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Tracking unaccounted greenhouse gas emissions due to the war in Ukraine since 2022

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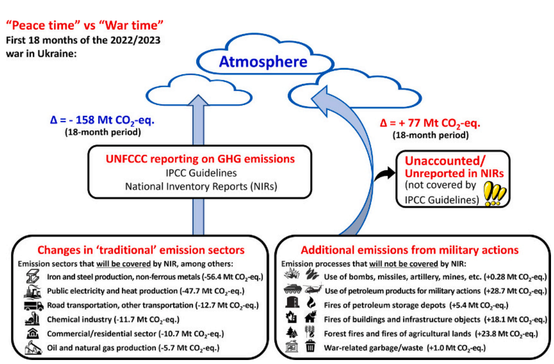
HIGHLIGHTS

- During a war GHG emissions due to military actions can increase significantly.
- The GHG emissions impact of conflict extends well beyond the time and place of physical conflict.
- The IPCC guidelines do not explicitly consider wartime GHG emission reporting.
- War-related GHG emissions for the first 18 months of the war in Ukraine were 77 $MtCO_2$-eq.
- The relative uncertainty of war-related emissions in Ukraine is estimated to be 22 % (95 % CI).

GRAPHICAL ABSTRACT



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ABSTRACT

Accounting and reporting of greenhouse gas (GHG) emissions are mandatory for Parties under the Paris Agreement. Emissions reporting is important for understanding the global carbon cycle and for addressing global

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climate change. However, in a period of open conflict or war, military emissions increase significantly and the accounting system is not currently designed to account adequately for this source. In this paper we analyze how, during the first 18 months of the 2022/2023 full-scale war in Ukraine, GHG national inventory reporting to the UNFCCC was affected. We estimated the decrease of emissions due to a reduction in traditional human activities. We identified major, war-related, emission processes from the territory of Ukraine not covered by current GHG inventory guidelines and that are not likely to be included in national inventory reports. If these emissions are included, they will likely be incorporated in a way that is not transparent with potentially high uncertainty. We analyze publicly available data and use expert judgment to estimate such emissions from (1) the use of bombs, missiles, barrel artillery, and mines; (2) the consumption of oil products for military operations; (3) fires at petroleum storage depots and refineries; (4) fires in buildings and infrastructure facilities; (5) fires on forest and agricultural lands; and (6) the decomposition of war-related garbage/waste. Our estimate of these war-related emissions of carbon dioxide, methane, and nitrous oxide for the first 18 months of the war in Ukraine is 77 $MtCO_2$-eq. with a relative uncertainty of +/−22 % (95 % confidence interval).

1. Introduction

Anthropogenic emissions of greenhouse gases (GHGs) cause global warming and other climate change effects (e.g., IPCC, 2018). Carbon dioxide (CO_2) emissions from the use of fossil fuels are particularly significant (IPCC, 2013; USGCRP, 2018), but GHG emissions also occur from industrial processes, waste management, agricultural activities and other types of land use change. International agreements like the Kyoto Protocol (UNFCCC, 1998) and the Paris Agreement (UNFCCC, 2015) have been adopted to create consistent emissions accounting for promoting and monitoring the reduction of emissions broadly.

The international community has developed a variety of methods and tools for GHG emission inventories in all categories of human activity (e.g., see IPCC, 2006; NAS, 2022; Roten et al., 2022; Maksyutov et al., 2022), and has implemented national reporting systems, in particular annual National Inventory Reports (NIRs) to the United Nations Framework Convention on Climate Change (UNFCCC, 2023; Boden et al., 2011). The main principle of these reports is that all emissions within a country's territory should be reported. In the analysis of emission processes, scientists, staff members of designated agencies, and other specialists generally operate with uncertain data and significant efforts have been invested in error analysis and in uncertainty assessment of national inventories (IPCC, 2001; Jonas et al., 2010, 2019; Ometto et al., 2014; Bun et al., 2007). The annual and country based NIRs do not include subnational emissions estimates, although a wide range of such approaches have been developed (e.g., see Janssens-Maenhout et al., 2019; Oda and Maksyutov, 2011; Oda et al., 2018; Liu et al., 2020; Bun et al., 2019; Gurney et al., 2020; Puliafito et al., 2021; Charkovska et al., 2019a, 2019b; Danylo et al., 2019), including widespread analysis of the errors and uncertainties of spatial data on emissions (Oda et al., 2019; Hogue et al., 2016; Kinakh et al., 2021). All of the aforementioned approaches for conducting aggregated and spatial emissions inventories and for undertaking uncertainty assessment are aimed at improving the understanding of emission processes and at developing mitigation strategies for global climate change.

The methods of analysis of emission processes from various categories of anthropogenic activity, and the international system of reporting on national GHG emission inventories, primarily provide details on human, peaceful activities (IPCC, 2006). The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) prescribe that "emissions from fuel delivered to the military in the country and delivered to the military of other countries that are not engaged in multilateral operations" be compiled under the heading "non-specified", category 1A5 in their tables (IPCC, 2006). This is to include all mobile and stationary sources but does not include international bunker fuels or "emissions from multilateral operations pursuant to the Charter of the United Nations" (IPCC, 2006), like the peaceful missions conducted by different international and regional organizations and alliances to maintain stability in many countries/territories around the world (Cruz, 2023). All emissions from bunker fuels (both civilian and peacetime military) are reported separately outside of national inventories. But the IEA notes that "The IEA has found that in practice most countries consider information on military consumption as confidential and therefore either combine it with other information or do not include it at all" (IEA, 2023, p. 47; see also e.g., Rajaeifar et al., 2022; Military Emissions, 2023; Parkinson and Cottrell, 2021; Michaelowa et al., 2022). Emissions from the military use of bunker fuel during peacetime are not included in NIRs but are used in the estimation of emissions from global bunker fuels. Due to the confidentiality of military information the reporting of GHG emissions from peacetime military activity (ensuring the functioning of aviation, fleet, military bases, training, etc.) is generally not transparent (Evergreen et al., 2022). Considering this non-transparency, in the case of a politically stable world (peacetime), the total emissions from military activity has been estimated by one source at possibly 6 % of the total emissions if we count both direct and indirect emissions and supply chain emissions back to ore mining (Parkinson, 2020).

In contrast to the above, the military activity during a war or open conflict, with associated invasions, occupation, and the need for defense, can change GHG emissions significantly, not only from explosions and the use of petroleum products, but also from the fires in buildings and forests, and on agricultural fields caused by military actions. These occur not only near the front line of conflict but also in the deep rear (we refer to these additional emissions as 'war-related emissions'). It should also be noted that wars and military conflicts can have a significant impact on the international monitoring and reporting systems of GHG emissions as the data collection and analysis systems are damaged. This involves primarily the collection and management of statistical data on emitting activities and can importantly affect the uncertainty of national and global emission inventories (NAS, 2022).

In this paper we analyze the impact of military conflict on the amount of GHG emissions and how this increases the uncertainty of emissions inventory data. In particular we show that emission processes have been significantly altered during the current war in Ukraine since February 24, 2022. On the one hand, in many sectors of human activity in Ukraine, emissions substantially decreased in 2022 (from public power and heat production, metallurgy, transport, the commercial and residential sectors, and others). At the same time, emissions related to refugees and internally displaced persons have increased, and even larger additional emissions are expected in the future because of the reconstruction of Ukraine. These changes in emissions will be reflected in future NIRs to the UNFCCC. Yet, on the other hand, during the current war, there are significant additional direct emissions. Due to their specifics these emissions will most likely not be taken into account in future NIRs and they are not covered by the current guidelines. This article focuses on the latest additional emissions caused by: missile launches and projectile firings and explosions; the use of petroleum products by military vehicles; fires at oil depots; fires in buildings and industrial infrastructure; fires in forests and on agricultural lands; and the destruction of wooden constructions. Even if a part of these emissions is somehow covered in future NIRs, the uncertainty of their estimates will be extremely high. Accounting for these additional emissions presents a challenge for scientists and policy makers; therefore, our results can serve as a starting point for the development of improved guidelines that would explicitly consider war-related emission processes. This paper is concerned with emissions that occurred during the first 18 months (February 24, 2022 – August 23, 2023) of the Russia/Ukraine war.

2. Materials and methods

2.1. Current and future changes to emissions caused by the war

In 2014, three Ukrainian provinces/oblasts were occupied by the Russian Federation: 1.) Autonomous Republic of Crimea and Sevastopol city (area 26,861 km^2); 2.) Donetsk oblast (8062 km^2); and 3.) Lugansk oblast (8377 km^2). The total area of these territories not controlled by Ukraine after 2014 was more than 43,300 km^2, which is greater than the area of the Netherlands (41,500 km^2). Moreover, the latter two regions are highly industrialized. Large power plants, metallurgical plants, coke plants, hard coal mines, etc. are located in these regions. For eight years, Ukraine did not have any statistics (activity data) from these territories, but Ukraine, as an Annex 1 country of the Kyoto Protocol, submitted NIRs to the UNFCCC every year (e.g., see the NIR for 2023 (UNFCCC, 2023)). Ukraine's NIRs cover the complete territory of the country including the occupied territories, but it is noted that estimates by Ukrainian experts were used for the occupied territories, i.e., for an industrialized territory the size of the Netherlands expert estimates have been used for all sectors and categories of human activity. Since 2016, Russia has also included the Crimea (but not Donetsk and Lugansk oblasts) in its NIRs (NIRR, 2023), which some scholars believe is an attempt to legitimize its claims of possession (Birnbaum, 2022).

On February 24, 2022, the Russian Federation (Russia) initiated a military invasion of Ukraine and more than 3000 settlements were occupied. Russia and Ukraine are both significant sources of GHG emissions and in 2020 were the 4th and 33rd largest emitting countries, respectively (Hefner et al., 2022; WPR, 2023). Both are Annex I countries under the Kyoto Protocol. The war has impacted traditional emissions in both countries and has had widespread impacts on economies, ecosystems, and GHG emissions globally - well beyond the area of conflict (de Klerk et al., 2022, 2023; Pereira et al., 2022a; Rawtani et al., 2022; Hassen and El Bilali, 2022).

The war-induced changes in emissions in the territory of Ukraine can be classified as follows:

A. *The current decrease of emissions caused by a reduction in the traditional human activities in many emission sectors, which will be reflected in Ukraine's future NIRs*. During the first year of the war a decline in economic activity and a corresponding decrease of emissions were recorded in major sectors, such as: public electricity and heat production (category 1A1a according to the IPCC (2006) reporting guidelines), manufacture of solid fuels (1A1c), iron and steel production (1A2a and 2C1), road transportation (1A3b), domestic aviation and navigation (1A3a,d), commercial/residential (1A4a,b), mineral industry (2A), and chemical industry (2B). We estimate that the reduction in total emissions from the territory of Ukraine during the first 18 months of the war was 157.7 $MtCO_2$-eq., (including 141.9 Mt CO_2, 457.2 kt CH_4, and 11.2 kt N_2O) below the 2021 level (see Appendix A for more details). This reduction, confirmed even by satellite monitoring data (Ialongo et al., 2023), was mainly due to a reduction of emissions from iron and steel production (36.0 % of the reduction), public electricity and heat production (30.4 % of the reduction), road transportation (8.1 %), the chemical industry (7.5 %), and commercial and residential sectors (6.9 %). It is important that this reduction of emissions should be reflected in Ukraine's future NIR, which will be submitted to the UNFCCC in 2024. But the uncertainty of these inventory data will be high due to the significant uncertainty of activity data from the temporarily occupied territories. This reduction of emissions in 2022–2023 did not occur as a result of appropriate mitigation efforts, but it was instead associated with colossal destruction and human suffering. Globally, a significant part of these "reduced" emissions has been transferred to other countries (e.g., via the footprint of refugees, the reallocation of iron and steel production, etc. (de Klerk et al., 2023)) and will be reflected in the NIRs of these countries.

B. *Current and future additional emissions from the territory of Ukraine caused by the war, which will be reflected in the next Ukraine NIRs*. Note that this includes both direct and indirect emissions from additional activities that will be covered by statistical reporting. The corresponding activity data and emissions will be reflected in future NIRs to the UNFCCC. Such additional direct and indirect emissions (during the war) include: emissions from the transportation of refugees and internally displaced persons (including the return of a partner, visits to Ukraine by displaced persons, etc.), emissions from the production of weapons, the transportation of weapons and equipment from foreign partners throughout the territory of Ukraine, emissions from rescue operations and the repair of infrastructure facilities, use of petroleum products to ensure the operation of electric generators during blackouts and the absence of a centralized electricity supply (see de Klerk et al. (2022, 2023) for details). After the end of the war many facilities will require area cleaning, de-mining, and reconstruction. This will include residential buildings and buildings related to health care, the social sector, education and science, culture, religion, sports, tourism, and retail. There will be a need for repair of civilian engineering infrastructure such as bridges and roads; the replacement of transport vehicles of different types; and the reconstruction and replacement of equipment in the energy sector, industry and business services, digital infrastructure, and utilities. These additional direct and indirect future emissions are estimated by de Klerk et al. (2022, 2023) to be 50.2 $MtCO_2$-eq.

C. *Current additional emissions which, due to their specificity, will likely not be covered by the next Ukraine NIRs*. Military operations during the war have resulted in certain types of substantial GHG emissions into the atmosphere that are likely to be incorrectly accounted for in national and global emissions inventories. This is due to the fact that the relevant military "human activity" is not covered by current emission-reporting guidelines (IPCC, 2006). A number of processes during the war are not covered by state statistical reporting and there are significant emissions caused by the Russian army within the territory of Ukraine. In this article we consider GHG emissions exclusively from the perspective of emissions from the territory of Ukraine that are unlikely to be included in national inventories and that will thus have an impact on the magnitude and uncertainty of national and global emissions estimates. Our study covers the whole of Ukraine, including the territories that are not occupied, the territories that were occupied in 2014 and 2022, as well as territories that were temporarily occupied but then liberated during the first 18 months of the war.

2.2. Methods for quantifying GHG emissions and calculating relative uncertainty

2.2.1. Method for quantifying emissions

A common approach to estimating emissions is to multiply the activity data by emission factors (Marland and Rotty, 1984), yielding estimates at global, national, or smaller scales on an annual basis. This basic approach, which consists of a linear combination of activity data and emission factors, was used to calculate the total emissions as a result of war-related operations in Ukraine during the first 18 months of the war. We considered emission processes that are not likely to be covered by future NIRs to the UNFCCC. Therefore, for the emissions calculation we used the following equation:

$$E_{CO_2-eq.} = \sum_{g=1}^{3} GWP_g \cdot \left(\sum_{i=1}^{N} a_i \cdot d_{g,i} \right) = \sum_{i=1}^{N} a_i \cdot \left(d_{CO_2,i} + GWP_{CH_4} \cdot d_{CH_4,i} + GWP_{N_2O} \cdot d_{N_2O,i} \right), \quad (1)$$

where $E_{CO_2-eq.}$ are the total emissions of all GHGs in CO_2-equivalents; a_i is the activity data (the amount of explosives and petroleum products used, the area of burned forest or agricultural land, etc.) for the i-th analyzed process; $d_{g,i}$ is the emission factor for the g-th greenhouse gas, $g \in \{CO_2, CH_4, N_2O\}$ for the i-th analyzed process; GWP_g is the global warming potential of appropriate greenhouse gas according to EPA (2023b): 1 for CO_2, 28 for CH_4, and 265 for N_2O; and N is the number of emission categories under analysis. The left part of Eq. (1) is convenient for estimating emissions by GHGs, and the right part is convenient for estimating emissions by emission categories/processes and for the calculation of uncertainties.

2.2.2. Data collection and improving their quality

Although the approach in Eq. (1) can be used to estimate emissions during the Ukrainian-Russian war, there are significant challenges with both the availability of activity data and with some emissions factors. For example, during the war the data on logistics and fuel use and on the number and type of military vehicles, equipment, and ammunition used are classified and are therefore not publicly available. During the war, the state system of collecting and verifying statistical data was also compromised. Many specialists of this system were mobilized to the army and participated in combat operations. Also, in accordance with the Law of Ukraine "On the Protection of the Interests of the Subjects of Submission of Reports and Other Documents During the Period of Martial Law or State of War" (TLU, 2023), during the period of martial law and for three months after its termination, the submission of any mandatory statistical reporting by enterprises is postponed. Therefore, starting from February 24, 2022, for 18 months under our analysis, the State Statistics Service of Ukraine (SSSU, 2023) has not been able to process and publish much relevant statistical data that can be used to estimate GHG emissions.

In this paper we have tried to collect and make maximum use of publicly available data and expert estimates, being aware that these data may be incomplete and that their uncertainty is high (see Fig. 1, showing how the data were collected and how their quality was improved). Regarding activity data, we primarily used official data from the State Statistics Service of Ukraine (SSSU, 2023) and data of Ukrainian ministries (e.g., (MDU, 2023); MEU, 2023); SEIU, 2023)). Also, we used the available data from reports of international and national organizations when available (e.g., (EFFIS, 2023); (FIRMS, 2023); (de Klerk et al., 2022, 2023); (KSE, 2022); PROC, 2023)), as well as information in the media (Censor, 2023). Regarding emission factors, we primarily used data from Ukraine's NIRs (e.g., (NIRU, 2023)), then data from other publications and various reports (e.g., GICHD, 2018). When the information about activity data, emission factors or their uncertainties was missing and filling of gaps was needed, we used expert assessment as IPCC (2001) suggests. The experts are experienced specialists in GHG inventories (Bun et al., 2007, 2019; Charkovska et al., 2019a, 2019b; Danylo et al., 2019; Puliafito et al., 2021) and uncertainty assessment (Jonas et al., 2010, 2019; Oda et al., 2019; Ometto et al., 2014) - in particular specialists in military affairs and fire assessment from the Lviv State University of Life Safety (LSULS, 2023). At least three experts participated in each expert assessment and their estimations were averaged. To make their judgment the experts took all available partial data about the analyzed processes into account. Detailed data on the activity data and emission factors used are given in Appendix B, and their relative uncertainties and the way they were obtained are given in Appendix C.

2.2.3. Method for calculating combined relative uncertainty

All input activity data and emission factors in Eq. (1) are associated with some uncertainty (Tellinghuisen, 2001; JCGM, 2008; ISO/IEC, 2008). In accordance with IPCC (2001) guidance, we consider them to be random variables with normal distributions, and we consider their relative (percentage) uncertainties as the half-width of the 95 % confidence interval divided by the mean (GWP_g we consider as constant values). Such relative uncertainties of the input quantities are given in Appendix C.

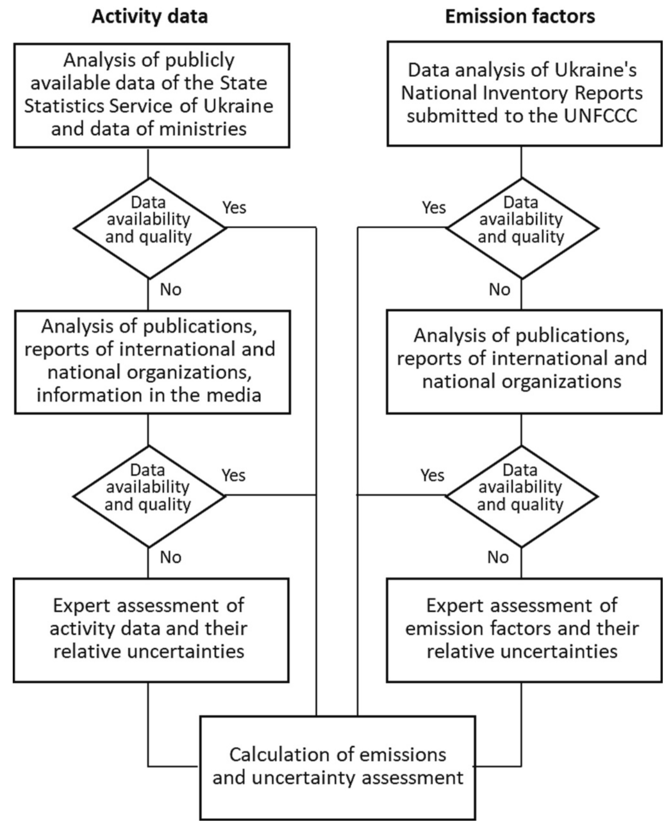

Fig. 1. The steps to collect the data, to assess data quality, and to fill the gaps when information was missing.

When calculating GHG emissions by category/process (by separate greenhouse gas as well as by total emissions), using Eq. (1), the problem of combining uncertainties appears (Mo and Min-Hyuk, 2021). IPCC guidance suggests two approaches for combining uncertainties (see IPCC (2001) Annex 1. Conceptual Basis for Uncertainty Analysis): (i) the error propagation equations with preliminary elimination of dependencies can be applied if the relative uncertainties of the input data are less than 30 %, and (ii) the numerical Monte Carlo method. We could not use the first approach, because for many analyzed categories the relative uncertainties of activity data and emission factors are higher than the 30 % allowed (see Appendix C), so we implemented the numerical Monte Carlo method instead.

Considering all activity data and emission factors as random variables with the mean values given in Appendix B (μ_i, $i = \overline{1,n}$, where n is the number of input random variables) and relative uncertainties U_i given in Appendix C (defined as the half-width of the 95 % confidence interval divided by the mean), we first calculated the standard deviation σ_i of each variable. We used an approximate estimate $\sigma_i = \mu_i \cdot U_i / 1.96$, where 1.96 is the coefficient that corresponds to the 95 % confidence interval of a normal distribution (Weisstein, 2023).

Then we performed the calculation iteratively (1 million iterations). At each iteration a random value of each analyzed random variable was generated (in accordance with the probability density function of a normal distribution with parameters μ_i and σ_i). Based on the calculated dataset, the 95 % confidence interval was specified by the confidence limits defined by the 2.5 percentile and 97.5 percentile of the cumulative distribution function of the estimated quantity. The mean value μ of the output was calculated as the middle of the confidence interval, the output relative uncertainty U was calculated as the half-width of the confidence interval divided by the mean value, and the output standard deviation σ was estimated using the formula $\sigma = \mu \cdot U / 1.96$. The combined relative uncertainties calculated in this way are given in Appendix C. Here the combined relative uncertainties of total emissions, as well as relative uncertainties by emission categories and by GHGs (based on the analysis of intermediate datasets in our computational experiment) are given. It is worth noting that, according to NIRs (e.g., NIRU, 2023; NIRR, 2023), the relative uncertainties of some emission factors for some greenhouse gases are extremely high, which in the case of a symmetrical probability density function deprives a small part of them of a physical meaning. However, we still used them in our math/computational experiment. Emissions from these categories/gases with high uncertainties are very small, so they have an insignificant impact on the combined relative uncertainty of the total emissions.

2.3. Emissions not covered by NIRs

2.3.1. The use of bombs, missiles, barrel artillery, mines, and small arms

GHG emissions from this type of military action have not been considered in previous studies (e.g., see Parkinson, 2020; Parkinson and Cottrell, 2021; Belcher et al., 2019; Woodman, 2016; Bradford and Stoner, 2017). This is probably because two Annex 1 countries have never before used these weapons so intensively and over such a large area. GHG emissions occur during firing (barrel artillery and small arms), during flight to the destination (missiles and drones), and during explosions (missiles, bombs, shells, grenades, drones, and mines). The emissions took place along both the frontline of the conflict and at the far rear of engagement, and the magnitude of the emissions will depend on the mass of the explosives and fuel (Figs. 2a and 3).

Fig. 2. Illustration of GHG emissions caused by military actions in Ukraine that have a chance of not being accounted for in official national reporting and global estimates: the use of bombs, missiles, barrel artillery, mines, and small arms (a); use of petroleum products for military purposes (b); emissions from fires of petroleum products at petroleum storage depots (c); emissions from fires of buildings and infrastructure facilities (d); emissions from forest fires and fires on agricultural lands (e); emissions from garbage/waste (f).

Fig. 3. Map of Ukraine including the occupied areas and territories with the highest CO_2 emissions.

Most of the explosives used in the military have a high oxygen content needed for chemical reactions, which is available in NO_2 groups. Upon detonation and heat releasing reactions the oxygen atoms combine with carbon and hydrogen atoms to form many gaseous products, e.g., CO_2, CO, H_2O, and N_2 (Oxley, 1998). In general, these chemical reactions of the combustion of gunpowder in the cartridge case and the explosion are complex, but it is important to summarize that GHGs are emitted, and additional oxidation of some substances occurs in the atmosphere.

As of February 24, 2022, these emissions have occurred from the territory of Ukraine, but the IPCC (2006) Guidelines do not provide a corresponding emission category in which they should be reported. Moreover, these emissions were caused by another country as a result of the attack, so we suggest Ukraine should not take responsibility for these emissions nor should they be required to include them in their national reports. This would contradict the principle of complete emission reporting to the UNFCCC.

2.3.2. *The use of petroleum products for military actions*

During the first 18 months of the war, the frontline of the conflict was more than 2000 km long on land. Many thousands of tanks, planes, helicopters, and other vehicles took part from both sides (Fig. 2b and Fig. 3) (de Klerk et al., 2023). The exact number of military vehicles and fuel consumed is not available from either side. The Ukrainian side regularly reports losses of Russian equipment (MDU, 2023). As of August 24, 2023 (18 months of the war), the reported Russian losses amounted to: 8511 armored combat vehicles, 4375 tanks, 5333 artillery weapons, 723 MLRS (multiple launch rocket systems), 315 aircraft, 316 helicopters, 7773 trucks and cisterns, and 18 ships (MDU, 2023; Censor, 2023). On the basis of these data, partial data from the media on percentage loss, as well as partial data on the proportions of use and losses of the Russian and Ukrainian armies, an expert estimation was used to convert these activity data into an 18 month time horizon and to estimate the uncertainty of these data (see Section 2.2 for details).

Russian tanks captured by the Ukrainian army have a reported fuel consumption of 460–500 l per 100 km. The consumption of aviation kerosene by a military aircraft, for example the SU-27, is 3040 kg per hour at cruising speed, without considering take-off and maneuvering. Petroleum products were also used by Russia for other purposes, for example for construction of fortifications in anticipation of a Ukrainian counteroffensive (de Klerk et al., 2023).

These emissions from the consumption of petroleum products for direct military operations took place from the territory of Ukraine. However, as most of them were caused by Russian equipment, Ukraine will not have data on the fuel consumed by the Russian army. Moreover, Russia does not have reliable data on the fuel consumed by its army because it does not get included in statistical reporting. Some of the fuel was obtained at oil depots or stolen from gas stations in Ukraine. A smaller amount of petroleum products was used by the Ukrainian army but this fuel also did not get included in statistical reporting. In particular, fuel was used from captured military vehicles, from warehouses of the Russian army which they abandoned during retreat, etc. IPCC reporting guidelines do not suggest who takes responsibility for these emissions. These increased emissions did not appear because of ineffective mitigation efforts, but rather as a result of the country's defense against an invasion, a circumstance not foreseen by the IPCC (2006) Guidelines.

2.3.3. *Fires of petroleum products at petroleum storage depots*

Petroleum storage depots throughout Ukraine were destroyed by missile attacks. During the first 18 months of the war the fires occurred at more than 30 major oil depots in many regions (Fig. 2c and Fig. 3): Kyiv (Vasylkiv, Kalynivka), Lviv (Lviv, Brody), Dnipropetrovsk (Dnipro, Kryvyi Rih, Novomoskovsk district), Zhytomyr (Zhytomyr, Chernyachy), Rivne (Dubno, Rivne), Volyn (Lutsk), Chernihiv regions, at oil depots of the occupied territories of Ukraine in the Donetsk (Donetsk, Makiyivka), Luhansk (Rovenky, Luhansk) regions, and Crimea (Dzhankoy, Sevastopol) as well as in Russia (Bryansk, Belgorod, Yeisk, Taman) (Censor, 2023). At each depot, the fire lasted several days and burned thousands of tons of petroleum products. The tank park of each of these oil storages was from 5000 to 100,000 m^3 but, in anticipation of attacks, the tanks were not completely filled. Petroleum products in a significant number of automobile fuel tanks at the front were also destroyed because of hostilities as were many gas stations and warehouses with petroleum products from industrial facilities along the front line and in the temporarily occupied territories. The largest oil refineries of Ukraine were also destroyed: Kremenchutsk (capacity of 18.6 million tons of oil per year), Lysychansk (16 million tons), Kherson, and Odesa. These additional emissions were caused by the war, are not well documented, and are not covered by the IPCC (2006) Guidelines.

2.3.4. Fires in buildings and other infrastructure

At the beginning of the war more than 3000 settlements were occupied by the Russian army. Months later, a significant part of these settlements was de-occupied by the Ukrainian army. As a result of these military actions, many administrative, residential, and commercial buildings and shopping centers, as well as industrial complexes and other infrastructure, were burned (Fig. 2d and Fig. 3). Cities such as Bucha, Irpin, Mariupol, Severodonetsk, Lysychansk, Izyum, Bakhmut, Avdiyivka, and many small cities and villages were almost completely destroyed. Because of the fighting, shelling, and the limited emergency services, it was not possible to put out many fires. Very large fires occurred repeatedly because of missiles attacks in cities and villages controlled by Ukraine (e.g. Kharkiv, Mykolaiv, Zaporizhzhia, Kyiv, and Nikopol, e.g., see Aimaiti et al. (2022)).

As a result of such fires in buildings and other infrastructure many wooden constructions (floors, furniture, windows, doors, attics, etc.), plus other combustible materials (clothes, plastic, etc.) burned. In general, when burning biomass the carbon emitted to the atmosphere as CO_2 is from carbon in the natural carbon cycle. In this case no new CO_2 is added to the atmosphere if the forests from which the biomass is extracted are sustainably managed. But during a war unsustainable management of forests occurs (Pereira et al., 2022a, 2022b). It was not burning biomass/biofuel for energy purposes, but useless burning of buildings and constructions that could still be used for many years. Also, new buildings and infrastructure will have to be built and this will cause additional high emissions (de Klerk et al., 2022, 2023).

Additional emissions caused by these fires occurred from the territory of Ukraine but not as a result of voluntary actions by Ukraine, a circumstance not foreseen by the IPCC (2006) Guidelines. Instead, the reconstruction activity will be included in the statistical reporting and will be reflected in the next Ukraine NIRs to the UNFCCC.

2.3.5. Forest fires and fires on agricultural fields

The military activity in Ukraine caused large-scale forest fires (Matsala, 2023; de Klerk et al., 2022, 2023) (Fig. 2e and Fig. 3). During the first three months of the war, in the very dangerous Chernobyl zone of exclusion alone, an area of forest greater than 22,000 ha burned (UNCG, 2022). During the first year of the war, significant forest fires occurred in the Kherson, Mykolaiv, Kyiv, Chernihiv, Sumy, Kharkiv, Donetsk, Dnipropetrovsk, and Luhansk regions as a result of shelling (in particular, in the area of the Siverskyi Donets River). In many cases the Russians deliberately used special incendiary projectiles to start fires. Extinguishing forest fires was complicated by hostilities, the presence of unexploded ordnance, and by mines laid in forest areas (Censor, 2023). As a result of the limited ability to fight low and medium intensity fires these fires evolved into high intensity fires, spreading over large territories (de Klerk et al., 2023). Such fires are not covered by the IPCC (2006) Guidelines because they are neither controlled burning of forest nor wildfires of forests (category 4A1). Rather it was the uncontrolled burning of forests due to military action, which could also contribute CO_2 to the atmosphere. The same was true of fires on agricultural land where Russian troops used incendiary shells to cause fires and destroy crops. August, when intense hostilities took place in the south of Ukraine, is the period of wheat ripening and harvesting. It was neither controlled burning of cropland nor wildfires of cropland (category 4B1).

2.3.6. Emissions from garbage/waste

As a result of missile attacks and other military operations many houses and commercial structures were destroyed by blast waves or damaged by military vehicles (Fig. 2f). This resulted in large amounts of unaccounted for waste such as wooden structures, windows, doors, furniture, household items, personal effects, fences, etc. that cannot be repaired (Censor, 2023). Many trees were cut down to use the wood to build trenches, dugouts, or other shelters. In both cases this wood will eventually become waste. Here we use the term “waste”, although this is not the typical waste sector according to IPCC Guidelines (IPCC, 2006). Part of the wood was burned for heating and cooking while the remaining organic material became garbage and waste and will have its carbon released to the atmosphere as CO_2 or CH_4 over time. These emissions also occurred from the territory of Ukraine, were caused by an anthropogenic factor, but were not voluntary emissions from Ukraine.

3. Results and discussion

In the sections that follow we describe our estimates of the main GHG (CO_2, CH_4, and N_2O) emissions from each of the above categories that are not covered by NIRs. Because these are based on limited and non-traditional information we also discuss the uncertainty in the values. Further details by category are provided in Appendix B.

3.1. Estimation of emissions not covered by NIRs: The use of bombs, missiles, barrel artillery, mines, grenades, and small arms

During attacks, Russia used a variety of cruise and ballistic missiles (Iskander, Kalibr, Tochka-U, Kyndzhal, Oniks, X-101, X-55, X-59, X-22, 5B55). As an example, one Iskander missile has a warhead with 480 kg of gunpowder and enough fuel for a flight of 500 km (launch mass is 3.8 t). In total, more than 5000 different types of missiles were launched over Ukraine during the first 12 months following Feb. 24, 2022. About 50 % of the missiles and 80 % of the kamikaze drones were shot down by Ukrainian air defenses, but the emissions from the detonation of the explosives and the combustion of the fuel still entered the atmosphere. The Ukrainian army used missiles in response, but in much smaller numbers. Russia used various types of aerial bombs, including a high-powered bomb with 1000 kg of TNT. Shahed-136 kamikaze drones were also used. Barrel artillery was used throughout the period of the war – up to 60,000 shells per day by Russia during the most intense periods (de Klerk et al., 2022, 2023; Censor, 2023). Many Russian missiles and projectiles were destroyed on the ground as a result of Ukrainian attacks on ammunition depots, but emissions from explosives and fuels also entered the atmosphere.

For our estimates, the basic activity data and characteristics used were taken from de Klerk et al. (2022, 2023), Oxley (1998), MEnU (2022), GICHD (2018), and Censor (2023), as well as basic chemical equations and characteristics of the explosion processes from Oxley (1998), and USAEC (2006). Where it was needed we used the estimates of experts from the Lviv State University of Life Safety (LSULS, 2023) for the assessment of the average shelling intensity and the average explosive mass. For calculating 18 months of emissions from the territory of Ukraine caused by both armies we used the following data on the number of weapons and the weight of explosives and propellant fuel: a.) barrel artillery and tank gun shells – 13.8 million in Russia and 4.75 million in Ukraine of 152/155 mm munitions or equivalent (propellant charge with average 9.5 kg of triple base powder and 8.5 kg of explosive composition); b.) MLRS (multiple launch rocket systems) – we assumed that there were 2 times more such systems than the 475 ‘Grad’ type lost during the first year, which fired an average of one full salvo per 3 days (6.4 kg of explosive and 45 kg of fuel); c.) 191.5 k bombs of type FAB-500 (213 kg of explosive); d.) missiles and means of anti-missile defense (10,000; 290 kg of explosive plus fuel for 350 km distance on average); e.) kamikaze drones 2300 (50 kg of explosive plus fuel for 500 km); f.) medium and heavy mortar projectiles and small caliber shells (12.0 mln); g.) mines 6.3 million anti-personnel and anti-tank mines (0.075 kg and 7.5 kg of explosive, respectively); h.) grenades (hand and drones) 0.5 per soldier per day on average (60 g of explosive); and i.)

small arms cartridges up to 30 cartridges per day for one infantryman (0.0161 kg of explosive). Based on our assessment, the uncertainty of activity data and explosive mass is high (+/− 50 %) compared to the uncertainty of activity data for many categories of emission processes during peacetime (here and hereafter the relative uncertainty of data is indicated two sigma). The emission factor uncertainty we assumed is +/− 20 %.

We estimated the total emissions from the use of bombs, missiles and drones, barrel artillery and tank guns, medium and heavy mortars projectiles and small caliber shells, land mines, hand and drone grenades, and small arms (by both sides, i.e., Russian as well as Ukrainian armed forces) during 18 months of the war in Ukraine to be 283.4 ktCO_2 (+/− 54.2 %) (see Table 1), which will not be reflected in NIRs to the UNFCCC. In this estimate, we did not take into account emissions from the manufacturing of ammunition because this activity is accounted for via statistical reporting and will be reflected in the NIR to the UNFCCC for the respective countries where production occurred.

3.2. Emissions from consumption of petroleum products for military actions

Here we take into account only the consumption of fuel for military operations directly on the front and not far from it because, as indicated above, taking into account and reporting emissions from this fossil fuel is problematic during a war. For the basic data on losses of Russian equipment, as well as data on their share in the total armament, we used data from MDU (2023), and Censor (2023). It is assumed that the amount of military equipment on the Ukrainian side was at least 3 times lower, which is based on partial data published in the media on the proportions of certain types of weapons used by the Russian and Ukrainian armies.

Using published and expert data on the average fuel consumption of the main military vehicles, the total volume of fuel used during 18 months of the war was estimated (MEnU, 2022) for land military vehicles (armored combat vehicles, tanks, MLRS, cars and cisterns, etc.), aviation (planes and helicopters), and ships. Our estimate coincides with the fuel volumes used by land military vehicles and aviation for the 12 months estimated by de Klerk et al. (2023). Our expert estimates also take into consideration fuel from Belarus, fuel transported by the Crimean Bridge for the southern grouping of troops, fuel stolen by the Russian military in the occupied territory, as well as fuel used by the Russian Black Sea Fleet. The relative uncertainty of the activity data is assumed to be +/− 40 %. The average calorific values of the petroleum products, emission factors for CO_2, CH_4, and N_2O, as well as the uncertainties of these emission factors (+/− 5 % for CO_2, and +/− 18 % for CH_4 and N_2O) given in NIRR (2023) were used for the calculation of emissions.

The total emissions of GHG from the consumption of petroleum products for military actions was estimated to be 28.66 MCO_2-eq. (+/− 39.7 %), including 26.78 MCO_2-eq. from the land military vehicles, 1.03 MCO_2-eq. from aviation, and 0.86 MCO_2-eq. from ships (see Table 1). The carbon dioxide total emissions (28.48 Mt) dominated compared to methane (0.254 kt) and nitrous oxide (0.677 kt) emissions (see Appendix B). The emission factors of old military equipment may be higher than the average values given in NIRR (2023). This estimate does not include emissions of other GHG emissions from light vehicles at the front, emissions from the transport of volunteers, transportation of military equipment of partners through the territory of Ukraine, emissions from small power generators used during blackouts, as well as fuel consumed by the strategic aviation of Russia (which launched massive missile attacks from the territory of Russia) because these fuels are covered by the national statistical reporting of the countries and can be reflected in the NIRs to the UNFCCC.

Table 1. Estimated war-related GHG emissions from the first 18 months of the 2022/2023 war in Ukraine. These are emissions that originated from the territory of Ukraine but due to their specificity will likely not be covered by Ukraine's next NIRs to the UNFCCC - or they may be reported in a nontransparent way with high uncertainty.

Emission sources	Emissions				Relative uncertainty, 95 % confidence interval
	CO_2, Mt	CH_4, kt	N_2O, kt	Total, MCO_2-eq.	
Use of bombs, missiles, barrel artillery, mines, etc.	0.28	–	–	0.28	+/− 54.2
Use of petroleum products for military actions	28.5	0.25	0.68	28.7	+/− 39.7
Fires of petroleum products at petroleum storage depots	5.4	0.21	0.04	5.43	+/− 20.3
Fires of buildings and infrastructure objects	17.8	5.0	0.73	18.1	+/− 49.8
Forest fires and fires of agricultural fields	21.1	63.3	3.5	23.8	+/− 38.2
Emissions from garbage/waste	–	36.8	–	1.03	+/− 69.4
Total emissions:	73.1	105.6	4.96	77.2	+/− 22.3

3.3. Emissions from fires of petroleum products at petroleum storage depots

Data on the amount of burned oil products (diesel fuel, gasoline, and LPG) that were destroyed due to missile attacks and shelling of petroleum storage depots, oil refineries, petroleum stations, and petrol trucks are not published. However, data on financial losses from lost fuel are published (Censor, 2023). From this, in combination with fuel prices known at the time of the fires, it is possible to estimate the approximate volumes. Moreover, the State Environmental Inspectorate of Ukraine published aggregated data on petroleum products burned as a result of shelling for 10 months (686,168 t) (SEIU, 2023). Based on the assumption of the same magnitude of fires up to the 18th month of the war, as well as taking into account the share of occupied territories from which the Ukrainian authorities do not have access to data, the total volume of burned oil products during 18 months of the war was estimated at 1557.5 kt; +/− 20 %. The emission factors of major petroleum products and their uncertainty were used from NIRU (2023) and MEnU (2022). On this basis, the total GHG emissions caused by fires at all these facilities during 18 months of the war was calculated as 5.43 MCO_2-eq. (+/− 20.3 %), including 5.41 Mt of CO_2, 210 t of CH_4, and 42.1 t of N_2O (see Table 1).

3.4. Emissions from fires of buildings and infrastructure

From the start of the war (February 24, 2022), many buildings and infrastructure in Ukraine were burned due to military actions. This included apartment buildings and private houses; hospitals and health care facilities; social sector facilities; educational and scientific institutions; cultural, religious, sports, and tourism sites; industry and business service facilities; shops and shopping malls; airports and seaports etc. (KSE, 2022). Every typical household in Ukraine has many wooden constructions and things made of wood or other combustible materials, including floors, windows and doors, furniture, roof constructions, auxiliary buildings, fences, etc. (here we assume 2.5 t of wood per household). Statistical data on the scale of these fires are not known. We used detailed data from KSE (2022) and MEnU (2022) on the number of destroyed features during the first 6 months of the war, as well as the damage assessment in monetary terms in each category. These data proxy for calculating the shares of wooden constructions and other combustible materials burned. We also used the linear dependence of the number of destroyed features over time given in KSE (2022) during the first year of the war and a coefficient of 0.5 from the 13th month onwards to scale the data to 18 months. The calorific value of wood for conifers and broad-leaved trees differs within a narrow interval. We used an averaged value for the calorific value (CFN, 2023). We used the values of emission factors from NIRU (2023) and the uncertainty assessment from Solazzo et al. (2021). The total amount of burned wooden constructions during 18 months of the war was estimated to be 8.41 Mt, with total GHG emissions of 17.88 $MtCO_2$-eq.

We assumed that there are 300 kg of the other combustible materials in an average burned household, materials like plastics, fabrics, shoes, books, etc.(1009 t in total for 18 months). Using emission factors for open burning of waste (IPCC, 2006), we estimated the corresponding GHG emissions to be 252.0 $ktCO_2$-eq. According to our assessment, the total emissions from fires of buildings and infrastructure is 18.14 $MtCO_2$-eq. (+/− 50.5 %), including 17.80 Mt of CO_2, 5.0 kt of CH_4, and 0.73 kt of N_2O (see Table 1 and Appendix B).

3.5. Emissions from forest fires and fires of agricultural fields

According to the State Environmental Inspectorate of Ukraine (SEIU, 2023), during the first 10 months of the war 59,150 ha (+/− 20 %) of forests were burned because of military operations. During the 11th and 12th months of the war intensive military operations continued which caused forest fires (near Bakhmut, Kreminna, and other forest regions), but their spread was less intense due to the winter season. However, during this period, a significant loss of forest stands was caused by intensive felling of hardwood trees for heating. Therefore, in our assessment we assumed that the magnitude of emissions during the last two months of the year was the same as previously.

We follow an approach from de Klerk et al. (2022, 2023) based on Tier 1 methods to estimate the total area of forest fires during the first year of the war and the corresponding emissions. The area of fires was calculated using satellite observations (FIRMS, 2023; EFFIS, 2023) at a 1 ha spatial resolution, as well as using JRC (2023) data. The weighted average value of forest stands (233 m^3/ha) has been applied and the fraction of burned branches, leaves, stumps, etc. has been analyzed. The above-ground and below-ground biomass content has been converted into tonnes of dry matter per hectare (NIRU, 2023). The crown fires (77 %) and surfaces fires (23 %) were analyzed separately. The fraction of biomass lost in fires is equal to 0.7 (NIRU, 2023). The default emission factors from the IPCC (2006) were applied (1569 g CO_2 /kg of dry matter burnt for CO_2, 4.7 g CH_4/kg for CH_4, and 0.26 g N_2O /kg for N_2O. An assumption was also applied that fires smaller than 1 ha, which are not covered by satellite data due to their resolution, are an additional 5 %. We scaled the resulting 12 month area of fires to 18 months of the war, using the assumption that forest fire intensity decreased by 50 %, while the intensity of fires on agricultural land and other landscapes remained at the same level. We applied the uncertainties of emission factors from NIRU (2023).

We estimated CO_2 emissions from forest fires during 18 months of the war to be 16.73 $MtCO_2$-eq. (+/− 44.2 %), including 14.84 Mt of CO_2, 44.5 kt of CH_4, and 2.46 kt of N_2O (see Appendix B). This estimate does not include forest destruction by military vehicles, and increased use of fuel wood by communities that lost access to fossil fuels and electricity. Regarding emissions from fires of agricultural lands, we estimated these to be 6.46 $MtCO_2$-eq. (+/− 84.7 %), including 5.73 Mt of CO_2, 17.2 kt of CH_4, and 0.95 kt of N_2O. Emissions from fires of other nature landscapes were estimated to be 648 kt CO_2-eq.

3.6. Emissions from garbage/waste

We used a similar approach to that described above for emissions from fires of buildings and infrastructure plus detailed data from KSE (2022) on the number of damaged features during the first 6 months of the war to estimate the amount of garbage/waste produced due to military actions during the 18 month period. This included damaged wooden constructions/objects, household items, etc. As in the assessment by de Klerk et al. (2022) a 33 % factor was assumed for damaged facilities, as well as the assumption that the intensity of damage remained the same during the next 6 months, but was two times lower at the beginning of the second year of the war. Due to the lack of more accurate data, we used the methane emission factor and the corresponding uncertainty for unmanaged waste disposal from NIRU (2023). Taking into account the level of destruction in both occupied settlements and unoccupied frontline settlements, as well as the damaged buildings and infrastructure far from frontline, we estimated CH_4 emissions from garbage/waste to be 36.8 kt (+/− 69.4 %) (see Table 1).

3.7. Total emissions not covered by NIR

Our estimate of the war-related emissions of CO_2, CH_4 and N_2O for the first 18 months of the war in Ukraine is 77 $MtCO_2$-eq., with the symmetric interval of combined relative uncertainty estimated to be +/− 22 % (95 % confidence interval), with a standard deviation $\sigma = 8.804$ $MtCO_2$-eq. (see Table 1). This estimate covers only emissions from the territory of Ukraine caused by two armies, which due to their specificity will likely not be covered by Ukraine's next NIRs to the UNFCCC - or they may be reported but in a non-transparent way with high uncertainty. The emissions from the consumption of petroleum products for military actions and emissions from forest fires (which were not obtained as a result of the sustainable management of forests) dominate. The Ukrainian Environmental Protection Minister was quoted on October 18, 2022 with an estimate of 31 $MtCO_2$-eq. emissions for the first 7 months of war (Birnbaum, 2022), but without specifying the structure of these emissions. de Klerk et al. (2023) show the numbers as 21.9 $MtCO_2$-eq. from warfare and 19.7 $MtCO_2$-eq. from fires, but this only covers the first 12 months of the war, and the same war-related emission processes and accounting boundaries are not always considered. For example, de Klerk et al. (2023) consider emissions from both the territory of Ukraine and outside, as well as future emissions due to reconstruction of civilian infrastructure (50.2 $MtCO_2$-eq.). Our assessment covers emissions from the territory of Ukraine only and from the perspective of estimating emissions likely to not be included in NIRs under the current international reporting system.

In 1990, the base year of the Kyoto Protocol, Ukraine was part of the former Soviet Union (USSR). The USSR had a very energy-intensive economy and its total emissions of CO_2 were 5th largest in the world (OCED, 2022). In 2021, which is the last year that emissions were reported to the UNFCCC before the war in Ukraine, Russia had the 4th largest CO_2 emissions (5.13 % of the global total according to WPR (2023)) and Ukraine was 33rd (0.49 % of the global total). According to the NIR submitted by Ukraine in 2023 (UNFCCC, 2023; NIRU, 2023) the total GHG emissions/removals for 2021, in all sectors, amounted to 224.2 Mt CO_2, 2862 kt CH_4, and 147.0 kt N_2O, with a total of 339.5 $MtCO_2$-eq. The total emissions of CO_2 from the use of fossil fuels amounted to 159.7 Mt.

We have demonstrated above that after February 24, 2022, during the first 18 months of the war in Ukraine, the emissions from military activities were large and may or may not be included in the publicly reported inventories of emissions. The publicly available estimates of national CO_2 emissions are generally assumed to have an uncertainty on the order of 5–10 % (Friedlingstein et al., 2020). According to the latest available estimates from Ukraine's NIR for 2021 the combined uncertainty estimate of total GHG emissions - excluding the land-use sector - is reported at 9.11 % (NIRU, 2023). The 2022 war fundamentally changed the structure and amount of emissions in all sectors of human activity in Ukraine. In particular, GHG emissions decreased in many traditional sectors and increased in many war-related sectors. This applies to emissions from electricity production (the power demand decreased significantly and many thermal power plants were damaged), from coke plants, metallurgical plants, aviation, shipping, etc., because many of these industries were not functioning normally. The structure of fossil fuel consumption fundamentally changed. In this analysis we have estimated a reduction in the total, pre-war emissions during the first 18 months of the war to be 158 $MtCO_2$-eq (Appendix A). At the same time, 18 months of war resulted in additional 77 Mt CO_2-eq. of emissions. Some of these changes in emissions will be taken into account when Ukraine submits a report on GHG emissions for 2022, as many of these categories and corresponding activity data are covered by state statistical reporting. However, human activities in the temporarily occupied territories will likely not be covered correctly by this reporting.

4. Conclusions

The war of 2022/2023 in Ukraine radically affected the amount and structure of GHG emissions not only in Ukraine, but also far beyond its borders. These changes are caused by many factors, including: refugees who took their carbon footprint with them to another country; global redistribution of production in a number of industries where Ukraine held a leading position, such as iron and steel production; diversification of the supply of natural gas and oil products from Russia which changed the structure of fossil fuel consumption; implementation of measures to increase the defense capability of countries neighboring the conflict; increasing the production of ammunition in many countries and its transportation to Ukraine; increasing the length/time/emissions of traditional air flights from Europe to East and Southeast Asia and much more. The aforementioned processes are covered by the national statistical reporting of each country, so the corresponding activity data and emissions will be reflected in their NIRs to the UNFCCC.

In this paper we focused on emission processes due to wartime activities that may not be covered in official national reporting. The sum of such 'unaccounted' for emissions of carbon dioxide, methane, and nitrous oxide for 18 months of the war in Ukraine is, by our first-order estimate, 77 $MtCO_2$-eq. (relative uncertainty estimated at 22 %, 95 % confidence interval). These emissions are greater than the annual total GHG emissions of Austria, Portugal, or Hungary.

Scientists and policy makers are working to reduce emissions, to understand their magnitude and to reduce their uncertainty. Despite concerns over climate change and many efforts to reduce/mitigate emissions, a war can suddenly override years of positive action, both in the war zone and outside. Among the consequences of war is the destructive impact on monitoring, reporting and verification of GHG emissions and their consequences for global change. Efforts to maintain accounts will continue in the science community but current international agreements do not include war-related emissions and do not attribute responsibility. The impact of open conflict has major consequences in the combat zone and clearly extends well beyond the time and place of the physical conflict - and could impact national commitments and treaty obligations.

The current IPCC (2006) Guidelines for reporting national emissions of greenhouse gases were developed for politically stable and peaceful international relations. Any revisions to these existing guidelines to cover war-related emissions will likely not easily solve the problem of responsibility because such changes will challenge the basic principle that each country is fully responsible for the emissions from its territory. The country being invaded (in the current case Ukraine) cannot, and should not, bear responsibility for those emissions generated on its territory by an aggressor country. These emissions could be attributed to the aggressor country. The evaluation of war-related emissions could also be carried out by an international team of experts that would have the appropriate UNFCCC/IPCC mandate for this. However, the mechanism for accurate and equitable reporting in this context is not currently available. Regardless of responsibility, war-related unaccounted/untracked emissions are currently entering the atmosphere, and the international community, scientists, and policy makers should be aware of this problem and its magnitude. How to address the accounting of war-related GHG emissions and the correct attribution of responsibility for these emissions remains a challenge.

CRediT authorship contribution statement

Rostyslav Bun: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gregg Marland:** Writing – review & editing, Writing – original draft, Conceptualization. **Tomohiro Oda:** Writing – review & editing, Writing – original draft, Conceptualization. **Linda See:** Writing – review & editing, Conceptualization. **Enrique Puliafito:** Writing – review & editing, Formal analysis. **Zbigniew Nahorski:** Writing – review & editing, Investigation. **Mathias Jonas:** Writing – review & editing, Formal analysis. **Vasyl Kovalyshyn:** Investigation, Formal analysis, Data curation. **Iolanda Ialongo:** Writing – review & editing, Conceptualization. **Orysia Yashchun:** Formal analysis, Data curation. **Zoriana Romanchuk:** Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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Appendix A. Estimating the decrease of GHG emissions in Ukraine in 2022/2023, caused by the reduction of traditional human activities during times of war – changes that will be reflected in Ukraine's future NIRs

The war in Ukraine (shelling, occupation, fires) has caused a reduction in human activities that use fossil fuels (power production, industry, transport, residential sector etc.), which has led to a reduction of GHG emissions from stationary and mobile sources. The State Statistics Service of Ukraine (SSSU, 2023) has not published data on fossil fuel use or emissions since February 24, 2022, but it has published data on gross domestic product, which correlates with human activity and emissions. According to these data, the decreases of gross domestic product in the corresponding quarters of 2022 compared to the quarters of 2021 were: 15.1 %, 37.2 %, 30.8 %, and 31.4 %.

Public electricity and heat production {sector 1A1a, according to IPCC (2006)}. The decrease in human activity has reduced the use of electricity, so power plants have reduced production and thereby reduced GHG emissions (March–September 2022). Here, the reduction of GHG emissions from power plants was one of the most important factors compared to all other factors. Early in the war the root cause of this was not the shelling of energy facilities, but a decrease in human activity in all spheres. By contrast, in the period after October 2022, the decrease in electricity production was caused by regular mass shelling of Ukraine's energy infrastructure facilities. Total electricity production in Ukraine for 2022 decreased by 27.5 % compared to 2021, with electricity production from thermal power plants decreasing by 35 % and thermal power and heat plants by 32 % (MEU, 2023). Based on the emissions of this sector in 2021 (NIRU, 2023), it is possible to estimate the reduction of emissions in the public electricity and heat production sector in 2022 to be 27.1 $MtCO_2$-eq. (27.0 $MtCO_2$, 1.2 $ktCH_4$, and 0.38 ktN_2O). Given that this reduction occurred over a period of 311 days, starting on February 24, 2022, we roughly estimated the reduction of emissions in the public power and heat production sector during the first 18 months of the war (from February 24, 2022 to August 23, 2023) to be 47.7 $MtCO_2$-eq. (see Table A1 for more details). For these estimates, the assumption was used that in the absence of a war, the intensity of emission processes in 2022 would have been the same as in 2021. We assume further that during the first 18 months of the war the intensity of emission processes in the sector did not change.

Manufacture of solid fuel products (1A1c). Coke plants located in the eastern part of Ukraine practically did not work starting from February 24, 2022. Based on the emissions of this sector in 2021 (NIRU, 2023), we calculated the reduction of emissions in 2022 to be 3.25 $MtCO_2$-eq., and for the first 18 months of the war to be 5.71 $MtCO_2$-eq.

A similar approach was applied to all emission sectors that had decreased GHG emissions due to the war in Ukraine (see Table A). The uncertainty of the above data is high due to the significant uncertainty in the activity data, especially from temporarily occupied territories.

Table A

Estimated decrease of emissions in Ukraine during 18 months of the war as a consequence of the reduction of traditional human activities in the main emission sectors.

Emission sector	Sectors according to IPCC (2006)	Average reduction of production/activity in 2022 compared to 2021, %	Reduction of emissions								
			2022 (311 days of the war)				2022/2023 (18 months of the war)				
			CO_2, Mt	CH_4, kt	N_2O, kt	Total, $MtCO_2$-eq	CO_2, Mt	CH_4, kt	N_2O, kt	Total, $MtCO_2$-eq	Share, %
Public electricity and heat production	1A1a	33.5	26.98	1.18	0.38	27.12	47.46	2.07	0.67	47.69	30.4
Manufacture of solid fuels	1A1c	84.0	3.23	0.63	0.02	3.25	5.68	1.11	0.03	5.71	3.6
Iron and steel production, non-ferrous metals	1A2a,b, 2C1,2	62.5	31.64	13.88	0.07	32.05	55.66	24.41	0.12	56.37	36.0
Chemical industry	1A2c, 2B	62.0	3.00	83.35	5.01	6.67	5.28	146.6	8.81	11.72	7.5
Pulp and paper production	1A2d	35.7	0.019	0	0	0.019	0.033	0	0	0.033	0.02
Food processing	1A2e	22.1	0.128	0.01	0	0.128	0.225	0.01	0	0.225	0.14
Road transportation, other transportation	1A3b,e	22.0	6.97	1.99	0.78	7.23	12.26	3.50	1.37	12.72	8.1
Railways	1A3c	50.0	0.188	0.01	0.08	0.209	0.331	0.02	0.13	0.367	0.23
Domestic aviation and navigation	1A3a,d	84.0	0.227	0.01	0.01	0.229	0.399	0.01	0.01	0.403	0.26
Commercial/residential sector	1A4a,b	32.0	6.09	0.31	0.04	6.11	10.71	0.55	0.07	10.74	6.9
Coal mining and handling, solid fuel transformation	1B1a,b	7.7	0.015	33.78	0	0.96	0.027	59.42	0	1.69	1.1
Oil and natural gas production	1B2a,b	8.4	0.173	124.8	0	3.67	0.303	219.5	0	6.45	4.1
Mineral industry	2A	28.6	2.01	0	0	2.01	3.54	0	0	3.54	2.3
Total:			80.68	259.9	6.38	89.65	141.9	457.2	11.2	157.68	100

Appendix B. Activity data and emission factors used and the calculated emissions

Table B

Activity data, emission factors, and calculated emissions.

Emission category/activity	Number (million)	Activity data used /Calorific value	Averaged emission factors			Emissions			
			CO_2	CH_4	N_2O	CO_2, kt	CH_4, t	N_2O, t	CO_2-eq., kt
The use of bombs, missiles, barrel artillery, mines, and small arms									
Barrel artillery and tank gun shells	18.55	333.9 kt[1)]	0.339 kg CO_2/kg[2)]	–	–	113.3	–	–	113.3
MLRS (multiple launch rocket systems)	6.9	356.1 kt[1)]	0.339 kg CO_2/kg[2)]	–	–	120.8	–	–	120.8
Bombs	0.191	40.8 kt[1)]	0.339 kg CO_2/kg[2)]	–	–	13.8	–	–	13.8
Missiles and means of anti-missile defense	0.010	11.4 kt[1)]	0.4 kg CO_2/kg[2)]	–	–	4.6	–	–	4.6
Medium and heavy mortars projectiles	12.0	15.6 kt[1)]	0.339 kg CO_2/kg[2)]	–	–	5.3	–	–	5.3

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Table B (*continued*)

Emission category/activity	Number (million)	Activity data used /Calorific value	Averaged emission factors			Emissions			
			CO_2	CH_4	N_2O	CO_2, kt	CH_4, t	N_2O, t	CO_2-eq., kt
Kamikaze drones	0.0023	0.35 kt[1)]	1.67 kg CO_2/kg[2)]	–	–	0.58	–	–	0.58
Land mines (anti-personnel and anti-tank)	6.3	14.4 kt[1)]	0.339 kg CO_2/kg[2)]	–	–	4.9	–	–	4.9
Grenades (hand and drones)	109.4	6.6 kt[1)]	0.339 kg CO_2/kg[2)]	–	–	2.2	–	–	2.2
Small arms cartridges	3300	52.8 kt[1)]	0.339 kg CO_2/kg[2)]	–	–	17.9	–	–	17.9
Total:						283.4			283.4
The use of petroleum products for military actions									
Land military vehicles (armored combat vehicles, tanks, etc.)	–	8368.2 kt[1)] 43.1 MJ/kg	73.9 kgCO_2/GJ[3)]	0.47 kgCH_4/TJ[3)]	1.74 kgN_2O/TJ[3)]	26,604.6	169.3	626.8	26,775.4
Aviation (planes, helicopters)	–	332.6 kt[1)] 42.8 MJ/kg	71.5 kgCO_2/GJ[3)]	0.5 kgCH_4/TJ[3)]	2.0 kgN_2O/TJ[3)]	1018	7.1	28.5	1025.8
Ships	–	273.5 kt[1)] 40.4 MJ/kg	77.4 kgCO_2/GJ[3)]	7.0 kgCH_4/TJ[3)]	2.0 kgN_2O/TJ[3)]	855.2	77.3	22.1	863.2
Total:						28,477.6	253.7	677.4	28,664.4
Fires of petroleum products at petroleum storage depots									
Destroyed petroleum storage depots, oil refineries, petrol trucks	–	1557.5 kt[4)] 45.0 MJ/kg	77.2 kgCO_2/GJ[5)]	3.0 kgCH_4/TJ[5)]	0.6 kgN_2O/TJ[5)]	5408.7	210.3	42.1	5425.7
Fires of buildings and infrastructure objects									
Wooden constructions	–	8411.0 kt[6)] 18.8 MJ/kg	111.2 kgCO_2/GJ[7)]	30.0 kgCH_4/TJ[7)]	4.0 kgN_2O/TJ[7)]	17,583.7	4750	632.5	17,884.3
Other combustible materials	–	1009.3 kt[6)]	216.5 kgCO_2/t[7)]	0.24 kgCH_4/t[7)]	0.1 kgN_2O/t[7)]	218.5	242.2	100.9	252.0
Total:						17,802.2	4992.2	733.4	18,136.3
Forest fires and fires of agricultural fields									
Forest – crown fires	–	59,508 ha[8)]	244.6 tCO_2/ha[9)]	732.7 kgCH_4/ha[9)]	40.5 kgN_2O/ha[9)]	14,555.7	43,602	2412	16,415.7
Forest – surface fires	–	17,775 ha[8)]	16.0 tCO_2/ha[9)]	48.0 kgCH_4/ha[9)]	2.65 kgN_2O/ha[9)]	284.6	852	47	320.9
Agricultural fields fires	–	585,451 ha[8)]	9.78 tCO_2/ha[9)]	29.3 kgCH_4/ha[9)]	1.62 kgN_2O/ha[9)]	5728.1	17,159	949	6460.0
Other nature/landscape	–	58,578 ha[8)]	6.23 tCO_2/ha[9)]	18.7 kgCH_4/ha[9)]	1.03 kgN_2O/ha[9)]	574.4	1721	95	647.8
Total:						21,142.8	63,334	3503	23,844.4
Emissions from garbage/waste									
Disposal of damaged wooden constructions/things, household items	–	1841.7 kt[6)]	–	20.0 kgCH_4/t[7)]	–	–	36,834.9	–	1031.4
Total:						73,114.7	105,625	4956	77,385.6

[1)]Expert assessment based on publicly available partial data from MDU (2023), de Klerk et al. (2023), Censor (2023), and the media; [2)] Expert assessment based on EPA (2023a) and Oxley (1998); [3)] Based on NIRR (2023) and NIRU (2023); [4)] Expert assessment based on publicly available partial data from SEIU (2023), MEU (2023), Censor (2023) and the media; [5)] Based on NIRU (2023); [6)] Expert assessment based on publicly available partial data from KSE (2022), SEIU (2023), Censor (2023) and thr media; [7)] Expert assessment based on NIRU (2023), CFN (2023), and LSULS (2023); [8)] Expert assessment based on Matsala (2023), de Klerk et al. (2023), and SEIU (2023); [9)] Expert assessment based on NIRU (2023), de Klerk et al. (2023), and Matsala (2023).

Appendix C. Relative uncertainties of activity data and emission factors (normal distributions); relative uncertainties of emissions

Table C
Uncertainties of input data and relative uncertainties of emissions.

Emission category/activity	Relative uncertainty of activity data, %	Relative uncertainty of emission factors (95 % confidential interval), %	Relative uncertainty of emissions (95 % confidential interval), %

(continued on next page)

Table C (*continued*)

Emission category/activity	Relative uncertainty of activity data, %	Relative uncertainty of emission factors (95 % confidential interval), %			Relative uncertainty of emissions (95 % confidential interval), %			
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2-eq.
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2-eq.
The use of bombs, missiles, barrel artillery, mines, and small arms								
Barrel artillery and tank gun shells, MLRS, bombs, missiles and means of anti-missile defense, medium and heavy mortar projectiles and small caliber shells, kamikaze drones, land mines, grenades, and small arms cartridges	50[1]	20[2]	–	–	54.2	–	–	54.2
The use of petroleum products for military actions								
Land military vehicles (armored combat vehicles, tanks, MLRS, cars and cisterns, etc.)	40[1]	5[3]	18[3]	18[3]	40.3	44.1	44.0	40.3
Aviation (planes, helicopters)	40[1]	5[3]	18[3]	18[3]	40.3	43.9	44.0	40.2
Ships	40[1]	5[3]	18[3]	18[3]	40.3	44.2	43.9	40.3
Total:					37.7	32.4	38.0	39.7
Fires of petroleum products at petroleum storage depots								
Destroyed petroleum storage depots, oil refineries, petroleum stations, and petrol trucks	20[4]	3.5[5]	85.4[5]	398[5]	20.3	88.4	402	20.3
Fires in buildings and of infrastructure								
Wooden constructions	50[6]	7.0[7]	100[7]	100[7]	50.4	114	115	50.5
Other combustible materials	50[6]	7.0[7]	100[7]	100[7]	50.5	114	114	51.9
Total:					50.3	109	88.9	49.8
Forest fires and fires of agricultural fields								
Forest – crown fires	20[8]	43[9]	41[9]	185[9]	47.6	45.8	188	44.2
Forest – surface fires	20[8]	43[9]	41[9]	185[9]	47.6	45.9	188	44.1
Agricultural field fires	20[8]	92[9]	23[9]	28[9]	94.9	30.5	34.5	84.7
Other nature/landscape	20[8]	100[9]	39[9]	48[9]	103	44.0	52.2	91.8
Total:					41.8	32.6	130	38.2
Emissions from garbage/waste								
Disposal of damaged wooden constructions/things, household items	50[6]	–	47.3[7]	–	–	69.4	–	69.4
Uncertainty of total emissions:					22.7	31.5	93.0	22.3

[1)]Expert assessment based on publicly available partial statistical/activity data from MDU (2023), Censor (2023) and the media; [2)]Expert assessment based on EPA (2023a) and Oxley (1998); [3)]Based on NIRR (2023) and NIRU (2023); [4)]Expert assessment based on publicly available partial data from SEIU (2023), MEU (2023), Censor (2023) and the media; [5)]Based on NIRU (2023); [6)]Expert assessment based on publicly available partial data from KSE (2022), SEIU (2023), Censor (2023) and the media; [7)]Expert assessment based on NIRU (2023), CFN (2023), and LSULS, 2023; [8)]Expert assessment based on Matsala (2023), de Klerk et al. (2023), and SEIU (2023); [9)]Expert assessment based on NIRU (2023), NIRR (2023), de Klerk et al. (2023), and Matsala (2023).

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