EU's goal of achieving climate neutrality by 2050 [1], [18].

This study aims to analyse GHG emissions in the LULUCF sector across different EU countries using relevant indices to evaluate how effectively each country manages land use and forestry in relation to economic output and population. By focusing on key GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The findings contribute to a deeper understanding of how various countries manage land use and forestry, which can inform future research and discussions on enhancing sustainability and emission reduction strategies within the EU.

2. METHODOLOGY AND DATA

Considering the framework of this study, it was decided to select clusters of countries instead of analysing all European countries. The cluster for this study was chosen based on Brodny and Tutak research [7], and consists of countries that had the largest amount of emissions into the atmosphere, considering the population and surface area in 2017 – Czechia, Denmark, Estonia, Ireland, Latvia, Lithuania, Luxembourg, Poland, and Finland.

The chosen countries are different in surface area, population and economic growth, it was decided to use indicators that would represent the emissions emitted by each country in relation to the country's population and GDP, which in turn will make it possible to compare different countries between each other [19]–[21]. It is possible to apply different indicators, such as emissions per GDP, emissions per country surface land forest area, emissions per population etc. In this study countries are compared using such indices as emissions per capita and emissions per GDP per capita (tCO_2 per capita, tCH_4 per capita, tN_2O per capita, tCO_2 per GDP, tCH_4 per GDP, tN_2O per GDP). Emissions per capita index was chosen because it measures the average individual contribution to a country's total GHG emissions. It can also help to identify disparities between countries, highlighting those with higher individual impacts [20], [22]. As for emissions per GDP per capita, this index integrates economic efficiency with individual prosperity, providing a comprehensive perspective on a country's sustainability and enables equitable international comparisons by considering economic output and population, informing policies for efficient, low-carbon development [23]–[25]. An additional index was introduced – CO_2 emissions per forest land surface area (tCO_2/ha), due to that largest removals of CO_2 almost in all countries occur from the source – forest land.

Emissions/removals per capita are calculated by dividing emissions of a given country (t) in LULUCF sector in 2021 by population in a given country in 2021 (capita). Emissions/removals per GDP per capita are calculated by dividing emissions of a given country (t) in LULUCF sector in 2021 by GDP per capita in a given country in 2021 (EUR million). CO_2 emissions/removals per forest land surface area are calculated by dividing emissions/removals of a given country (t) from forest land in 2021 by forest land surface area in a given country in 2021 (ha) [26]. Indicators were calculated for CO_2, CH_4 and N_2O. Data for emissions were taken from countries NIR 2021 [27] and information about countries population were taken from System of National accounts [28] and GDP per capita from Eurostat [29]. Index values for CO_2 it should be noted that a negative value will be considered a better result because emissions is not only emitted but also sequestered, for CH_4 and N_2O best value is considered 0, for all GHG worst value is considered positive number. The step-by-step methodology for the overall study is presented in Fig. 1.

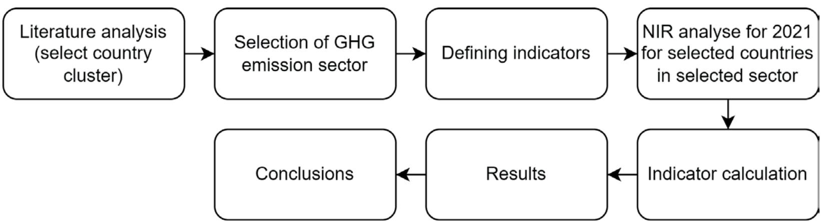

Fig. 1. Methodology chart.

TABLE 1. NET EMISSIONS AND REMOVALS IN THE LULUCF SECTOR BY DIFFERENT GASES

	CO_2 emissions/removals (t)*	**CH_4 (t)**	**N_2O (t)**
Latvia	956 294.48	31 010.86	2150.392
Lithuania	–6 238 066	3.120 406	555.0388
Estonia	2 535 165.2	2689.672	1026.786
Czechia	8 342 100	310	30
Poland	–21 844 518	275.2893	6573.911
Denmark	2 089 060	10380	150
Ireland	6 278 983.4	22 367.91	1633.835
Finland	–2 148 639.4	30 399.56	6732.297
Luxemburg	–613 855.88	Not occurring	32.10

*Positive figures indicate emissions, negative removals

Table 1 shows that Luxemburg NIR has removal CO_2 –613.86 kt, and the largest CO_2 emissions is from settlements (42.86 kt), cropland (29.88 kt), wetlands (2.23 kt) and other land (0.17 kt). Looking further, compared to other countries, Luxemburg does not have significant emissions in this sector, except N_2O (0.03 kt). Considering this information, in further analysis this country will not be looked at [30].

3. GREENHOUSE GAS EMISSION AND AIR POLLUTANT COMPARISON IN SELECTED COUNTRIES

3.1. Comparison of CO_2 Emissions and Sinks from LULUCF Sector per Capita and per GDP by Selected Countries

From Table 1, Poland has largest removals of CO_2 (–21 844 518 t) and Czechia has largest CO_2 emissions (8 342 100 t). However, from Fig. 1 it can be seen that introducing indicator tCO_2 per capita, Lithuania shows better results than Poland, which means that in Lithuania there are larger amount of removed CO_2 emissions per person; Poland runs second. Estonia has largest emission amount per capita from selected countries, although when looking in direct emission amount in this sector (Table 1), Estonia is ranged as only the third largest polluter; second is Ireland. Czechia has largest net amount of CO_2 emissions but considering emissions per capita it has better results than Estonia and Ireland, who have lower net emissions, it follows that the Czech Republic produces less emissions and have larger emission sink per person than Ireland or Estonia.

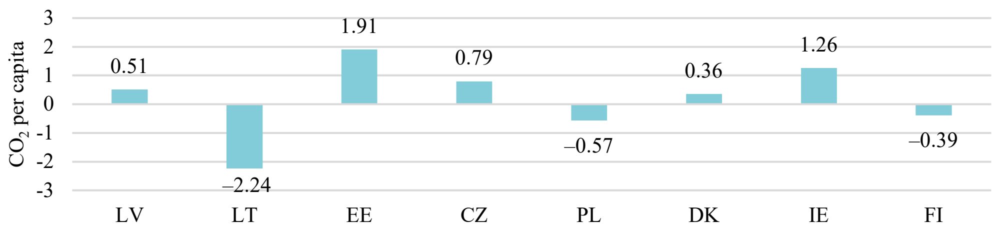

Fig. 2. CO_2 emissions/removals from LULUCF sector in 2021 per population (tCO_2 /capita).

Latvia, Estonia and Lithuania have similar country profile (size, GDP per capita (12 870 (LV), 16 350 (EE), 14 870 (LT) EUR [29])), nevertheless Lithuania has better indicator values in both cases, it can be explained by fact that Latvia and Estonia have smaller population (1.87 (LV), 1.31 (EE), 2.78 (LT) million in 2021 [28]). The difference can be explained by capacity of carbon sequestration in biomass and roundwood removals. For instance, Estonia reports that managed forest in country (which is the main source of carbon sink) are predominantly mature, with about 39 % of stands over 60 years old, as well area with early development stages have been increased in last decade [31], [32], all this lead do decline in carbon sequestration. In 2020 and also in 2021 Latvia experienced increase in forest harvesting rate and increase of mortality and reduction of increment of living biomass in forest land (this tendency was observed also in 2015 and 2014) [33], [34].

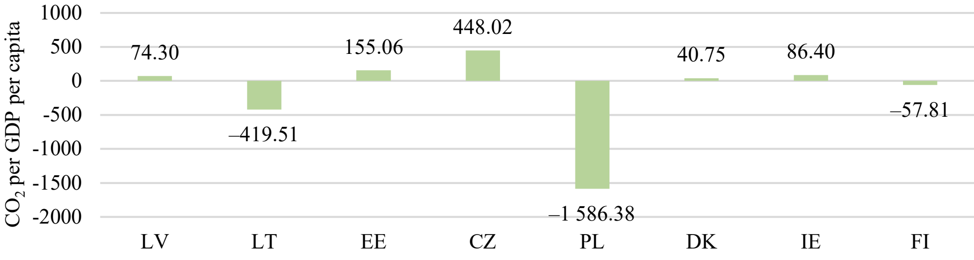

Fig. 3. CO_2 emissions/removals from LULUCF sector in 2021 per GDP per capita (tCO_2/EUR).

When indicator tCO_2 per GDP per capita is applied, Poland has the best score, but Czechia has the worst score, from all selected countries (see Fig. 3). This means that Poland is managing land and forest resources more efficiently than other selected countries, contributing to low emissions relative to its economic output and vice versa with the Czechia.

As forest is one of the main carbon sink in EU countries (from selected countries in 2021 Latvia, Lithuania, Poland, Finland, Denmark, Ireland – largest CO_2 sinks occur from source forest land, only in Estonia and Czechia it is from harvested wood production), and have great potential to mitigate climate change by increasing carbon sequestration by increasing tree growth, and reducing harvesting [35]. Thus, to analyse CO_2 emissions from LULUCF sector an additional indicator was applied for CO_2 emissions – CO_2 per forest land surface area (tCO_2/ha).

From Fig. 4 can be seen that Denmark has the best results in CO_2 removals/emissions from forest land, previously (see Fig. 2 and Fig. 3) showed positive indicator values. Finland – a country with the largest forest land from selected countries, is only the second by CO_2 removals (see Table 1), although Poland have less than two times forest land area, but the indicator (tCO_2/ha) shows that Poland reports higher amount of removals in comparison to forest surface land area than Finland. Comparing Net CO_2 removals from forest lands in Finland in 2021 with 2020 values, the amount has decreased twice (in 2020–22 938.51 kt CO_2 [36], in 2021–10 774 kt CO_2 [37]), that can be explained by the fact that between 2020 and 2021 roundwood removal in Finland in volume increased by 11 % [36]. Although Poland also reports negative change in CO_2 removals dynamic, which assumingly is caused by natural causes, like droughts since 2014, which reduced capacity for wood grown leading to loss of sequestrated carbon [38], or hurricane winds in 2017, which caused tree falls therefore reducing carbon sink [39], and significant changes in the dynamics of dead wood decomposition [40], nevertheless forest land remains the main CO_2 sink category in the country.

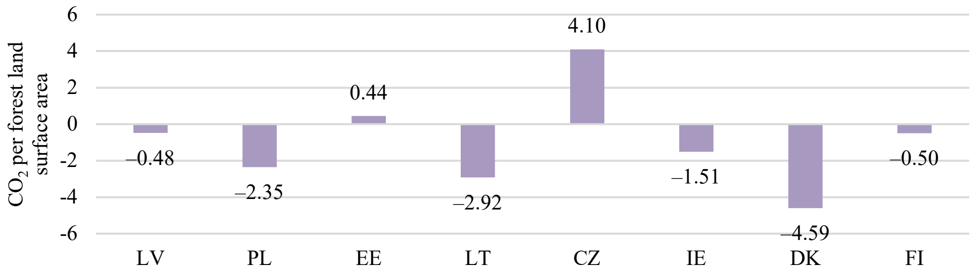

Fig. 4. Total emissions/removals from forest land source in LULUCF sector in 2021 (kt) in relation to total forest land area by countries in 2021 (tCO_2/ha).

From NIR reports, it can be seen that Czechia (2678.8 kha [41]) and Estonia (2447.41 kha [31]) have a similar forest land surface area with Lithuania (2230.66 kha [42]), nevertheless these two countries report more emissions than removals from this source. Czechia reports fourth year in row (from 2018) contribution of CO_2 emissions from LULUCF sector, such trend is explainable due to the fact that Czechia had exceptionally high sanitation harvest following an unprecedented extreme weather (drought), as well bark-beetle outbreak in forests have been registered since 2015 [41], these outbreaks can lead lower plant productivity by causing tree mortality, shifting carbon from living trees to dead organic material [43]. In Estonia 39 % of forest is considered as mature (stands over 60 years old), leading to not so rapid carbon sequestration, as it can be in young forests [44].

Although Lithuania has less forest land than Latvia (34.2 % vs. 50.6 % of the total surface land area), it reports four-time greater amount of CO_2 removals from forest land use. Previous reports indicate that net CO_2 removals from forest land in Latvia have declined by over three times since 2019 [34]. This decrease is attributed to increased forest harvesting, higher mortality rates, and reduced growth of living biomass in forested areas [34].

Indicator values from Fig. 4 indicates that Latvia, Denmark and Ireland have reported CO_2 removals from forest land, but nevertheless these removals are not enough to compensate CO_2 emissions from whole LULUCF sector (see Fig. 2) as it is in Poland. In case of Ireland and Denmark that can be explained by relatively small forest land surface area 781 kha and 645 kha [45], [46], where Latvia in last years showed overall decrease in emission removals from forest land due to increased harvesting rate.

From selected countries from all indicators best values are shown from Poland and Lithuania. This means these two countries manage land and forest resources more efficiently regarding population and economic output compared to other countries. Worst values for all three indicators come from Czechia, Estonia and Ireland. The high emissions could be due to inefficient practices or other factors like increased deforestation. Additionally, these countries might be facing natural challenges, such as pest outbreaks or extreme weather, that reduce their forests' capacity to act as carbon sinks.

3.2. Comparison of CH_4 Emissions from LULUCF Sector per Capita and per GDP by Selected Countries

Comparing countries by indicator t CH_4 per capita, we can see that from selected countries Latvia reports highest methane values considering the population (see Fig. 5), as well as the highest total methane values (see Table 1).

Comparing Latvia to neighbouring countries (similar in land surface size), it can be seen that it reports much higher methane values. For example, Lithuania reports a thousand times smaller volume of emissions than Latvia and Estonia report ten times smaller volume than Latvia in 2021 in LULUCF sector. This difference is likely due to method used (Tier1/2). For instance, Lithuania applies Tier 1 method to estimate non-CO_2 emissions from peatlands and assumes that CH_4 emissions from drained peatlands are insignificant according to IPCC guidelines 2006 [9], [42], while Latvia and Estonia calculate emissions from peat extractions and applies Tier 2 method with countries specific EF and default EF from IPCC wetland supplement [47].

From Latvia NIR biggest source of methane emissions comes from drained and rewetted organic soils and results in 30.33 kt, other emissions come from biomass burning 0.68 kt. In Estonia is similar tendencies as in Latvia, CH_4 emissions in LULUCF sector are from drained and rewetted organic soils 2.68 kt and <0.01 kt from biomass burning [34]. Estonia is not estimating methane emissions from rewetted organic soils [31], but Lithuania report shows that CH_4 from rewetting organic soils is not occurring [42], so this can be considering as one of the reasons why Latvia had much higher CH_4 emissions than neighbouring countries [34].

Knowing from 2021 NIR that total area of drained organic soil from wetland land use category, Latvia had 31.62 kha [34] area of peat extraction lands, Lithuania 13.41 kha [42] and Estonia 25.51 kha [31]. Interesting that Latvia reports 127 times higher value for CH_4 emissions (518 t) from this source than Estonia (4 t), considering similar peat extraction land area, this difference can be explained by that both countries use Tier 2 method and uses country specific EF (Latvia 10.83 kg CH_4 ha^{-1} yr^{-1}, Estonia 3.96 kg CH_4 ha^{-1} yr^{-1}).

If comparing Latvia to other selected countries Latvia had largest area of rewetted soil for which methane emissions were calculated (49.68 ha), second largest is for Denmark (21.99 ha), other countries had much less or non [34], [45]. In Latvia in forest land section rewetting occurs usually due to wearing of drainage system and is approved during the site visit (in 2021 it was 40.64 ha), both countries area applying EF from IPCC guidelines 288 kgCH_4/ha for forest land and wetland organic soils [34], [45].

If looking into Poland it has second lowest CH_4 emissions level from selected countries. It’s interesting, considering countries surface area and large economic activity. From NIR all CH_4 emissions comes from biomass burning (wildfires) and results in 0.28 kt (in 2021) (see Table 1). From NIR in 2021 Poland had larger forest fire area than Latvia (841.08 ha comparing to 743.7 ha), but in total Latvia reports higher CH_4 emissions 0.37 kt [34], compared to Poland 0.21 kt, that can be explained by fact that Latvia uses IPCC due to higher EF 6.1 g kg^{-1} d.m. burned, (Poland EF 2.3 g kg^{-1} d.m. burned) [34], [40].

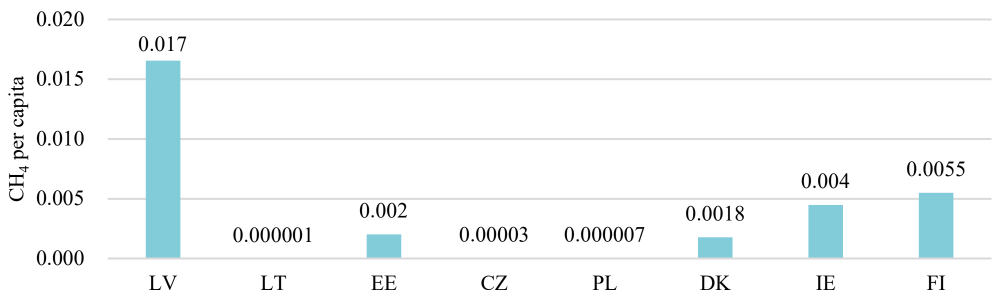

Fig. 5. CH_4 emissions from LULUCF sector in 2021 per population (tCH_4 /capita).

Fig. 6 shows t CH_4 per GDP per capita and can be seen similar trend as in the previous figure (see Fig. 4) – Latvia has higher indicator much higher values than other countries. From Table 1 can be seen that Latvia have similar CH_4 emissions to Finland, nevertheless if comparing these countries considering these two indicators Latvia performs worse than Finland. That can be explained by fact that Finland has three times bigger population and more than half higher GDP per capita values. Only difference in trend between emissions per GDP per capita and emissions per capita is that Czechia have lower indicator value than Poland in relation to countries GDP per capita, since both countries have similar CH_4 emissions. That can be explained with that Czechia had higher GDP per capita value that Poland in 2021. Comparing all countries GDP per capita Poland had lowest, nevertheless but reported emissions are so low, that GDP doesn't impact much Poland indicators values.

If comparing used EF in countries by CH_4 biomass burning Estonia and Latvia have highest EF 6.1 g kg^{-1} d.m. burned, comparing to Eastern Europe countries from this study Lithuania and Finland 4.7 [36], [42], Poland 2.3 [40] (g kg^{-1} d.m. burned). This can also be one of the reasons why Latvia reports significantly higher methane emission value than other countries per capita or GDP per capita.

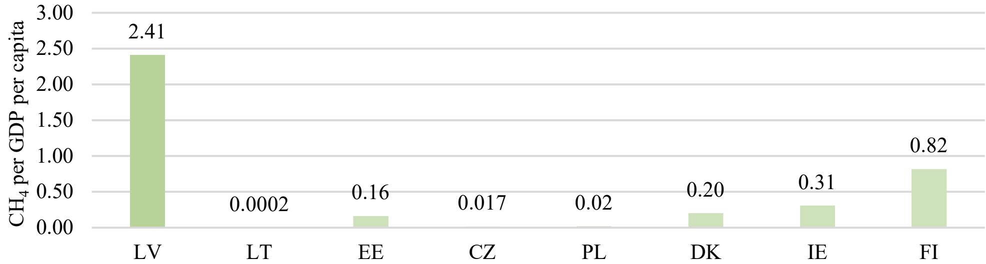

Fig. 6. CH_4 emissions from LULUCF sector in 2021 per GDP per capita (tCH_4/EUR).

Just like with CO_2 emissions, Lithuania and Poland have the best values for both indicators, making them the most efficient countries in managing CH_4 emissions in the LULUCF sector. Worst results are from Latvia and Finland, and this can be explained by assumptions made in countries during the calculation of emissions.

3.3. Comparison of N_2O Emissions from LULUCF Sector per Capita and per GDP by Selected Countries

When calculating the indicator N_2O per capita, due to low N_2O emission amount, compared to CO_2 and CH_4, it was decided for calculation use emission values in kiloton (kt) and population in millions (m).

From Table 1 can be seen that the lowest net N_2O emissions has been observed in Czechia and Denmark. Czechia reports N_2O from forest land and cropland land source, but Denmark from forest land, cropland and settlements (minor values also in wetland and grass land source <0.001 kt) [41], [45]. Comparing countries by emissions per capita Czechia and Denmark still show best indicator results, but Latvia and Finland indicate highest values (ktN_2O/capita million). Interesting that from Table 1 Poland has second largest value of N_2O emissions after Finland, but if considering population, it performs better than Estonia or Latvia, who have much lower population (see Fig. 7), that means that Poland emits less N_2O per person from land use and forestry activities.

When comparing countries with similar populations in 2021 – Finland, Denmark, and Ireland – there are notable differences in N_2O emissions. Finland reports the highest emissions among these countries (see Table 1), this is primarily due to its extensive area of drained organic soils from forest lands, which is main N_2O source in LULUCF sector in Finland [36]. Finland has a significantly larger forest land area (21645 kha) compared to Denmark (781 kha [45]) and Ireland (645 kha [46]). Although Finland for organic soils applies country specific EF (0.33 N_2O-N ha^{-1} yr^{-1}), which is smaller than IPCC guidelines provided EF 2.8 N_2O-N ha^{-1} yr^{-1} (used by Denmark and Ireland), due larger forest area N_2O emissions results in higher values comparing to other countries.

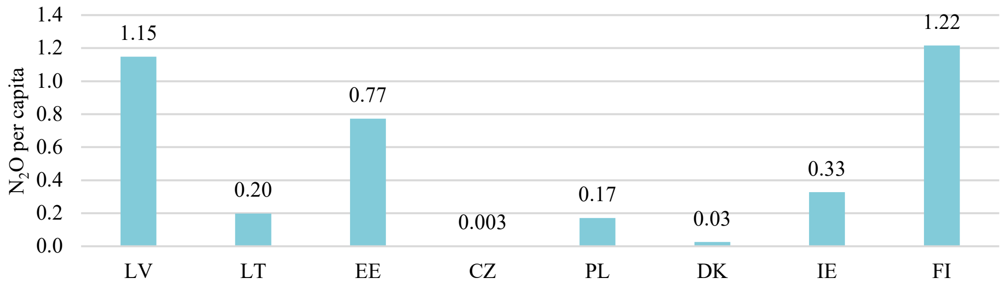

Fig. 7. N_2O emissions from LULUCF sector in 2021 per capita (ktN_2O/capita).

Looking at Latvia (see Table 1), it reports much higher N_2O emissions value than similar countries (Estonia and Lithuania). Main source of N_2O emissions in Latvia and Estonia are from drained organic forest land soil, but in Lithuania – from grassland converted to cropland. When indicator ktN_2O/capita is applied for Estonia, it shows third highest indicator value, which means, that Estonia pollutes more emissions per capita than other countries, for example Ireland, with a slightly higher value of N_2O emissions (see Table 1), but indicator is more than twice lower, due to larger population. In both countries largest pollution of N_2O in LULUCF were reported form drained organic soils from forest lands, Estonia reported smaller drained organic soil from forest land area than Ireland, but still had higher emission value, that can be explained by EF which was used for calculation, for nutrient rich organic soil Ireland applied 2.8 N_2O-N ha^{-1} yr^{-1}, but Estonia 3.2 N_2O-N ha^{-1} yr^{-1} (both values are from IPCC Wetlands supplement 2013 [47]). Comparing Estonia with Latvia, who use same EF as Denmark, only Latvia reports higher value of drained organic soil from forest land 379.27 kha, (Estonia 288.03 kha), resulting in higher N_2O value. From all three Baltic states Lithuania reports lowest amount of N_2O, that can be explained by smallest area of drained organic soil from forest land reported (153.92 kha [42]), as well Lithuania uses lower EF 0.6 N_2O-N ha^{-1} yr^{-1} from the IPCC 2006 guidelines, where Latvia and Estonia for nutrient rich forest soils uses IPCC Wetlands supplement 2013 provided EF.

From Fig. 8 it can be seen that Poland has the highest N_2O emissions per GDP per capita in the LULUCF sector compared to other countries, therefore indicating that Poland generates significant N_2O emissions relative to its economic output from land use and forestry activities. Comparing with previous indicator (see Fig. 7) Poland had third best indicator value in relation to capita. That can be explained by that Poland had the largest population and one of the lowest GDP per capita from selected countries leading to lower indicator values regarding GDP per capita. In Poland biggest amount of N_2O emissions comes from source – land converted to settlements (422.52 kha), which means that land forest land is cleared for infrastructure construction (roads, railways etc) [40].

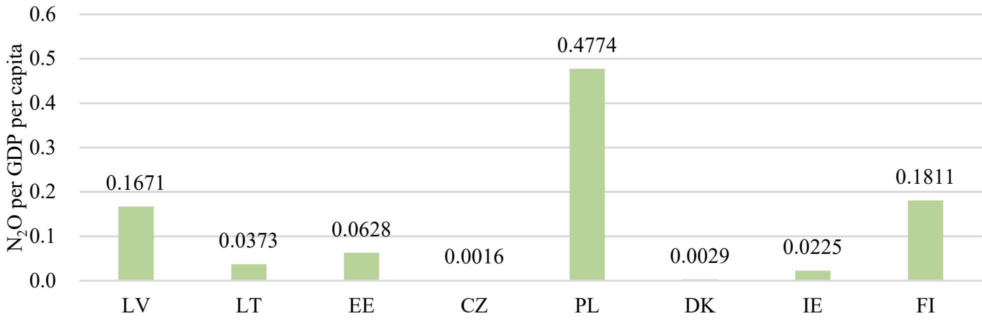

Fig. 8. N_2O emissions from LULUCF sector in 2021 per GDP per capita (tN_2O/EUR).

When analysing emissions per capita Ireland had higher indicator value that Lithuania (see Fig. 7), but when indicator emissions per GDP per capita were applied Lithuania had twice higher value. From previous mentioned Ireland main source of N_2O emissions was drainage of organic soils in forest land, but in Lithuania land use change (grassland to cropland). Considering that Ireland has twice bigger population in 2021 – and three-times higher amount emitted N_2O, it had higher indicator value regarding populations, but regarding GDP per capita indicator values are much lower due to higher GDP per capita value [42]. Analysing Irelands N_2O emissions, can be seen that indicator N_2O per GDP per capita can be relatively favourable, indicating efficient management of N_2O emissions in relation to its economic output. However, N_2O emissions per capita are higher, suggesting that despite economic efficiency, the country experiences significant net N_2O emissions from land use and forestry activities. In the case of Lithuania both indicators are stable, that mean that they remain in the same order compared to other countries, thus indicating that country manages emissions efficiently relative to it is economic output and population.

Compared to CH_4 and CO_2 emission indicator values, for N_2O most efficient countries are Denmark and Czechia, due to initial low N_2O emission amount. Highest indicator values are from Latvia, Finland, Estonia and Poland, where Poland and Finland have highest net N_2O emissions, and Poland has the worst results in relation to economic output, but Finland to population.

4. Conclusion

This study aimed to analyse countries with different profiles applying specific indicators for a comprehensive assessment. During the analysis, it was observed that significant differences exist even between countries with similar GDP, population, and land surface area, such as Latvia, Estonia, and Lithuania. Although the Baltic states share similar political and economic backgrounds, they perform differently regarding GHG emissions from the LULUCF sector. Latvia had highest contribution to CH_4 from selected countries, while Estonia led in CO_2 emissions within the Baltic. Lithuania, on the other hand, had the largest CO_2 sink in the Baltics and the second largest among all the countries analysed.

These differences can be attributed to the approaches used by each country (Tier 1/2/3) to calculate emissions. Based on IPCC guidelines, countries can use predefined EF that can vary depending on climate and soil conditions or country-specific EFs calculated through research. Additionally, natural disasters, such as wildfires or droughts, can cause variations in emissions, as countries with similar profiles do not necessarily experience identical environmental events. Therefore, even with similar country profiles and EFs, emission levels can differ. To account for these variables, it is advisable to conduct analyses over a larger period (5–10 years), allowing for the smoothing of indicators in response to natural disasters or other anomalies.

Fig. 4 shows that almost all selected countries, except Estonia and Czechia, contribute to CO_2 emission removal from forest land use. Nevertheless, in Latvia, Denmark, and Ireland, this sink cannot compensate for the CO_2 emitted from the entire LULUCF sector. When comparing countries based on land surface area, Latvia is much smaller than Poland and has a smaller forested area, nevertheless, reports much higher CH_4 values (see Fig. 5 and Fig. 6). This discrepancy can be explained by the fact that Poland does not calculate emissions from draining and rewetting organic soils or other management of organic soils, marking these emissions as "Not applicable" in their NIR. In contrast, these are considered the main sources of CH_4 emissions in Latvia (from forest land). Additionally, countries like Czechia or Lithuania mark some activities as "Not occurring" or "Not estimated." For example, Lithuania's 2021 NIR states that due to a lack of data and sufficient knowledge to provide default equations for Tier 1 for non-CO_2 GHG emissions from drained organic soils, only N_2O emissions are accounted.

The study has shown that a country with large population, such as Poland, shows better values even if it emits much more than other countries, meaning that these countries are more efficient in land use and forest management in relation to population (see Fig. 7). The same tendency shows if specific country has much higher GDP per capita value, for example, Ireland in relation to N_2O had better value than Poland with lower GDP per capita, making it more efficient in managing emissions from LULUCF from economic output. As well there is observed tendency where countries with lower GDP per capita value and lover population have higher indicator value, making them not so efficient in managing emissions in LULUCF sector compared to other selected countries, for example, Latvia and Estonia. Therefore, it is recommended that when analysing countries with significant differences in population or GDP, new indicators should be introduced to decrease the impact of these differences on the results. Additionally, analysing data over multiple years could reveal trends in emissions and removals within the LULUCF sector.

References

[1] European Commission. Press release. The Commission calls for a climate neutral Europe by 2050. 2018.

[2] Bäckstrand K. Towards a Climate-Neutral Union by 2050? The European Green Deal, Climate Law, and Green Recovery. *Routes to a Resilient European Union: Interdisciplinary European Studies*. Springer International Publishing, 2022:39–61. https://doi.org/10.1007/978-3-030-93165-0_3

[3] European commission. Communication from the commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions Stepping up Europe's 2030 climate ambition, 2020.

[4] Dupont *et al.* Three decades of EU climate policy: Racing toward climate neutrality? *Wiley Interdisciplinary Reviews* https://doi.org/10.1002/wcc.863

[5] Ylä-Anttila T., Gronow A., Stoddart M. C. J., Broadbent J., Schneider V., Tindall D. B. Climate change policy networks: Why and how to compare them across countries. *Energy Research & Social Science* 2018:45:258–265. https://doi.org/10.1016/j.erss.2018.06.020

[6] Li S. *et al.* The heterogeneous driving forces behind carbon emissions change in 30 selective emerging economies. *Patterns* 2023:4(7). https://doi.org/10.1016/j.patter.2023.100760

[7] Brodny J., Tutak M. The analysis of similarities between the European Union countries in terms of the level and structure of the emissions of selected gases and air pollutants into the atmosphere. *J Clean Production* 2021:279. https://doi.org/10.1016/j.jclepro.2020.123641

[8] Directive (EU) 2016/2284 of the European Parliament and of the Council – of 14 December 2016 – on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC, 2016.
[9] National Greenhouse Gas Inventories Programme. IPCC 2006 Guidelines for National Greenhouse Gas Inventories. 2006.
[10] Xiao L., Guan Y., Guo Y., Xue R., Li J., Shan Y. Emission accounting and drivers in 2004 EU accession countries. *Applied Energy* 2022:314. https://doi.org/10.1016/j.apenergy.2022.118964
[11] Bin Furkan H., Rakibul Hasan K. M., Uddin M. J. Greenhouse gas emission, GDP, tertiary education, and rule of law: A comparative study between high-income and lower-middle income countries. *Heliyon* 2023:9(6):e16265 https://doi.org/10.1016/j.heliyon.2023.e16265
[12] Ellison D., Lundbland M., Petersson H. Reforming the EU approach to LULUCF and the climate policy framework. *Environ Sci Policy* 2014:40:1–15. https://doi.org/10.1016/j.envsci.2014.03.004
[13] Korosuo A. *et al.* The role of forests in the EU climate policy: are we on the right track? *Carbon Balance Management* 2023:18(1). https://doi.org/10.1186/s13021-023-00234-0
[14] Tubiello F. N. *et al.* The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990–2012. *Glob Change Biology* 2015:21(7):2655–2660. https://doi.org/10.1111/gcb.12865
[15] Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU, 2018.
[16] Herold A., Gores S., Urrutia C. 2030 climate target plan: review of Land Use, Land Use Change and Forestry (LULUCF) Regulation – ENVI Workshop Proceedings, Publication for the committee on Environment, Public Health and Food Safety, Policy Department for Economic, Scientific and Quality of Life Policies, European Parliament, Luxembourg., 2021.
[17] Paquel K. *et al.* Analysis of LULUCF actions in EU Member States as reported under Art. 10 of the LULUCF Decision Final study, 2017.
[18] Kazanavičiūtė V., Dagiliūtė R. Impact of LULUCF accounting rules for climate change mitigation goals: winning or losing? *Journal of Environmental Engineering and Landscape Management* 2023:31(3):164–175. https://doi.org/10.3846/jeelm.2023.19466
[19] Calavera R., Alberto J. GDP per capita and greenhouse gas emissions in Europe. MPRA Paper 113512, 2022.
[20] Yang S., Wang X., Ge Z., Dong G., Ma M., Han X. Global Per Capita CO_2 Emission Trends. *Atmosphere (Basel)* 2023:14(12). https://doi.org/10.3390/atmos14121797
[21] Nowarski J. CO_2 Emissions per GDP. Asian Institute of Technology – Thailand, 2022. http://doi.org/10.5281/zenodo.7294873
[22] Yu S., Gao X., Ma C., Zhai L. Study on the concept of per capita cumulative emissions and allocation options. *Advances in Climate Change Research* 2011:2(2):79–85. https://doi.org/10.3724/SP.J.1248.2011.00079
[23] United Nations Statistics Division. Gross domestic product per capita Economic development Macroeconomic Performance Core indicator. [Online]. [Accessed 15.03.2024]. Available: https://www.un.org/esa/sustdev/natlinfo/indicators/methodology_sheets/econ_development/gdp_percapita.pdf
[24] Vernia J. T. How air pollution is related to gdp per capita of the oecd countries, 2023.
[25] Ahmad A., Wahyudi H., Lestari W. R. The Effect of GDP Per Capita, Population, and Income Inequality on CO_2 Emissions in Indonesia. *International Journal of Energy Economics and Policy* 2024:14(1):365–370. https://doi.org/10.32479/ijeep.15224
[26] Nowarski J. CO_2 Emission per GDP Forecast 2020–2100. Zenodo, 2022. http://doi.org/10.5281/zenodo.7264412
[27] UN Climate Change. National Inventory Submissions 2023. [Online]. [Accessed 27.03.2024]. Available: https://unfccc.int/ghg-inventories-annex-i-parties/2023
[28] United Nations Statistics Division. National Accounts - Analysis of Main Aggregates (AMA).
[29] Eurostat. [Online]. [Accessed 27.08.2024]. Available: https://ec.europa.eu/eurostat/databrowser/view/sdg_08_10/default/table?lang=en
[30] Bechet T. *et al.* Luxembourg's national inventory report 1990–2021, 2023.
[31] Kupri H.-L. *et al.* National inventory report HWP greenhouse gas emissions in Estonia 1990–2021, 2023.
[32] Forest Department of the Ministry of the Environment and Estonian Environment Agency. National Forestry Accounting Plan 2021–2025, 2019.
[33] Krumsteds L. L., Lazdins A., Butlers A., Ivanovs J. Recalculation of forest increment, mortality and harvest rate in Latvia according to updated land use data. *Rural Development* 2019:1:295–299. https://doi.org/10.15544/RD.2019.037
[34] Skrebele A. *et al.* Latvia National Inventory Report. Greenhouse Gas Emissions in Latvia from 1990 to 2021 in Common Reporting Format (CRF), 2023.
[35] Kilpeläinen A., Peltola H. Carbon Sequestration and Storage in European Forests. In: Hetemäki L., Kangas J., Peltola H. (eds) *Forest Bioeconomy and Climate Change. Managing Forest Ecosystems* 2022:42. Springer, Cham. https://doi.org/10.1007/978-3-030-99206-4_6
[36] Forsell P. *et al.* Finland's National Inventory Report, 2023.

[37] Forsell P. *et al.* Finland's National Inventory Report 1990–2020, 2022.
[38] Martínez-Sancho E., Treydte K., Lehmann M. M., Rigling A., Fonti P. Drought impacts on tree carbon sequestration and water use – evidence from intra-annual tree-ring characteristics. *New Phytologist* 2022:236(1):58–70. https://doi.org/10.1111/nph.18224
[39] Lindroth A. *et al.* Storms can cause Europe-wide reduction in forest carbon sink. *Global Change Biology* 2008:15:346–355. https://doi.org/10.1111/j.1365-2486.2008.01719.x
[40] Bebkiewicz K. *et al.* Poland's national inventory report greenhouse gas inventory for 1988–2021, 2023.
[41] Roskova Z. National Greenhouse Gas Inventory Report of the Czech Republic reported inventories 1990–2021, 2023.
[42] Konstantinavičiūtė I. *et al.* Lithuania's national inventory report 1990–2021, 2023.
[43] Ghimire B. *et al.* Large Carbon Release Legacy from Bark Beetle Outbreaks across Western United States. *Global Change Biology* 2015:21(8). https://doi.org/10.1111/gcb.12933
[44] Center for the Study of Carbon Dioxide and Global Change. Growth rates of old versus young forest trees, 2014. [Online]. [Accessed 27.08.2024]. Available: http://www.co2science.org/articles/V1/N2/B5.php
[45] Nielsen O.-K. *et al.* Denmark's National Inventory Report 1990–2021, 2023.
[46] Duffy P. *et al.* Ireland's National Inventory Report 2023. [Online]. Available: www.epa.ie
[47] Stocker T. F. *et al.* IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, vol. 1585. Cambridge: Cambridge University Press, 2013.