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РАДІОБІОЛОГІЯ ТА РАДІОЕКОЛОГІЯ
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^{137}Cs RELEASE FROM COMBUSTIBLE MATERIALS BURNING UNDER DIFFERENT ENVIRONMENTAL CONDITIONS IN THE CHORNOBYL EXCLUSION ZONE

Wildfires in radioactively contaminated territories in northern Ukraine have intensified over the past decade, raising concerns about the atmospheric resuspension of technogenic radionuclides, particularly ^{137}Cs. Despite numerous studies on this topic, empirical data on radionuclide emissions from burning combustible materials in near-natural environments remain limited. This study provides new estimates of ^{137}Cs release during the combustion of moss, herbaceous vegetation, forest litter layers, and green pine branches collected at six Chornobyl sites representing pine and birch forests as well as meadows.

Using a custom-built aerosol filtration system, we quantified ^{137}Cs activity in smoke aerosols and determined its fraction of release relative to both fuel activity and the total ecosystem inventory. The results revealed a clear dependence of the cesium radioisotope release on the vertical position within the pine litter profile during burning: the upper layers (moss and fresh litter) contributed a greater amount to the atmospheric release, despite having a lower total ^{137}Cs activity compared to the deeper humified layer. An increase in moisture content (from 5–13 % to 15–29 %) significantly reduced radionuclide emissions from pine litter (by approximately one order of magnitude), whereas combustion of green pine branches with moisture contents exceeding 100 % had unexpectedly high ^{137}Cs releases (up to 24 %). The mean proportion of cesium radioisotope release increased along the sequence: pine forest – birch forest – meadow (0.075–0.45 %) for mechanically intact and dried above-ground layers of moss/grass vegetation and litter/detritus.

The obtained ^{137}Cs release factors relative to its total activity in the studied sites generally align with empirical estimates and modelling results for the spring 2020 Chornobyl wildfires, where this parameter has been estimated to range between 0.01 and 0.4 %. Our materials indicate that ^{137}Cs release in the Chornobyl landscapes is unlikely to exceed 1 % of its gross inventory in ecosystems, even during large-scale wildfires.

Keywords: radionuclide, radioactive aerosol, emission, wildfires, combustible materials.

1. Introduction

Over the last decade, the northern regions of Ukraine have been characterized by a substantial increase in the proportion of large wildfires, and the Chornobyl Exclusion Zone (CEZ) was no exception: during this relatively short period (2015–2024), at least three years (2015, 2020, and 2022) experienced total burned areas exceeding 10,000 ha. Although fires also occurred in other years, their sizes were relatively small (up to 1,000 ha). The largest wildfires in the radioactively contaminated region occurred in April 2020, when about 67,000 ha of the CEZ (with a total area of approximately 260,000 ha) were affected by fire [1, 2]. The active burning phase of those wildfires lasted for more than 20 days [1, 2]. This period has been the most thoroughly studied in aspects of assessing radionuclide resuspension into the atmosphere caused by the upward transport of smoke aerosols during wildfires on radioactively contaminated territories since the Chornobyl Nuclear Power Plant (ChNPP) accident (1986), based on various simulation approaches [3].

At the same time, publications providing empirical estimates of the share of technogenic radionuclide emissions from combustible materials into the atmosphere are relatively few [4–7], and even fewer of them were conducted under natural or near-natural conditions [8, 9]. One of the primary tasks of these previous studies was to probabilistically assess the effective internal dose resulting from the inhalation of radioactive combustion products by local residents living near the CEZ and by personnel directly engaged in firefighting operations. The past findings indicated that the additional dose from such exposure was negligible compared to the already existing technogenic radionuclide contamination in the region outside the CEZ [1]. In contrast, for firefighting personnel operating in the most contaminated areas surrounding the ChNPP, particularly within the so-called "Red Forest", the additional internal effective dose may reach approximately 30 % of the external dose formed by gamma radiation [10, 11]. Although available empirical evidence shows that smoke aerosols emitted during wildfires exert an insignificant radiological impact on human health outside the CEZ: this remains true even if wildfires occur in the most radioactively contaminated areas and their smoke plume crosses adjacent territory. However, the information on social media about fires in the Chornobyl landscapes often triggers heightened public concern among residents of nearby regions and personnel working within the CEZ [1]. The emergence of such social tension among the population is largely attributable to insufficient public awareness as well as the absence of accessible and reliable data. Thus, new empirical assessments of the fraction of radionuclide activity resuspended during the combustion of contaminated materials are essential not only for expanding the available experimental dataset but for supplying more objective information on the actual level of radiological risk faced by different social groups in Ukraine.

In this study, the authors present the results of an evaluation of the release of ^{137}Cs activity from the combustion of various types of combustible materials, including moss, grass vegetation, forest litter, and green pine branches with shoot diameters up to 1.0 cm. The materials were collected from different Chornobyl ecosystems: coniferous forest (Scots pine – *Pinus sylvestris*), deciduous forest (Silver birch – *Betula pendula*), and meadow (represented by herbaceous vegetation mainly from the *Poaceae* family). Particular attention was given to ^{137}Cs emissions during combustion at different moisture contents and within individual layers of organic soil horizons in pine stands, which have most frequently been affected by wildfires in the study region. Some samples of moss, herbaceous vegetation, and forest litter were collected intact: without disturbing their natural structure, in order to preserve the in-situ distribution of ^{137}Cs activity and moisture content during active combustion experiments.

2. Materials and methods

2.1. Location and field sampling

Field material collection has been conducted at six sites (see more detail in Fig. 1 and Table 1) located 3.5–5.6 km from Unit 4 of the ChNPP. A tree inventory was carried out at all forest sites. The obtained biometric parameters of the trees were then used to calculate the main forest stand parameters, such as average age (A), stand diameter (D), average height (H), and basal area or cross-sectional area at breast height (BA) (see Table 1). Combustible material samples were collected from at least three sampling points at each site. The sampling areas for herbaceous vegetation, mosses, and the organic soil horizon ranged from 0.08 to 1.0 m^2 at each point. After taking the layers suitable for combustion, mineral soil samples were immediately collected at the same points to a depth of 20 cm to determine the ^{137}Cs activity concentration and to assess the contamination density of soils with the studied radioisotope at the selected sites (see Table 1). Specialized cylindrical core samplers with an internal diameter of 5 cm and a length of 20 cm were applied for this purpose.

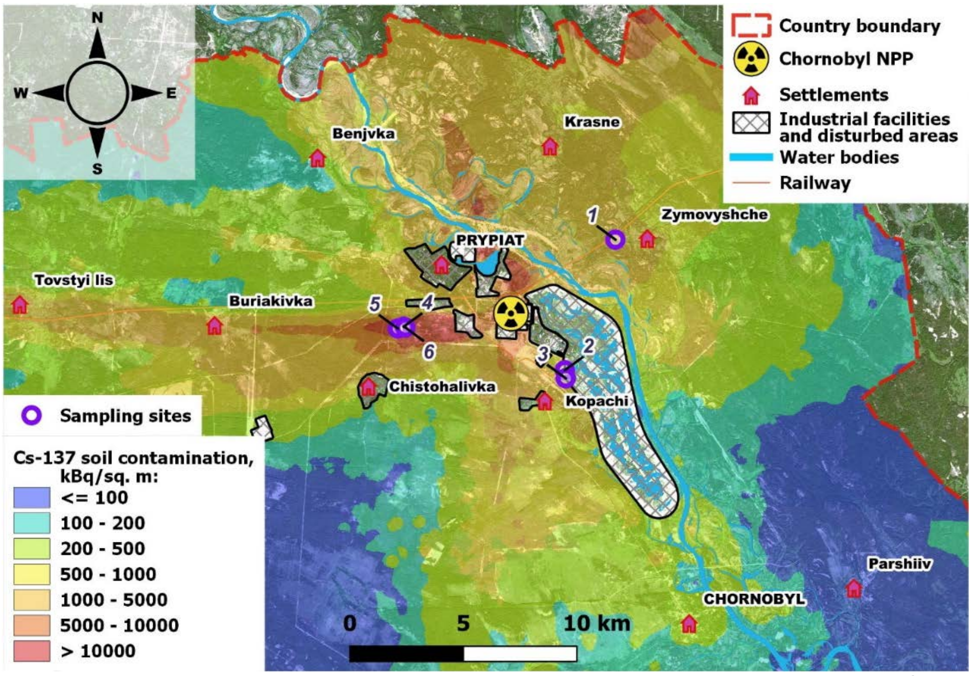


Fig. 1. Location of the sampling sites with their ID numbers (shown as white-masked digits) and ^{137}Cs contamination density of soil as of 1 January 2021. The background is a Sentinel-2B satellite composite image acquired in October 2020. (See color Figure on the journal website.)

Table 1. **Short description of sampling sites**

Site No.	Year of sampling	Landscape	A, yr	D, cm	H, m	BA, $m^2 \cdot ha^{-1}$	^{137}Cs contamination density of mineral soil as of January 2021, $kBq \cdot m^{-2}$
1	2017	Pine forest	55	17	20	44	590 ± 380
2	2024	Pine forest	62	18	16	43	3980 ± 1280
3	2024–2025	Pine forest	62	25	26	48	2300 ± 70
4	2025	Birch forest	35	21	17	25	28400 ± 11000
5	2025	Meadow	–	–	–	–	14700 ± 6400
6	2025	Open-canopy pine stands	23	7.6	5.0	1.3	44500 ± 23700

Notes. A is the average age of the stand; D is the stand diameter; H is the average stand height; BA is the basal area.

To examine the patterns of ^{137}Cs activity emission during the burning of different layers of combustible materials located near the mineral soil in pine forests, their samples were collected separately from the green forest floor (GFF: consisting mainly of mosses and sometimes grasses – primarily from the *Poaceae* family) and from the individual layers of pine forest litter: the fresh litter or litterfall layer (L), the fragmented layer (F), and the humified layer (H) [12]. These activities were carried out at Site 1 (see Table 1).

The assessment of the secondary resuspension of this radionuclide during wildfires under different moisture contents was performed using combined samples of GFF and the organic soil horizon collected at Sites 2–3 in pine stands. All layers were left undisturbed during sampling to preserve their natural structure before burning; however, a substantial portion of the lower litter layer directly adjacent to the mineral soil could remain uncollected under such conditions. Additionally, three supplementary sampling points were selected at this stage to determine the moisture content in the just-mentioned forest components.

The determination of "maximum" radionuclide emissions in the case of burning of litter and herbaceous vegetation in three landscape types (pine forest, birch forest, and meadow) was based on field materials from Sites 3–5. In these experiments, all herbaceous vegetation and litter were dried to air-dry conditions before burning. These layers were collected with minimal disturbance, including the lower humified organic soil horizon at each sampling point, which was not combusted in experiments with different moisture contents. It was included and spread out before burning to reproduce the natural arrangement of the studied layers within the ecosystem.

At Site 6 (see Table 1), five to seven live green branches of Scots pine were selected from three low trees and burned immediately after sampling using a butane gas burner. Each branch bundle was subjected to 10 s of ignition and 50 s of self-burning; this operation was repeated three times. This procedure was intended to estimate the likely ^{137}Cs release during crown fires in pine stands.

2.2. Burning combustible materials and sampling of smoke aerosols from the air

Combustion of the collected organic material was performed using a specially designed and hand-made field-scale setup located outside the sampling sites (Fig. 2). Since most incineration work was carried out during dry weather conditions to avoid the occurrence and spread of actual fires in the surrounding ecosystems, burning was conducted in areas with minimal natural fuel inventories.

The field-scale setup consisted of an aerosol sampler, a filtration unit, a vacuum pump, and air hoses (see Fig. 2, *a* and *b*). The aerosol sampler had the form of a collapsible square pyramid (see Fig. 2, *c*) with a base area of 0.96 m^2 and a height of 0.8 m. Its sides were made of 0.5 mm-thick mirror-finished stainless-steel sheets (AISI 304 grade) that could be easily disassembled for transportation. Combustible materials were placed on a 1 m^2 square stainless-steel plate positioned beneath the sampler at a height of 10–20 cm. Combustion of the biomass samples occurred solely due to the release of their intrinsic thermal energy, without the use of external ignition sources, except in the case of green pine branches (as described above). The burning time of organic material ranged from 7 min for litter and herbaceous vegetation collected from a meadow landscape to 4.5 h for pine forest litter with a moisture content of 15–29 %. The duration of combustion depended on the temperature of the surface of the residues after active burning, which was measured using a BEBETECH GM320 infrared pyrometer. The fire experiment was considered complete when the temperature of the entire surface of the burned residue sample decreased to below 60 °C.

Smoke aerosol filtration was performed using Petryanov's filter cloth [10, 13]. The effective filtering surface area of the cylindrical support with perforations, onto which the cloth was wound (see Fig. 2, *d*), was approximately 0.19 m^2. This filtration element was installed inside a sealed container (a standard 40 L plastic barrel). Standard water hoses with reinforced double-layer walls made of heat-resistant polyvinyl chloride (working temperature up to 105 °C, length of 3.0 m, and inner diameter of 20 mm) were used to transfer air containing smoke aerosols from the sampler to the filtration unit.

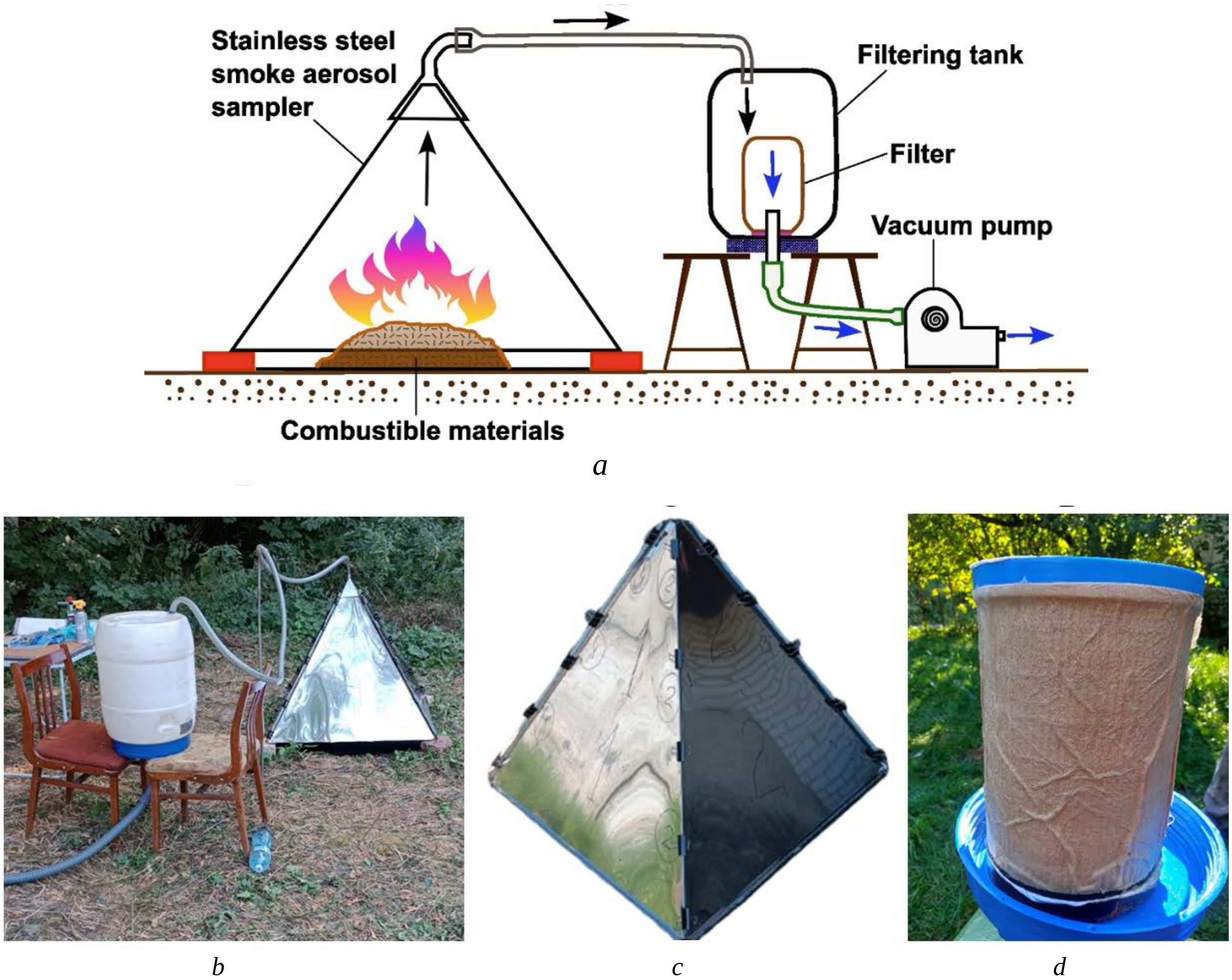


Fig. 2. Field-scale combustion setup for biomass samples with aerosol sampling system: schema (*a*); general view (*b*); aerosol sampler (collapsible pyramid) with stainless-steel sheets (*c*); filtration unit with Petryanov's filter cloth after completion of aerosol pumping (*d*). (See color Figure on the journal website.)

When combustion of the sample was completed, the contaminated Petryanov's filter cloth was carefully removed. All components of the aerosol sampler, filter unit, and hoses (after being longitudinally cut) that had come into direct contact with smoke aerosols were wiped clean with paper towels moistened with mineral turpentine or special acetone solution. Next, the Petryanov's filter cloth and the used cleaning towels were packed in airtight bags and transported to the laboratory. Before and after burning, the organic samples were weighed to calculate the "burnout" fraction. An aliquot of the residual combustible material remaining after combustion was collected to determine the ^{137}Cs content.

2.3. ^{137}Cs measurement and calculations

Before measuring ^{137}Cs activity, all soil samples were dried for three days at 105 °C and mechanically homogenized. Other samples, including organic combustion residues, contaminated aerosol filters, and paper towels, were ashed at 440 °C for three days. This extended ashing time, compared with the standard protocol (24 h) [14], was applied to ensure complete oxidation of organic material, as partial structural preservation was observed after one day of thermal treatment. The resulting ash was subsequently dissolved in 1 M HNO3 [14]. Determination of ^{137}Cs activity in the prepared samples was performed using cylindrical containers with a volume of 130 mL and a low-background gamma spectrometer equipped with a high-purity germanium detector (GEM-30185, EG&G ORTEC, USA) and a multichannel analyzer (ASPEC-927). The system was fitted with passive shielding and operated with GammaVision-32 software [15]. The detection limit for the studied radionuclide in each sample was 1 Bq, and the measurement uncertainty did not exceed 8 % ($p = 0.95$). All values of ^{137}Cs content parameters were recalculated as of 1 January 2025.

Computation of intermediate and final results, as well as the construction of plots, was performed using Microsoft Excel software. Descriptive statistics, such as the arithmetic mean (AM) and standard deviation (SD), were applied to summarize the obtained results.

The ^{137}Cs contamination density at each site ($D_{Cs\text{-}137}$, kBq m^{-2}) was estimated based on the mass of the air-dried sample (M_{dry}, kg), the measured activity concentration of the radionuclide in the sample ($AC_{Cs\text{-}137}$, Bq kg^{-1}), and the sampling area of the corresponding ecosystem element (S, m^2): GFF, herbaceous vegetation, or organic/mineral soil horizon according to the Eq. 1:

$$D_{Cs-137} = \frac{AC_{Cs-137} \cdot M_{dry}}{S}. \quad (1)$$

The assessment of ^{137}Cs activity density in aboveground woody biomass was carried out using a regression model for tree-biomass estimation (t·ha^{-1}) [16] and the previously identified relationships between ^{137}Cs activity concentrations in forest litter layers and tree components (wood, bark, branches, and needles/foliage) [12]. Measurement of ^{137}Cs content in the fresh litter layer enabled the calculation of its concentration in stem wood at the forest sites, after which this radionuclide parameter was recalculated for other tree organs using generalized ratios of the studied radioisotope activity concentration between the organs of pine and birch trees [12]. This approach made it possible to determine the ^{137}Cs inventory for individual forest ecosystem elements and to estimate its total activity within the investigated plots in kBq m^{-2}.

Moisture content (ω, %) of the collected combustible material samples at each site was calculated as:

$$\omega = \frac{\left(m_{wet} - m_{dry}\right)}{m_{dry}} \cdot 100, \quad (2)$$

where m_{wet} and m_{dry} represent the fresh (immediately after sampling) and air-dry weights of the sample (g), respectively.

Additionally, based on the results of small-scale fire experiments, the authors determined the percent residual fraction of organic samples after combustion by dividing the mass of combustible material remaining after burning by its initial mass before combustion and multiplying by 100.

Release factors of ^{137}Cs activity from specific combustible materials into the atmosphere (RF_{fuel}, %) and relative to the total radionuclide inventory in the ecosystem (RF_{total}, %) were evaluated using Eqs. 3 and 4:

$$RF_{fuel} = \frac{A_{emission}}{A_{fuel}} \cdot 100, \quad (3)$$

$$RF_{total} = RF_{fuel} \cdot \frac{D_{fuel}}{D_{total}}, \quad (4)$$

where $A_{emission}$ is the ^{137}Cs activity of smoke aerosols deposited on the filter surface of the field-scale combustion setup (Bq); A_{fuel} is the radionuclide activity in the combustible material before burning (Bq): it is calculated as the sum of the radioisotope activity in the burned remains of the biomass fuel, and the activity deposited on the filter surface, and separately on other surfaces of the aerosol sampling system (Bq); D_{fuel} is the ^{137}Cs contamination density in the ecosystem element used for experimental combustion (kBq m^{-2}); and D_{total} is the total ^{137}Cs contamination density for all ecosystem per unit area (kBq m^{-2}).

In this article, the terms "release", "emission", and "resuspension" are used interchangeably to describe the same phenomenon and parameter. The primary dataset containing ^{137}Cs activity measurements for aerosols and combustible materials, including supporting information for individual sample burning, has been deposited in the Zenodo data repository (https://doi.org/10.5281/zenodo.17991452) [17]).

3. Results and discussions

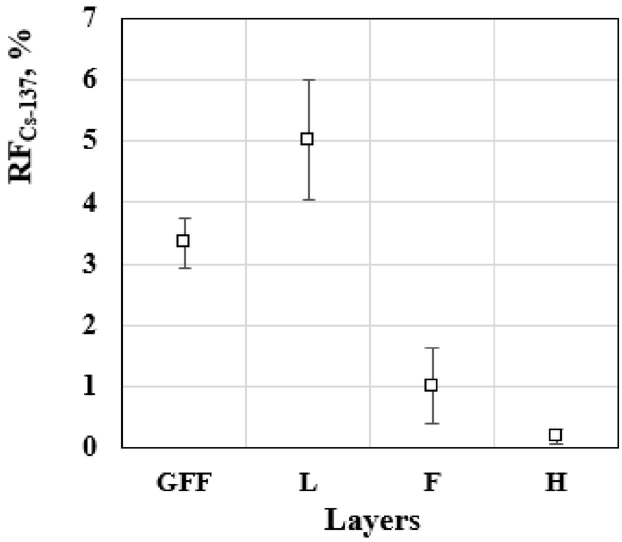
The main summarized parameter values for the fire experiments conducted in this study are presented in Table 2. The output data on ^{137}Cs RF_{fuel} during the combustion of pine organic soil cover demonstrate considerable variability even under similar conditions (see details at https://doi.org/10.5281/zenodo.17991452) [17]. For example, when burning the moss layer and pine litter separately from Site 1, compared with the combined undisturbed layers from Site 3 (previously dried to an air-dry state), the obtained RF_{fuel} values differed by nearly one order of magnitude (see Table 2). The probable reason for this phenomenon lies in the markedly heterogeneous vertical distribution of ^{137}Cs within the organic and mineral soil horizons [12], as well as in differences in the applied methodological approaches. At Site 1, sampling was carried out layer by layer, and the remnants of mineral soil in the humified litter layer were easily separated after drying; therefore, inorganic soil inclusions had little influence on the output values. In contrast, at Site 3, all litter layers were collected together to preserve the natural vertical distribution of the radionuclide and moisture content, so the mineral soil residues at the bottom of the litter layer were not removed, since active separation would destroy the native structural pattern of this forest component. It is precisely at the "litter-mineral soil" boundary that the largest portion of ^{137}Cs activity is typically observed in the Chornobyl landscapes (about 50% of the total activity in forest ecosystems) [12, 18–20]. Therefore, the inclusion of even a small fraction of upper mineral soil can significantly reduce the ^{137}Cs RF_{fuel} values, as these mineral particles contain extremely high ^{137}Cs activity concentrations but do not participate directly in combustion.

Table 2. **Main parameters of small-scale fire experiments on ^{137}Cs emissions into the atmosphere during the combustion of collected samples (see details at Zenodo repository [17])**

Site No.	Landscape	Type of combustible material	Number of samples	Mass of the sample in the precombustion state, g	Moisture content, %	Portion of remains after burning,%	RF_{fuel}, %	RF_{total}, %
1.	Pine forest	Separation combustion for GFF and litter layers (L, F, H)	3	Total: 829±311 GFF: 73±9 L: 63±14 F: 258±127 H: 435±311	<1	Total: 40±1 GFF: 21±1 L: 14±2 F: 30±1 H: 59±1	Total: 0.60±0.35	Total: 0.053±0.043
2.	Pine forest	Undisturbed litter layers (L and F)	3	506±120	15–29*	47±13	0.16±0.12	0.0046±0.0046
3.	Pine forest	Undisturbed GFF (moss) and litter layers (L and F)	4	89±13	5–13*	27±7	1.7±1.3	0.050±0.050
3.	Pine forest	Undisturbed GFF (moss) and all litter layers	3	181±11	<1	41±3	0.075±0.015	0.011±0.004
4.	Birch forest	Undisturbed GFF (grassy vegetation) and all litter layers	3	127±4	<1	51±3	0.15±0.05	0.0019±0.0016
5.	Meadow	Herbaceous vegetation and its detritus	3	69±2	<1	15±4	0.45±0.19	0.0068±0.0054
6.	Open-canopy pine stands	Green pine branches (branches <1 cm, twins and needles)	3	306±113	106–207	36±4	18.0±6.1	0.19**

Notes. *The moisture content range in the collected forest litter layers. ** Calculated assuming a basal area of the pine stand of 13.6 m^2 ha^{-1} (corresponding to a relative stocking of 0.9), which represents a fully developed forest stand. For the existing low-density stand at Site 6 (1.3 m^2 ha^{-1}), no data on stand biomass is available in the handbook references [16].

Separate combustion of moss and litter layers from Site 1 clearly shows that the proportion of ^{137}Cs RF_{fuel} decreases with the burning of deeper layers (Fig. 3, *a*). Fresh litterfall exhibited the highest levels of radionuclide release (AM ± SD :5.0 ± 2.4 %), followed by the moss cover (3.3 ± 1.0 %), whereas the humified layer was characterized by the lowest values (0.19 ± 0.19 %). Moreover, suppose the layers were hypothetically burned from the surface down to the mineral soil: by the same emission coefficients for each layer as obtained from the separate combustions. In this case, the generalized value of this parameter decreases sharply once combustion reaches the humified litter layer (up to 0.60 ± 0.43 %) (see Fig. 3, *b*). When the humified layer is omitted, the RF_{fuel} value increases to 1.8 ± 0.8 %, which closely corresponds to the values obtained for undisturbed samples from Site 3 (1.7 ± 1.0 %) that combined the moss cover (GFF) with the fresh litterfall (L) and fragmented (F) litter layers at moisture contents of 5–13 %



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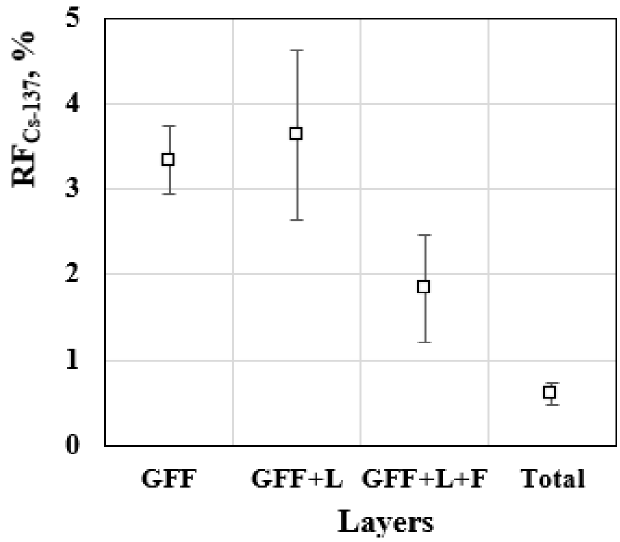

b

Fig. 3. ^{137}Cs release factors for the separate combustion of GFF and pine litter layers (L, F, H) (*a*) and the recalculated values for their combined burning along the vertical profile down to the mineral soil horizon (*b*).

(see Table 2). Thus, although the majority of ^{137}Cs activity in forest litter is localized in the lower humified part (about 70–90 %) [12, 18–20], the results of this study indicate that the upper layers are the primary source of cesium radioisotope release into the atmospheric air during combustion, even under conditions of extreme drought. According to the calculations for Site 1, the distribution of emitted ^{137}Cs activity is as follows: moss (GFF) – 39 ± 13 %, fresh litter (L) – 14 ± 7 %, fragmented litter (F) – 24 ± 20 %, and humified litter (H) – 23 ± 23 %.

The results obtained from burning of undisturbed pine litter (L and F layers) with different moisture contents were quite predictable (see Table 2, rows 2 and 3): increasing moisture led to a reduction in ^{137}Cs release into the air (RF_{fuel}) and to an increase in the mass of unburned residues. According to field materials, when samples with moisture levels of 5–9 % and 15–29 % were combusted, the radionuclide emission in the latter case was nearly an order of magnitude lower, while the mass fraction of GFF and litter residues after combustion was 1.5–2 times higher. Simultaneously, when burning green pine branches with moisture exceeding 100 % (see Table 2, row 7), ^{137}Cs emissions in one of the experiments reached the highest observed value (24 %). This indicates fundamentally different mechanisms of radionuclide release during the combustion of forest litter versus green branches. The most likely reason for this enhanced volatilization of the radioisotope from “living” vegetation organs is that ^{137}Cs is predominantly present in a soluble form within intracellular moisture [21, 22], which readily evaporates when heated by an open flame. This phenomenon was observed only in the present study, as a detailed review of the scientific literature did not reveal any descriptions of a similar process. Therefore, further studies are required to confirm this observation. Even though the proportion of studied radionuclide localized in pine crowns is relatively small (maximum values reach only about 5 % of the total ^{137}Cs inventory in forest ecosystems [12]), crown fires in pine forests of the CEZ can nevertheless be considered one of the major contributors to the ^{137}Cs resuspension into the atmosphere and its long-distance transport from the areas of primary radioactive fallout in 1986. Moreover, under natural wildfire conditions, the combustion of pine crowns likely occurs at substantially higher temperatures and for a longer duration than in our experimental setup, which probably leads to even greater fractions of radionuclide release in aerosol forms.

Fire experiments involving the combustion of undisturbed above-ground layers of moss/grass vegetation and litter/detritus from different landscape types under air-dry conditions showed that the proportion of ^{137}Cs activity emitted from the samples exhibited an increasing trend along the sequence: pine forest – birch forest – meadow (see Table 2: 0.075 % – 0.15 % – 0.45 %, respectively). However, when the calculated RF_{fuel} values were multiplied by a weighting coefficient representing the sample mass per unit area (see Table 2, column 5), the significant differences between the resulting indicator values for the compared ecosystems disappeared. This effect arises because, within this landscape sequence, the inventory of combustible materials at the study sites is inversely related to the magnitude of ^{137}Cs RF_{fuel}. Consequently, if the organic materials at all plots had comparable average radionuclide activity concentrations, their ^{137}Cs resuspension would be expected to have similar levels. For this reason, the results of this study suggest that, despite the high litter stocks in pine forests, the other ecosystem types examined here "compensate" for the lower biomass through proportionally higher fractions of radionuclide activity emission during combustion. Thus, in terms of the potential proportion of ^{137}Cs release from biomass fuel, the examined ecosystems can be considered broadly equivalent.

A comparison of the RF_{fuel} values obtained in this study with those reported earlier shows that, in principle, the results for pine forests are consistent with earlier estimates of ^{137}Cs release during real wildfires in the most contaminated areas of the CEZ. Previous publications generally reported emissions of about 2–4 % [8, 9], which corresponds to the values calculated for the upper layers of forest litter and moss that were combusted in our experiments. However, some contradictions remain. In the work of V.I. Yoschenko et al. (2006) [9], the calculated RF_{fuel} for the meadow area (up to 0.5 %) was lower than that for the pine forest. Although this value is comparable to the output data of our measurements for meadow (0.45 ± 0.15 %), it does not support our observation that undisturbed forest litter in pine stands exhibits substantially lower emissions (0.075 ± 0.015 %) than meadow fuel. This discrepancy is likely caused by differences in sampling methodology, which plays a crucial role and can substantially influence the resulting resuspension values, as noted earlier in the first and second paragraphs in the Results section of this paper.

It should also be emphasized that previous studies conducted under laboratory conditions (where combustion was sustained using external heating sources) often reported ^{137}Cs emissions from combustible materials (litter, leaves, needles, branches) as high as 40–92 % in individual experiments [4–6]. These values far exceed those obtained in any field-based investigations, indicating that such laboratory results must be interpreted with great caution, as they may not adequately reflect real combustion processes during wildfires. Simultaneously, natural or semi-natural experiments such as this study involve large uncertainties. In every such experiment, part of the activity may be lost due to the ingress of smoke aerosols into the ambient atmosphere outside the filtering system, and because it is practically impossible to completely clean all internal surfaces of the sampling system from deposited aerosols.

Despite extensive data on radionuclide release from both field observations and laboratory research, there is still a lack of sufficiently robust, large-scale datasets collected under natural wildfire conditions. Therefore, ongoing research in this field remains crucial.

A review of several early scientific papers assessing the resuspension of technogenic radionuclide activity in the CEZ during wildfires shows that many of them used clearly overestimated radionuclide release rates. For example, the works by N. Evangeliou et al. (2014, 2015, 2016) applied an assumed emission value of 20 % for ^{90}Sr and ^{137}Cs relative to the total soil contamination density: levels that have never been observed under current environmental conditions in the studied region [23]. The selection of these values by the authors was likely influenced by laboratory-based results that did not incorporate empirical data on the combustion of natural fuels under conditions approximating real wildfires [4–6]. At the same time, a number of studies focused on the large wildfires that occurred in April 2020 in the CEZ and adjacent territories during drought conditions reported significantly lower and more realistic ^{137}Cs emission levels [3]. The ^{137}Cs RF_{total} for the most intense wildfires has been estimated at approximately 0.01–0.4 %, based on the results of various modeling approaches reported by different researchers [3], as well as simple additional calculations (dividing the total emitted radionuclide activity by its gross inventory in the burned areas during specific periods). The observations obtained in this paper (see Table 2, last column) and in other near-natural experiments also indicate that the ^{137}Cs EF_{total} value rarely approaches even 1 % of the gross ecosystem inventory. Such elevated values would be possible only under conditions of very high ^{137}Cs aggregated transfer factors from soil into plant biomass and its subsequent substantial accumulation in dead organic matter near the ground surface. This situation can occur on poor sandy sod-podzolic soils, which are common in the region and may store up to 35% of the total ^{137}Cs inventory in pine litter [12]. As demonstrated by the results of this investigation, a similarly high release may also arise in forest ecosystems with high biogeochemical mobility of the radionuclide during crown wildfires in dense coniferous stands.

The list of radionuclides present in the CEZ is not limited to ^{137}Cs; it is much broader, and their contribution to biota exposure becomes significant near the ChNPP. Empirical measurements of their activity concentrations in the air during real wildfires have shown that, nowadays, several of these radioisotopes (primarily ^{90}Sr, $^{238-240}Pu$, and ^{241}Am) provide substantially higher internal effective radiation doses for personnel directly involved in firefighting than ^{137}Cs [3, 11]. At the same time, these radionuclides remain the least investigated. Therefore, further research is essential for the quantitative assessment of their release during wildfires. However, such studies require more advanced radiometric methods and costly equipment, which makes them extremely difficult to implement at the necessary high international level in Ukraine under current conditions without external support.

4. Conclusions

The results of this study provide new empirical observations on the fraction of ^{137}Cs released from combustible materials during burning under different environmental and experimental conditions in various Chornobyl landscapes. The combustion of individual moss and litter layers obtained from pine stands demonstrated a clear decrease in the proportion of ^{137}Cs emission with increasing depth and degree of decomposition within the organic soil horizon (from 5.0 ± 2.4 % to 0.19 ± 0.19 %). Therefore, although the humified (bottom) litter layer contains the largest portion of the radionuclide inventory in forest litter (up to 70–90 % in pine stands) [12, 18–20], it did not exceed the radionuclide release observed from the upper moss layer and fresh litterfall under the near-natural combustion conditions used in this investigation.

Fire experiments with mechanically undisturbed above-ground fuel samples from sites representing different landscape types (pine forest, birch forest, and meadow), dried to air-dry conditions, revealed an increasing trend in ^{137}Cs release from pine stands (0.075 ± 0.015 %) toward grasslands (0.45 ± 0.19 %). However, when differences in fuel mass per unit area were taken into account, these trends remained but were no longer statistically significant. Thus, the above-ground combustible materials of the studied ecosystems can be considered broadly comparable in their potential to the radioisotope activity release under similar activity concentrations. Although increasing moisture content in pine litter clearly reduces radionuclide resuspension, the combustion of fresh green (live) pine branches, characterized by very high moisture content in crown tissues (106–207 %), simultaneously exhibited unusually high ^{137}Cs emissions (up to 24 %). This phenomenon has not been previously described in scientific publications.

A comparison of the existing near-natural experimental results with earlier modelling research demonstrates that many of the latter substantially overestimated real radionuclide RF_{total} [23], likely due to the use of laboratory-based combustion scenarios that do not reflect natural wildfire conditions [4–6]. More recent simulation studies and field-based observations (including the results of this investigation) indicate that ^{137}Cs RF_{total} during wildfires in the CEZ typically ranges between 0.01 and 0.4 %, and would achieve 1 % of the gross ecosystem inventory only under exceptional circumstances.

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ВИКИД ^{137}Cs ПІД ЧАС ЗГОРЯННЯ ГОРЮЧИХ МАТЕРІАЛІВ ЗА РІЗНИХ УМОВ НА РАДІОАКТИВНО ЗАБРУДНЕНИХ ЗЕМЛЯХ

Ландшафтні пожежі на радіоактивно забруднених територіях північної України інтенсифікувалися за останнє десятиліття, що викликає занепокоєння щодо ресуспензії техногенних радіонуклідів, в тому числі ^{137}Cs. Незважаючи на численні дослідження з цього аспекту, емпіричні дані щодо викидів радіонуклідів при спалюванні горючих матеріалів в умовах, наближених до природних, залишаються фрагментативними. За результатами цього дослідження отримані нові спостереження щодо викиду ^{137}Cs під час згоряння моху, трав'янистої рослинності, шарів лісової підстилки та зелених (живих) гілок сосни, зібраних на шести ділянках у зоні відчуження, що представляють соснові та березові ліси, а також луки.

Використовуючи спеціально створену систему аерозольної фільтрації, було кількісно оцінено активність ^{137}Cs у димових аерозолях і визначено його частку викиду відносно активності у спаленому матеріалі, так і загального запасу на закладених ділянках. Вихідні розрахунки дали змогу ідентифікувати залежність величини викиду радіоізотопу від вертикального розміщення шару в профілі соснової підстилки при їх роздільному спалювані, водночас верхні шари (мох і свіжий опад) мали більший внесок у викид активності радіонукліда, незважаючи на меншу активність ^{137}Cs порівняно з глибшим, гуміфікованим шаром. Збільшення вмісту вологи (з 5–13 % до 15–29 %) суттєво зменшило рівень емісії радіонукліда із соснової підстилки (приблизно на один порядок), тоді як горіння зелених соснових гілок із вмістом води понад 100 % мали несподівано високі викиди ^{137}Cs (до 24 %). Середньозважена частка емісії радіоізотопу зростала у послідовності: сосновий ліс – березовий ліс – луг (0,075–0,45 %) для механічно непорушених і повітряно сухих поверхневих шарів мохової/трав'яної рослинності та підстилки/детриту.

Отримані коефіцієнти викиду ^{137}Cs відносно загальної активності на досліджуваних ділянках переважно узгоджуються з емпіричними оцінками та змодельованими результатами лісових пожеж навесні 2020 р. в Чорнобильській зоні відчуження, де цей показник оцінювався в межах 0,01–0,4 %. Зібрані у дослідженнях матеріали свідчать, що викиди ^{137}Cs у чорнобильських ландшафтах навряд чи перевищать 1 % від загального запасу в екосистемах, навіть під час масштабних лісових пожеж.

Ключові слова: радіонуклід, аерозоль, емісія, лісові пожежі, горючі матеріали.

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