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Special Series

Wildfires in the Chernobyl exclusion zone—Risks and consequences

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EDITOR'S NOTE:

This article is part of the special series “Ecological consequences of wildfires.” The series documents the impacts of large-scale wildfires in many areas of the globe on biodiversity and ecosystem conditions in both terrestrial and aquatic ecosystems, the capacity for systems to recover, and management practices needed to prevent such destruction in the future.

Abstract

Following the 1986 Chernobyl accident, an area approaching 5000 km² surrounding the nuclear plant was abandoned, creating the Chernobyl exclusion zone (CEZ). Although this area likely contains the most radioactive terrestrial ecosystem on earth, the absence of humans and associated activities for nearly 35 years since the accident has resulted in increases in wildlife numbers. Both the Belarussian and Ukrainian components of the CEZ are now designated as nature reserves; together they form one of Europe's largest protected areas and have been described as an iconic example of rewilding. Forests and former agricultural land (now scrub) dominate the CEZ and wildfires are an annual event. In April 2020, the CEZ suffered its most widespread fires to date when greater than 800 km² of the 2600 km² Ukrainian portion of the CEZ was burnt. Large-scale fires in the CEZ have implications for wildlife, as they do elsewhere, but they also pose additional radioecological and radiological protection questions. We discuss the implications of wildfires in the CEZ, considering effects on wildlife and changes in radionuclide mobility. We also demonstrate that the risk to firefighters and the wider public from the inhalation of radionuclides in smoke resulting from fires in the CEZ is likely to be low. However, further experimental and modeling work to evaluate potential doses to firefighters from inhaled radioactive particles would be valuable, not least for reassurance purposes. *Integr Environ Assess Manag* 2021;00:1–10 © 2021 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Chernobyl, Cs-137, Sr-90, Radionuclide availability, Smoke inhalation

INTRODUCTION

The 1986 Chernobyl disaster remains the world's largest nuclear accident (Smith & Beresford, 2005). The subsequent

abandonment of approximately 2600 km² of land surrounding the nuclear power plant in Ukraine and a similar-sized area in Belarus created the Chernobyl exclusion zone (CEZ). Although contamination levels vary considerably across the CEZ (e.g., Kashparov et al., 2018, 2020), the area contains what is likely earth's most radioactive terrestrial ecosystem. Radionuclides with the highest activity concentrations in soil are now ¹³⁷Cs and ⁹⁰Sr, with others, including Pu-isotopes and ²⁴¹Am, present in lower concentrations (e.g., see Beresford, Barnett, et al., 2020). Dose, or exposure, rates are still (in 2020) sufficiently high such that in some areas of the CEZ, radiation-induced effects on wildlife would be anticipated (Beresford, Horemans, et al., 2020), and some recent studies report effects in the

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most contaminated areas (e.g., Horemans et al., 2018; Lerebours et al., 2020). However, the extent to which wildlife is impacted by radiation in the CEZ is highly contentious (Beresford, Horemans, et al., 2020; Chesser & Baker, 2006; Mothersill et al., 2020), with some studies reporting effects at extremely low dose rates within natural background exposure levels (e.g., Mousseau & Møller, 2011).

The Belarussian portion of the CEZ (currently 2162 km²) was declared a nature reserve, the Polesie State Radioecological Reserve (PSRER), in 1988; in 2016, most of the Ukrainian CEZ was designated as the Chernobyl Radiation and Ecological Biosphere Reserve (2270 km²). Together these two areas (totaling 4432 km²) are mainland Europe's third-largest nature reserve. The absence of humans and associated activities for more than 30 years has resulted in increases in wildlife numbers. Deryabina et al. (2015) reported that in the Belarussian CEZ, the relative abundances of Eurasian elk (*Alces alces*), roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*), and wild boar (*Sus scrofa*) were similar to those in four uncontaminated Belarussian nature reserves with wolf abundance higher in the CEZ than the other reserves. In addition, the authors also reported rising trends in elk, roe deer, and wild boar abundances in the first 10 years after the accident. A total of over 1200 plant and over 340 vertebrate species have been recorded in the CEZ, with over 60 vertebrate species listed in the Ukrainian Red Data Book (<http://chornobyl-gef.com/en/tasks-of-the-reserve.html>; see <https://radioecology-exchange.org/content/ukrainianrussianbelarussian-publications> for a compilation of papers on wildlife in the CEZ). Since 1986, the management of the CEZ has largely involved minimal intervention with regard to wildlife and habitat evolution. The exception was the introduction of *Bison bonasus* (European bison) in the PSRER and *Equus ferus przewalskii* (Przewalski's horse) in the Ukrainian CEZ. Both of these introduced species have spread across large areas of the CEZ and are breeding (Gashchak & Paskevich, 2019; Gashchak et al., 2017). Perino et al. (2019) suggested that the CEZ is the only area in Europe where a diverse range of species interact in sizable numbers in a large wilderness complex and can thus be considered one of the most iconic natural experiments on rewilding in recent history. For scientific research, the CEZ is now a key site for both a radioecological perspective and also for ecosystem restoration (or rewilding).

Wildfires in the CEZ

Wildfires are an annual event in the CEZ, with more than 1250 fires registered between 1993 and 2014 in the Ukrainian CEZ (Goldammer et al., 2014). Before 2020, the most widespread fires in 1992 and 2015 resulted in over 100 km² of the CEZ being burnt (Goldammer et al., 2014; Kashparov et al., 2017). In 2016, about 80% of the Red Forest was burnt (<https://www.ceh.ac.uk/redfire>); the Red Forest is an area of approximately 4–6 km² to the west of the Chernobyl Nuclear complex where pine trees were killed by high levels of radiation in 1986 (Smith & Beresford, 2005). Although the 2016 Red Forest fire impacted a relatively

small area of the CEZ, it was significant as the Red Forest is likely the most radiologically contaminated terrestrial ecosystem on Earth. In early April 2020, fires started to burn in the Ukrainian CEZ and eventually spread over the subsequent month to become the largest wildfire in the 34-year history of the CEZ; Protsak et al. (2020) estimated that the total area burnt was 870 km² or about one-third of the land area of the Ukrainian CEZ. The spring 2020 fires also burnt the Red Forest again, with trees that were killed (but not badly burnt) in the 2016 fire providing fuel for the 2020 fire.

It has been suggested that a lack of forest management in the CEZ increases the risk of large-scale wildfires (Ager et al., 2019; Goldammer et al., 2014), with climate change potentially exacerbating this risk (Evangelou et al., 2016). Ignition sources, linked primarily to human activity, have been identified as the key factor which has caused the much greater incidence and extent of wildfires in the Ukrainian CEZ as compared with the Belarussian sector (Ager et al., 2019). However, there are relatively few firefighters, given the size of the CEZ, and many areas are inaccessible to fire trucks (Evangelou et al., 2016; Goldammer et al., 2014).

Fires in the CEZ give rise to a number of concerns and scientific questions. Some of these, such as impact on wildlife or carbon emissions, are common to other areas that experience large-scale wildfires (e.g., Dickman & McDonald, 2020; Silva et al., 2020), whereas others are unique to radiologically contaminated environments. We explore some of these issues below, illustrating some points with results from our recent and ongoing studies on wildfires in the CEZ (see CHAR, 2021; RED FIRE, 2021).

WILDFIRES IN THE CEZ: SCIENTIFIC QUESTIONS

Do large-scale fire events in the CEZ lead to significantly increased radiation exposure via smoke inhalation?

Wildfires in the CEZ result in the mobilization of radionuclides to the atmosphere, and increased concentrations of radionuclides in the air are detected in the CEZ during fire events (see an example from the 2016 Red Forest fire in Figure 1 for a static monitoring point located about 4 km to the south-east from the southern edge of the Red Forest) and beyond (e.g., Gueibe et al., 2020; IRSN, 2020). This mobilization of radionuclides gives rise to widespread media coverage of the potential radiation risk to populations across Europe (see examples cited by Evangelou and Eckhardt, 2020), with responsible organizations having to provide comment on the actual risk (e.g., Greek Atomic Energy Commission, 2020; Gueibe et al., 2020; IRSN, 2020).

Since the April 2020 forest fires in the CEZ, a number of modeling studies have estimated the source term and atmospheric transport based on fire extent, the fractional release of radioactivity from burned biomass, and far-field air monitoring data (e.g., Evangelou & Eckhardt, 2020; Gueibe et al., 2020; Protsak et al., 2020). Estimates of release from three of these studies (Evangelou & Eckhardt, 2020; Protsak et al., 2020; Talerko et al., 2021) are shown in Table 1 and compared with the initial 1986 Chernobyl release. A third

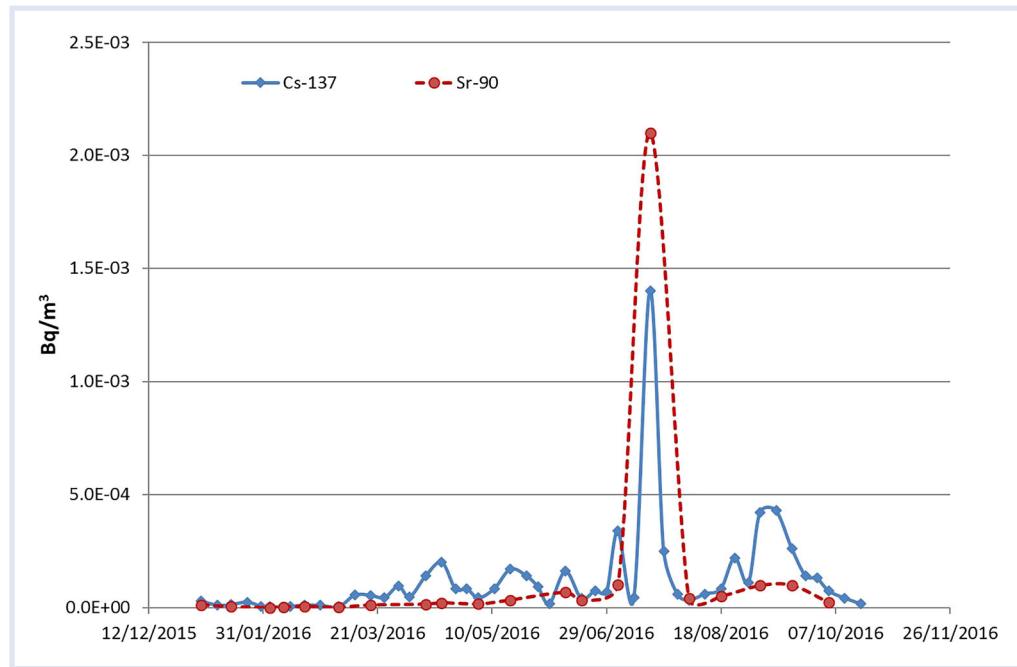


FIGURE 1 Strontium-90 and ¹³⁷Cs air activity concentrations at a permanent monitoring site located close to the Red Forest at Kopachi (51.344645°, 30.112411°; see <http://www.srp.ecocentre.Kyiv.ua/MEDO-PS/index.php?lang=ENG&online=1> for location which is about 4 km south-east of the southern edge of the Red Forest). The increase in air activity concentrations coincides with the 2016 Red Forest fire (July 15–17, 2016); the monitoring site is located about 4 km south-east of the southern edge of the Red Forest. Data from the air monitor are also available for ^{238,239,240}Pu, which peaked at the same time as ¹³⁷Cs and ⁹⁰Sr (maximum concentration— 1.7×10^{-6} Bq m⁻³). Data courtesy of State Specialized Enterprise (SSE) “Ecocentre.” These data are not used in the assessment of dose rates following the 2020 fires

study (Gueibe et al., 2020) estimated a ¹³⁷Cs source term of 1000 GBq based on back calculation from measurement stations in Europe, in broad agreement with the value from Protsak et al. (2020). Such estimates are subject to some uncertainty, as they do not take into account the type of fire, burning of soil litter and other organic matter, or the radionuclide concentrations of different vegetation types. However, remobilization represents only a tiny fraction of the initial Chernobyl accident release. The 630 GBq ¹³⁷Cs release estimated by Protsak and co-workers, for example, represents only 0.00074% of the release of ¹³⁷Cs during the 1986 accident.

In the CEZ and surrounding areas, wildfires give rise to concerns of risk to firefighters and local populations, and

there is a need for well-founded dose assessments to be made. Below we present two illustrative risk scenarios for the 2020 wildfire fires: One for a worker carrying out high-intensity exercise within the CEZ (“firefighter scenario”), and the other for a child aged 1–2 years living in Kyiv during the period April 6–27, 2020. For both scenarios, we used conservative (dose-maximizing) assumptions; however, potential limitations of dose models should be noted when, as in the CEZ, radioactive (or “hot”) particle inhalation may be an issue (see discussion below). To estimate the exposure of a firefighter, we assumed an 8-h shift and no personal protective equipment (PPE). For the child living in Kyiv, approximately 100 km to the south of Chernobyl, no reduction in air activity concentration due to time spent indoors was

TABLE 1 Estimated source terms for the April 2020 forest fires

| Radionuclide | Release from 2020 fires (Evangelidou & Eckhardt, 2020) | Release from 2020 fires (Protsak et al., 2020) | Release from 2020 fires (Talerko et al., 2021) | 1986 Chernobyl release (Smith & Beresford, 2005) |
|-------------------|--|--|--|--|
| ¹³⁷ Cs | 341 GBq | 630 GBq | 574 GBq | 85 000 000 GBq |
| ⁹⁰ Sr | 51 GBq | 13.5 GBq | | 10 000 000 GBq |
| ²³⁸ Pu | 2000 MBq ^a | | | 35 000 000 MBq |
| ²³⁹ Pu | 33 MBq | 59 MBq | | 30 000 000 MBq |
| ²⁴⁰ Pu | 66 MBq | | | 42 000 000 MBq |
| ²⁴¹ Am | 504 MBq | | | 156 000 000 MBq ^b |

^aThis appears to be a significant overestimate, as a fractional release of ²³⁸Pu in a fire should be no different to other Pu isotopes and contamination density is similar to ^{239,240}Pu.

^bAccounting for ingrowth from ²⁴¹Pu to ²⁴¹Am.

assumed (i.e., the child was assumed to spend 100% of his/her time outdoors). Inhalation dose coefficients were estimated as the most conservative values presented in the IAEA Basic Safety Standards (IAEA, 2014), and inhalation rates were taken from Moya et al. (2011) and assumed to be 95th percentile of the high-intensity exercise values for firefighter and the child. This is likely to significantly overestimate the dose for a child, as the average breathing rate over a period of many days will be significantly (three to four times) lower than the value we assumed for high-intensity exercise. For the firefighter scenario, data were made available by SSE “EcoCentre” from mobile air monitors deployed at the fire front during the April 2020 fires; ambient dose rate measurements were also available at each mobile air monitoring site.

Activity concentrations in air for the firefighter scenario were assumed to be equal to the highest reading from the SSE “EcoCentre” mobile measurements made at the fire front (0.18 Bq m⁻³ of ¹³⁷Cs; 1.2 Bq m⁻³ of ⁹⁰Sr; 87 μBq m⁻³ of ²³⁸Pu; 260 μBq m⁻³ of ²³⁹⁺²⁴⁰Pu). This was for a mobile monitor at the western edge of the Chernobyl power station site in an area of relatively high contamination and external dose rate (13–17 μSv h⁻¹), so it is less than typical contamination density in the Red Forest hotspot but higher than the vast majority of the CEZ. For the child in Kyiv, cumulative ¹³⁷Cs measurements in air, as measured by Ukrainian air monitoring stations and reported by IRSN (IRSN, 2020), were summed for the period April 6–27; the average ¹³⁷Cs activity over this period was 110 μBq m⁻³ and the cumulative air concentration was 0.056 Bq m⁻³ h. ⁹⁰Sr activity concentrations in air in Kyiv were estimated using an average ¹³⁷Cs:⁹⁰Sr ratio of 3 from SSE “EcoCentre” monitoring in the CEZ during the 2020 fires. Pu isotopes and ²⁴¹Am were estimated on the basis of the ¹³⁷Cs measurement data and using the ratio in source term estimates (Table 1) from Protsak et al. (2020) and Evangelidou and Eckhardt (2020). All air concentrations used in the two illustrative risk scenarios are presented in Table 2.

In agreement with previous estimates (e.g., Kashparov et al., 2000, 2017), our inhalation doses estimated for firefighters were comparatively low (even assuming no PPE) and

were insignificant for the child in Kyiv (Table 3). Air monitoring at Dytiatki, on the southern boundary of the CEZ, did not show significantly greater radioactivity in air than measurements in more distant Kyiv; the average ¹³⁷Cs concentration at Dityatky was 200 μBq m⁻³ as compared with 160 μBq m⁻³ at the Kyiv sampling site for the period April 13–20, 2020 (IRSN, 2020). As shown in Table 3, external dose to firefighters (predominantly from radionuclides present in the soil) is significantly greater than inhalation dose, even without accounting for reduced inhalation dose due to PPE; a similar observation was made by Kashparov et al. (2017) when assessing the exposure of firefighters responding to CEZ wildfires in 2015. Firefighters typically spent a maximum of 7 days in the CEZ (V. Kashparov, personal communication, December 10, 2020), so external and inhalation doses (assuming no PPE) could in some cases be higher than this maximum estimate for an 8-h shift. It is unlikely, however, that an individual firefighter would spend all of his/her time in the CEZ in the most contaminated “hotspots,” nor is it likely that those working in more contaminated areas would be without PPE.

Despite uncertainties in estimates of air activity concentrations, particularly for ²⁴¹Am and in the case of the Kyiv child assessment ⁹⁰Sr and the actinides, there is no reason to believe that individual inhalation doses from the 2020 fires were significant. It should, however, be noted that measurements near the fire front are relatively sparse, and improved monitoring and modeling of activity concentrations in air experienced by firefighters would be valuable.

Our estimates of the inhalation effective dose for the child in Kyiv over period April 6–27, 2020 (Table 3) are consistent with the results of Talerko et al. (2021) who estimated an effective dose for the adult population of Kyiv during the fire period of about 0.03 μSv (from inhalation of ¹³⁷Cs and ⁹⁰Sr). This is less than 0.01% of the annual dose limit of exposure of the population in Ukraine (1 mSv per year).

Radioactive fuel particles (often referred to as “hot” particles) were released by the Chernobyl accident and largely deposited in the CEZ (Kashparov et al., 2018). Although now largely degraded (Beresford et al., 2016), some small particle fragments remain in the environment.

Potentially, firefighters working in the more contaminated areas (without adequate PPE) could inhale remobilized hot particles along with dust particles containing radionuclides. It should be noted that the estimate in Table 3 assumes lung clearance rates as used in IAEA (2014) and, thus, does not account for the potential long-term retention of one or more hot particles in the lung. A study by Garger et al. (2013) evaluated dose rates to the lung from a 20-μm (diameter) Chernobyl hot particle, finding lower dose conversion coefficients than those assumed here due to relatively low solubility. Garger et al., however, used a model which assumed a relatively rapid clearance rate of hot particles from the lung. A study of lung tissue from Chernobyl accident victims, liquidators, and evacuees (Vlasov et al., 1997) found that a small proportion of hot particles could be retained in the lung for years after exposure. This could potentially lead

TABLE 2 Measured (normal font) and estimated (italic font) time-integrated radionuclide air concentrations for the two illustrative risk scenarios

| Radionuclide | Firefighter scenario 8-h integration period (Bq h m ⁻³) | Child in Kyiv April 6–27, 2020 (Bq h m ⁻³) |
|--------------|---|--|
| Sr-90 | 9.6 | <i>0.019</i> |
| Cs-137 | 1.44 | <i>0.056</i> |
| Pu-238 | 7.0 × 10 ⁻⁴ | <i>1.8 × 10⁻⁶</i> |
| Pu-239, 240 | 1.9 × 10 ⁻³ | <i>3.6 × 10⁻⁶</i> |
| Pu-241 | 2.6 × 10 ⁻² | <i>5.0 × 10⁻⁵</i> |
| Am-241 | 2.5 × 10 ⁻² | <i>4.5 × 10⁻⁵</i> |

TABLE 3 Total doses estimated over the specified time periods for illustrative risk scenarios during the 2020 fires

| Scenario | External dose | Inhalation dose without personal protective equipment |
|---|----------------------|---|
| Firefighter working 8 h in “hotspot” near ChNPP | 120 μSv^a | 7.6 μSv |
| Child aged 1–2 in Kyiv over the period April 6–27, 2020 | Background | 0.08 μSv |

^aCalculated from ambient dose rate measurements made at the monitoring site.

to significant lung doses. For illustration, we have estimated the dose from alpha and beta radiation from ^{90}Sr , ^{137}Cs , ^{238}Pu , ^{239}Pu , ^{240}Pu , and ^{241}Am to lung tissue. A 5- μm -diameter (i.e., of inhalable size) hot particle was assumed with activities based on particles found in the Red Forest in 1999 (Kashparov et al., 2017). No environmental decomposition and no self-absorption of alpha radiation were assumed and activities were decay-corrected to 2020. This gave an estimated equivalent alpha radiation dose to the lung of approximately $140 \mu\text{Sv y}^{-1}$ and an effective equivalent whole-body dose of $16 \mu\text{Sv y}^{-1}$, if the particles were retained in the lung and if solubility and internal absorption were low.

The probability of significant hot particle retention in the lung is believed to be low and most inhaled particles are likely to be of smaller diameter (Vlasov et al., 1997). Furthermore, radioactive particles are potentially unlikely to be remobilized as they are in the soil profile and not surface litter which will be burnt during wildfires (Yoschenko et al., 2006). Long-term retention of around 600 such particles in the lung, however, would be needed to give an annual dose similar to natural radon effective (i.e., whole-body equivalent) dose limits which are of order $10\,000 \mu\text{Sv y}^{-1}$. Adequate PPE should reduce the probability of hot particle inhalation. If PPE is not worn, there are also significant (nonradiation-related) risks from smoke inhalation (Navarro et al., 2019) in addition to potential radiation risks. Further experimental and modeling work to evaluate potential hot particle doses to firefighters would be valuable, not least for reassurance purposes. However, we note that

measurements of plutonium at the monitoring site used for the firefighter scenario gave an accumulated 78 mBq of $^{239,240}\text{Pu}$ in 300 m^{-3} of air sampled. One 5- μm -diameter radioactive particle is estimated to contain 120 mBq of $^{239,240}\text{Pu}$ activity, implying that there were no hot particles of significant size in the 300 m^{-3} of smoke sampled at this site.

Do wildfires increase the mobility of radionuclides in the environment?

Fires in the CEZ will result in the burning of surface soil and deposition of comparatively highly contaminated ash on the soil surface. Enhanced surface contamination with radionuclides has previously been observed elsewhere in the world following wildfires (Amiro et al., 1996; Johansen et al., 2003; Paliouris et al., 1995). Soon after a forest fire close to the Red Forest in 2018, we found that the activity concentration of both ^{90}Sr and ^{137}Cs in ash collected from the ground surface was, on average, 10 times higher than that in the top 10-cm soil layer. At these same sites, the percentages of ^{90}Sr and ^{137}Cs per meter square present as ash varied from about 1% to more than 30% (Figure 2). This raises the question, will the mobility and/or bioavailability of radionuclides be increased as the consequence of the fire? It could be anticipated that radionuclides present in ash will be relatively readily leached into the soil profile and hence be available for plant uptake and consequently for transport through food chains.

Changes in the mobility and/or bioavailability of trace elements and heavy metals have been observed following wildfires (Burton et al., 2016; Pereira et al., 2011; Stankov

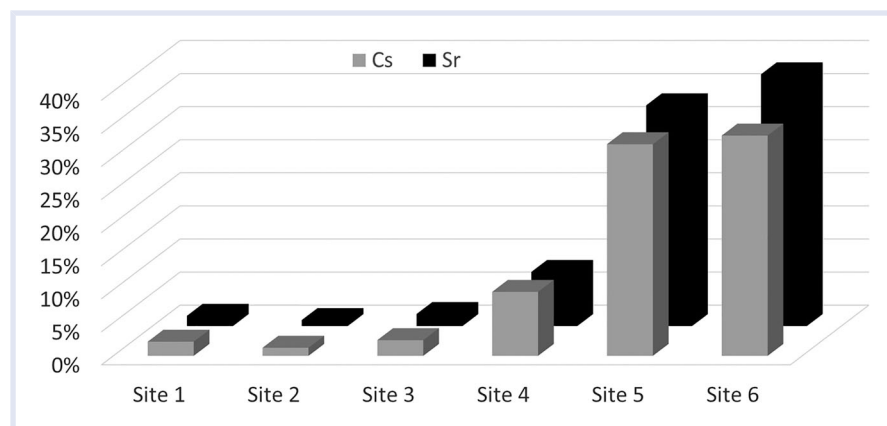


FIGURE 2 ^{90}Sr and ^{137}Cs present as ash at sites in the Chernobyl Exclusion Zone following a 2018 fire event. Ash was removed from the ground surface over a measured area and the underlying soil then sampled to 10-cm depth; results are presented as the percentage of radionuclides in ash and soil to a depth of 10 cm

Jovanovic et al., 2011). From controlled burning studies, both Amiro et al. (1996) and Horrill et al. (1995) found relatively high fractions of cesium in the ash to be soluble. Soil samples we collected about 2 months after the 2016 Red Forest fire suggested that ^{90}Sr was more available (determined as the percentage extracted by 0.05 M $\text{Ca}(\text{NO}_3)_2$ and 1 M $\text{Mg}(\text{NO}_3)_2$ from soils (0–10 cm) collected from burnt areas (median = 60% extracted; $n = 15$) than unburnt areas (median = 37% extracted; $n = 7$) ($p < 0.01$ Mann–Whitney). This difference was not seen when the sites were resampled 1 year later and there was no difference in the availability of ^{137}Cs from burnt and unburnt areas in either 2016 or 2017. To separate the extractant from the soil for these measurements, samples were centrifuged at 20 000 g for 10 min, the supernatant removed by pipette, and filtered through cellulose acetate membrane syringe filters (0.45 μm).

In addition to potentially increasing radionuclide mobility for uptake into food chains, wildfires give rise to concerns of increased radionuclide run-off into watercourses. Following a forest fire at Los Alamos (New Mexico), Johansen et al. (2003) observed increased particulate-associated ^{137}Cs run-off in the short term (first few months after the fire). Similarly, at a study plot established in late 2017 in the Red Forest (i.e., after the summer 2016 fire), Igarashi et al. (2020) also found increased particulate ^{137}Cs run-off; increased soil erosion is an acknowledged impact of wildfires (Neary et al., 2005). For public reassurance purposes, there is a need to determine if wildfire events in the CEZ may give rise to significant increases in the exposure of humans via the water pathway (for example, some surface waters in the CEZ flow into the Kyiv Reservoir, which is a source of drinking water).

What is the impact of wildfires on CEZ wildlife?

The CEZ is now home to a diverse range of wildlife including many rare and protected species, and large-scale wildfires give rise to concerns over impacts on these. Although the 2020 CEZ wildfires covered a relatively large area (approximately 870 km²), observations of wildfires elsewhere in the world suggest that the direct effect of fire and smoke on mobile medium and large mammals would have been limited, as they are able to move rapidly over distances sufficient to take them away from the fire (e.g., Singer et al., 1989). Less mobile animal species, of all taxa, will be more vulnerable to fire; however, burrowing or sheltering under moist litter can be protective (see review by Lyon et al., 2000). Whereas adult birds will generally be able to avoid fire, nestlings and eggs will be vulnerable. Some bird species, including eagles, owls, woodpecker, tits (Paridae), and grouse (Tetraoninae), would have been nesting at the time of the extensive April 2020 CEZ wildfires. After wildfires, there will be indirect effects on biota as a consequence of modification of habitat and consequently food source; the duration of such impacts will depend upon the severity and spatial extent of the wildfire and the degree of connectivity between unburnt patches. Impacts on food sources may also be positive, with some species being

attracted to burnt areas. For instance, food for predators and scavengers may be more exposed and/or plentiful in burnt areas, and herbivores may be attracted to abundant vegetation regrowth (Lyon et al., 2000).

In the CEZ, fire will impact wildlife as it would in similar ecosystems elsewhere; however, the question is raised: “Will fire and radiation act as combined stressors impacting on recovery?” Although it is too early to comment upon the impact of the widespread 2020 wildfires, we can discuss some initial observations made in the Red Forest over the year after the fire in July 2016.

Studies in the Red Forest 2016–2017. Twenty motion-activated trap cameras were deployed across the Red Forest using a grid pattern over an area of approximately 8 km² in September 2016 and left in place until early September 2017. Ambient dose rates at the sites ranged from approximately 1 to 130 $\mu\text{Sv h}^{-1}$. The diversity of medium and large mammals recorded by the cameras was similar to that observed elsewhere in the CEZ (Deryabina et al., 2015; Webster et al., 2016; <https://tree.ceh.ac.uk/content/exposure-uncertainty>). Small packs of feral (domesticated) dogs were observed in the Red Forest, which we had not observed at other monitoring sites (<https://tree.ceh.ac.uk/content/exposure-uncertainty>) in the CEZ; it is likely that these are animals fed by workers, and others, around the nearby Chernobyl nuclear power plant complex. Table 4 summarizes camera trap observations by season. There is no overall time trend apparent in the observations with time since the July 2016 fire. Example photographs of each species observed from the cameras deployed in the Red Forest can be found in the Supplementary Materials (Plate S1).

In August 2017, small mammals were trapped from eight sites in the Red Forest, three of which were not burnt in the July 2016 fire and five that were. At each of these sampling sites, a 60 m x 60 m trapping grid was used, with traps positioned at 10-m intervals (each grid having a total of 49 traps). Trapping was conducted over 8 days (see Antwis et al., 2021, for details). At this time, approximately 1 year after the fire, trapping rates were similar at burnt and unburnt sites (Table 5), potentially suggesting that the fire had minimal impact on Red Forest small mammal populations or, more probably, that populations had recovered relatively rapidly. However, though yellow-necked mice (*Apodemus flavicollis*) and striped field mice (*Apodemus agrarius*) were trapped similarly at burnt and unburnt sites, bank voles (*Myodes glareolus*) were largely caught at unburnt sites and wood mice (*Apodemus sylvaticus*) at burnt sites. There was some indication of a difference in the fecal microbiome of yellow-necked mice trapped at burnt compared to unburnt sites, which may indicate differences in food availability (Antwis et al., 2021).

DISCUSSION

Wildfires within the CEZ are, and will remain, a common occurrence. Given the importance of the CEZ for studies of the impact of ionizing radiation on wildlife, which is required

TABLE 4 A summary of medium and large mammals recorded by 20 trap cameras in the Red Forest (September 2016–September 2017) by season

| Species | Autumn 2016 | Winter 2016/2017 | Spring 2017 | Summer 2017 |
|---|-------------|------------------|-------------|-------------|
| Brown hare (<i>Lepus europaeus</i>) | 10.1 | 4.3 | 30.7 | 21.8 |
| Red squirrel (<i>Sciurus vulgaris</i>) | 0.2 | - | - | 0.7 |
| Eurasian wolf (<i>Canis lupus lupus</i>) | 1.2 | 0.7 | 0.3 | 0.7 |
| Dog (<i>Canis familiaris</i>) | 0.5 | 0.1 | 0.7 | 0.5 |
| Red fox (<i>Vulpes vulpes</i>) | 2.9 | 0.3 | 1.6 | 2.9 |
| Raccoon dog (<i>Nyctereutes procyonoides</i>) | 0.2 | 0.1 | 1.0 | 2.3 |
| Marten (<i>Martes</i> sp.) | 0.1 | - | 0.1 | 0.1 |
| European badger (<i>Meles meles</i>) | - | - | 1.0 | 0.4 |
| Eurasian lynx (<i>Lynx lynx</i>) | 0.1 | 0.4 | 0.3 | 0.2 |
| Przewalski's horse (<i>Equus ferus przewalskii</i>) | 0.7 | 0.7 | 0.7 | - |
| Wild boar (<i>Sus scrofa</i>) | 0.2 | 0.2 | 1.0 | 0.1 |
| Red deer (<i>Cervus elaphus</i>) | 3.6 | 2.5 | 4.8 | 6.3 |
| Eurasian elk (<i>Alces alces</i>) | 12.1 | 2.9 | 6.5 | 15.5 |
| Roe deer (<i>Capreolus capreolus</i>) | 2.0 | 0.2 | 9.6 | 9.7 |

Note: Results are presented as the number of events (i.e., number of times that species activated a camera trap) per 100 trap days.

to help develop radiological environmental protection frameworks (Beresford, Horemans, et al., 2020; Mothersill et al., 2020), the potential impacts of fires on radionuclide mobility and wildlife need to be understood to aid interpretation and prevent misinterpretation, of future radiological studies conducted in the CEZ.

With respect to potential impacts of wildfires on CEZ wildlife, there has been a generally positive change in species diversity and abundance since the 1986 accident (Deryabina et al., 2015); this has occurred irrespective of the numerous annual wildfire events. However, the extent of the 2020 fires was unprecedented, impacting approximately

one-third of the area of the Ukrainian CEZ. Furthermore, the common occurrence of relatively widespread wildfires may result in long-term habitat change within the CEZ. We estimate that in 1986, approximately 35% of the Ukrainian CEZ was pine plantation and that by 2006, pine forest had spread, largely naturally, to cover about 50%–60% of the Ukrainian CEZ (Fukarevych, 2006). On the basis of our field observations, wildfires in the CEZ pine plantations result in long-term habitat change, as the area tends to naturally regenerate with deciduous trees, shrubs, and herbaceous vegetation. Any gradual reduction in the area of pine in the CEZ will have some impact, both negative and positive, on species abundance and diversity.

Compared with other wildfire events, those at Chernobyl give rise to concern with regard to increased radiation exposure due to inhalation of contaminated smoke by firefighters and wider populations. As we demonstrate above for the 2020 fires, the estimated inhalation doses (and hence the risk) are low (Table 3); these findings are in agreement with previous assessments conducted following earlier fire events in the CEZ (Kashparov et al., 2000, 2017). There is, however, a need for further research on the potential for, and dose effects of, long-term retention in the lung of radioactive particles mobilized by fires. Although there have been suggestions of higher risk to populations across central Europe (Evangelidou et al., 2014), this is not supported by the widespread monitoring data available for the 2020 CEZ wildfires (e.g., Gueibe et al., 2020; IRSN, 2020). Given the negative public perception of radiation, effective public communication of radiation risk is challenging (Bryant et al., 2020). To provide the necessary reassurance to firefighters

TABLE 5 Small mammal trapping rates at burnt and unburnt sites in the Red Forest; trapping rate is estimated as the total number of animals (all species combined) caught at a site relative to the number of traps times the number of nights trapped

| Site | Burnt | Ambient dose rate ($\mu\text{Sv h}^{-1}$) | Trapping rate |
|------|-------|---|---------------|
| A | No | 24 | 0.058 |
| C | No | 36 | 0.078 |
| F | Yes | 28 | 0.079 |
| G | Yes | 154 | 0.068 |
| H | Yes | 37 | 0.099 |
| J | Yes | 42 | 0.108 |
| L | Yes | 11 | 0.102 |
| X | No | 28 | 0.150 |

and the wider populations, there is a need to develop approaches to ensure that radiation risk from CEZ wildfires can be communicated in an understandable, transparent, and unbiased manner.

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DATA AVAILABILITY STATEMENT

Some of the data relevant to this paper have been published via the Natural Environmental Research Council Environmental Information Data Centre (see Barnett et al., 2021; Beresford et al., 2018). Further data can be provided upon request from corresponding author Nicholas A. Beresford (nab@ceh.ac.uk).

SUPPORTING INFORMATION

Plate S1. Example photographs for each species recorded in Table 4 from wildlife camera taps ($n = 20$) deployed in the Red Forest September 2016 to 2017: Brown hare (*Lepus europaeus*); Eurasian lynx (*Lynx lynx*); Red squirrel (*Sciurus vulgaris*); Eurasian wolf (*Canis lupus lupus*); Raccoon dog (*Nyctereutes procyonoides*); European badger (*Meles meles*); Red fox (*Vulpes vulpes*); Dog (*Canis familiaris*); Roe deer kids (*Capreolus capreolus*); Red deer (*Cervus elaphus*); Eurasian elk (*Alces alces*); Przewalski's horse foal (*Equus ferus przewalskii*). The date the photograph was taken is shown on each picture.

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