Fires in nuclear forests: silent threats to the environment and human security

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In the Chernobyl Exclusion Zone, forest and fire management need to be strengthened to reduce the risk of wildfire and corresponding radiation exposure.

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Over recent decades, a number of nuclear accidents resulting in radioactive contamination of large areas of forest land have occurred in different parts of the world. The growing number of new nuclear power plants implies an increasing risk of similar events in the future. This article analyses wildfire risks and hazards for firefighters and persons working in the Chernobyl Exclusion Zone (CEZ), and for the environment, as well as the specificities of current fire management in the best documented case – which is the CEZ. In the CEZ, insufficient forest and fire management during the past 28 years, along with dead wood due to insects and diseases, has resulted in a high wildfire hazard in the 260 000 ha of forests and grasslands of the Ukrainian part, an area that is highly contaminated with long-living radionuclides of plutonium (^{238}Pu, $^{239+240}Pu$, ^{241}Pu), ^{241}Am, ^{137}Cs and ^{90}Sr. Up to 9 000 ha of pine forests are completely dead and are in the highest wildfire risk category. In most of the middle-aged pine plantations, 9–20 percent of trees have already died, and another 31 percent are expected to die during the next decade. Combined with the fact that nuclear radiation leads to a decreased speed of decomposition of dead organic material, this development will increase available fuel and the corresponding wildfire hazard. The numerous wildfires that have already occurred in the

Above: View of the Chernobyl reactor, 2012

CEZ, including the catastrophic fires of 1992 (17 000 ha), have revealed the existence of ignition sources across the whole CEZ, including in the most contaminated areas. Fire prevention and suppression activities pose serious risks for firefighters, who may reach their annual radiation dose limit over a relatively small number of days. In addition, the current management infrastructure is inadequate to mitigate existing and future wildfire risks. Recommendations for urgent steps to improve fire management in the CEZ are therefore proposed.

HISTORY OF NUCLEAR ACCIDENTS

Since the 1950s, three major nuclear incidents have led to wide-scale radioactive contamination of the environment: releases from the Mayak Production Association in the Chelyabinsk region (Southern Ural Mountains), Russia (Trabalka, Eyman and Auerbach, 1980); the Chernobyl Nuclear Power Plant (NPP), USSR (1986); and the Fukushima NPP (2011) (Steinhauser, Brandl and Johnson, 2014). In the last two cases, exclusion zones were established for the most contaminated areas around the damaged reactors.

In addition, a number of minor nuclear incidents have occurred, including the Three Mile Island NPP accident in 1979, where major environmental contamination was averted. However, the rapid growth in new nuclear energy facilities, particularly in the Asia–Pacific area is leading to an increasing probability of accidents in the future and therefore calls for better documentation of available experience on the management of existing radioactive contaminated territories. The Chernobyl NPP disaster is the best studied of all the disasters mentioned above and will therefore be discussed in the following in more detail.

THE CHERNOBYL ACCIDENT AND ENVIRONMENTAL CONTAMINATION

An explosion in reactor No. 4 of the Chernobyl Nuclear Power Plant in northern Ukraine on 26 April 1986 resulted in the release of up to 12 000 PBq[1] of radioactive material into the environment (IAEA, 1996). Twenty-eight years after the disaster, radioactive contamination continues to be an important environmental issue in Ukraine, Belarus and Russia. Shortly after the explosion, residents were permanently evacuated from the most contaminated 30-km radius zone around the plant, a zone that in 1996 was extended along the western contamination path. This area has been designated as the Chernobyl Exclusion Zone (CEZ). The radioactive elements ^{137}Cs and ^{90}Sr, with a half-life period of 30 and 29 years respectively, are amongst the most widely spread. Because of their physical-chemical properties, they are the most likely to affect human health. The 10-km zone surrounding the Chernobyl NPP is in addition highly contaminated by plutonium,[2] with half-life times ranging from around one hundred to thousands of years. The radioactive decay of ^{241}Pu will generate contamination by another radionuclide of significance to human health, ^{241}Am, which is expected to increase over the next 100 years (IAEA, 2006).

ESTABLISHMENT OF THE CEZ

The main reasons for establishing the CEZ in 1986 were to restrict exposure of the population to contaminated areas and to enforce a special protection regime to minimize propagation of radionuclides outside the zone. An automated system (ASKRO), using 39 sensors, was established to monitor aerial radioactivity. The system covers the core of the CEZ. An additional environmental monitoring system was established to monitor the level of radioactive contamination of soils, underground and open water, vegetation and wildlife.

Spring floods of the Prypiat River[3] and vegetation fires are the two most important factors that contribute to the migration of radionuclides outside the CEZ.

To prevent the washing out of radionuclides during spring floods, artificial dams were built along the most contaminated locations of the Prypiat River. It has been observed that radionuclides still migrate with floodwater during spring time, although this poses a relatively low threat to the population due to a high level of dilution with clean water.

The significance of wildfires as a threat was fully realized only six years after the accident, when large and numerous wildfires in August 1992 burned up to 17 000 ha of contaminated forests and grasslands. Some of the fires crossed the border into Belarus and spread into the Belarusian part of the CEZ. Following these catastrophic wildfires, the specialized Chernobyl Forestry Enterprise, with a total staff of 400, was established to carry out forest and fire management in the CEZ and prevent the migration of radionuclides out of the zone.

NATURAL CONDITIONS, FORESTS AND LAND USE IN THE CEZ

Before the Chernobyl NPP accident, land use in the current territory of the CEZ was equally divided between agriculture and forestry. Now, all of the CEZ lands outside of the villages, the towns of Chernobyl and Prypiat, and the former NPP, have been categorized as “forest lands” and cover a total area of 240 000 ha. Of this, 150 000 ha (57 percent) is made up of forest, while some consists of grasslands. However, due to the natural regeneration of forests on former agricultural fields, especially in locations where disturbances of the grass layer have occurred, forest area is increasing, primarily in areas adjacent to forests. The CEZ is largely characterized by dry sandy soils (glacial outwash), and Scotch pine (*Pinus sylvestris*) forests therefore prevail, currently representing 89 000 ha, while other forest

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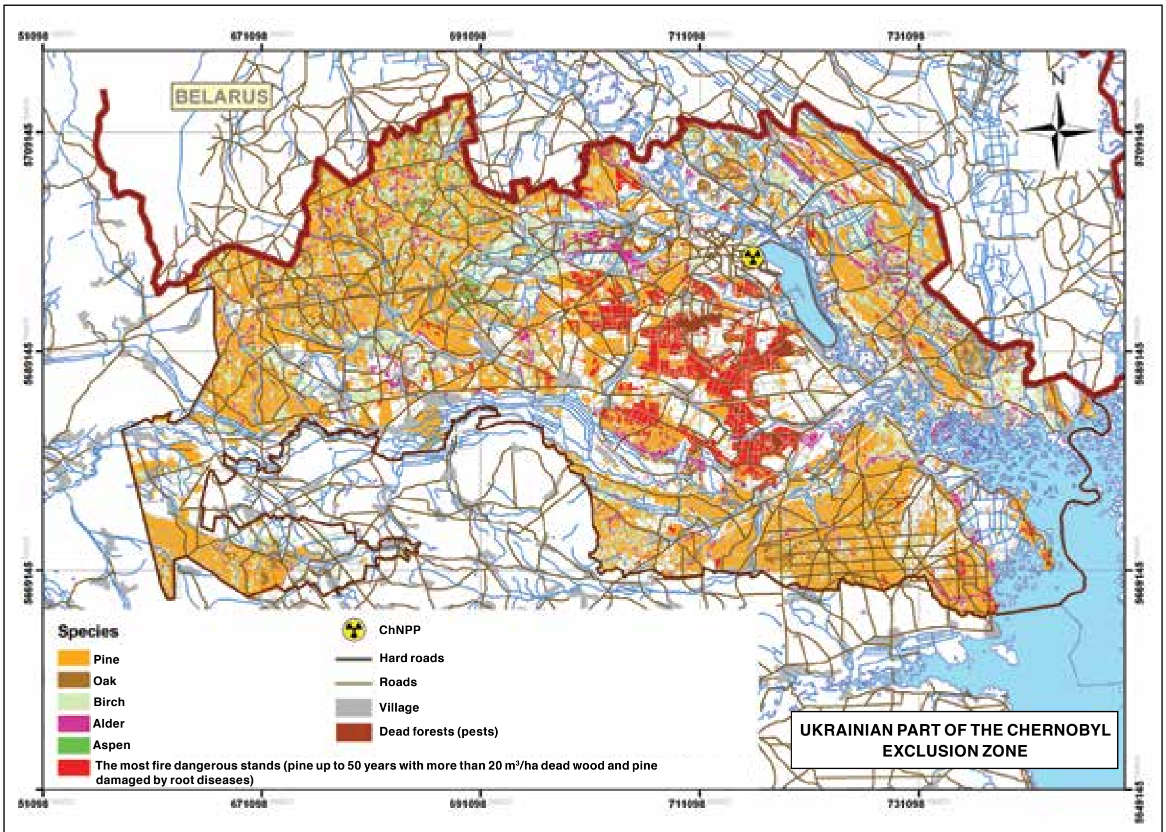
[1] PBq = Peta-Becquerel = 10^{15} Becquerel.

[2] ^{238}Pu, $^{239+240}Pu$, and ^{241}Pu will be referred to below as “plutonium”.

[3] The Prypiat river flows past the Chernobyl NPP and its water has been used for cooling the nuclear reactors.



1
Distribution of main forest species in the CEZ

Note: The red-marked areas are Scotch pine (*Pinus sylvestris*) forests damaged by root rot (*Heterobasidion annosum*).
Source: Zibtsev, Borsuk and Gilitukha, 2012.

lands are covered by deciduous softwoods (mostly *Betula pendula*, *Populus tremula* and *Alnus glutinosa* – 50 800 ha) and oak (*Quercus robur* – 7 500 ha) (Figure 1).

THINNING

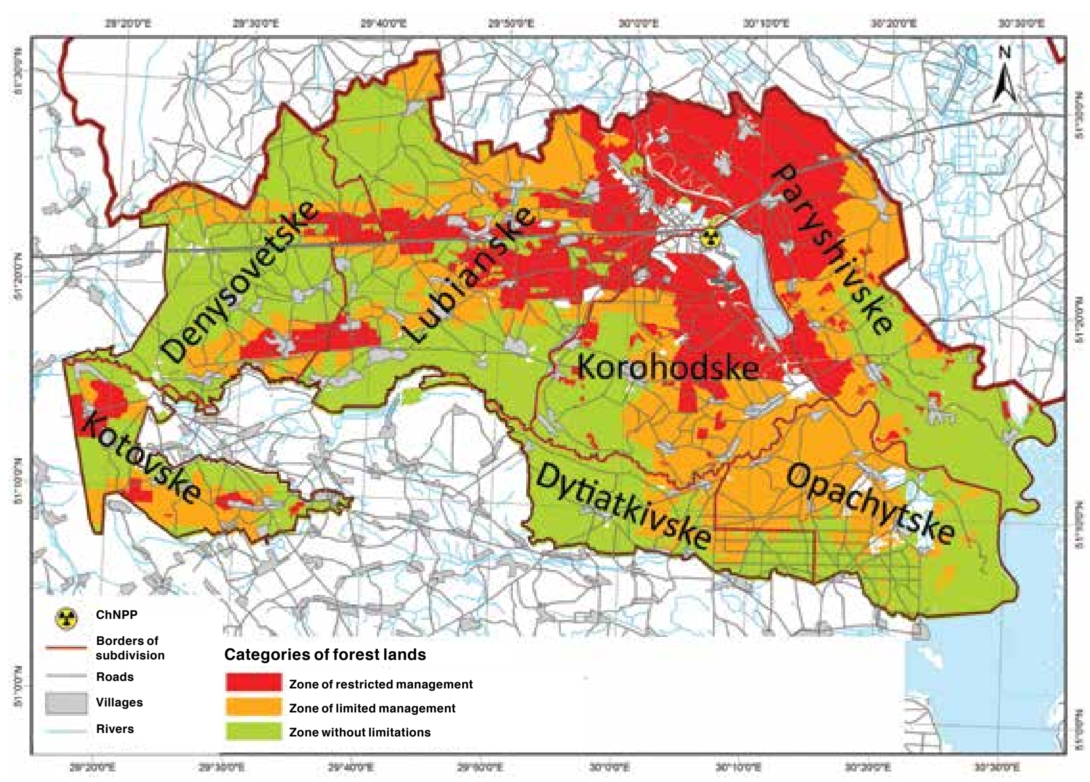
Historically, more than 50 percent of the pine forests in the CEZ were monoculture plantations created in the 1950s and 1960s by a very dense scheme of planting (7 000 to 10 000 seedlings per ha). Since 1986, thinning operations have been dramatically reduced or completely abandoned in the majority of pine stands because of the present level of radiation.

The latter has significant consequences for wildfire hazard. The magnitude of a wildfire depends on the amount of available fuel, which is essentially determined by the intensity of thinning and removal of debris. With reference to the 2006 Forest Management Plan for the CEZ, a significant portion of planned silvicultural measures were not implemented due to a lack of funding and personnel. For example, between 2004 and 2006 only 50 percent of planned early thinning in young stands (up to 20 years old) was undertaken, in middle-aged stands only 20 percent, and in premature stands 20 percent. Timber from the last-mentioned type of thinning is of commercial use, primarily as pillars for coal mining. It needs to be underlined that silvicultural measures are only executed on sites approved by the Radiological Control Service of the CEZ (“Ecocenter”) if the contamination of the timber (roundwood without bark) is lower than the allowable threshold of 1 000 Bq/kg (Ukraine Ministry of Health Protection, 2005). Failure to carry out minimum silvicultural interventions in forests increases fuel loads and negatively impacts upon forest health.

FOREST HEALTH, INSECTS AND DISEASES

Massive outbreaks of the pine lappet moth (*Dendrolimus pini*) took place in the CEZ in 1997 and 2006, of the nun moth (*Lymantria monacha*) in 1995, and of the common pine sawfly (*Diprion pini*) in 2003. Due to a lack of effective protection measures, up to 8 500 ha in the most contaminated central part of the CEZ was damaged heavily by these insects. Another 12 300 ha were damaged by root rot (*Heterobasidion annosum* (Fr.) Bref.) (Figure 1). Forest inventory data show that 15 300 ha of forests in the CEZ have been damaged by different agents, including 5 300 ha by pests (Ukrderglisproekt, 2007). As a result, fire hazard in large areas of forest has increased substantially. Remote sensing data have confirmed that 9 000 ha of forest are completely dead due to fires and pests (Zibtsev and Gilitukha, 2012).

2
Locations of forest ranger districts and the different CEZ contamination zones



Source: Zibtsev, Borsuk and Gilitukha, 2012.

DISTRIBUTION OF RADIONUCLIDES IN FORESTS

Threats to forest personnel, the population and the environment from radioactive vegetation fires in the CEZ depend on the distribution of contamination in fuel, contaminated volumes available, and types of fire. During the first month after the accident in late April 1986, radioactive fallout was deposited on the plant surfaces, especially on Scotch pine stands, since deciduous plants had not yet produced spring foliage. Within 4 to 6 months, most of the radionuclides had migrated into the ground, accumulating in mosses and soils. The vegetation root systems then gradually absorbed those radionuclides characterized by a higher chemical availability and mobility in the environment. Within three to four years, a stable state of radionuclide distribution in soil and vegetation cover was reached. Today, the concentration of each radioactive element varies considerably between different components of the vegetation. Depending on site-specific characteristics and soil humidity, 70-85 percent of radionuclides are currently concentrated in the top soil layers of forests and grasslands, forest litter and mosses, and 15-30 percent are deposited in trees (bark, needles, timber and branches) or grasses (Zibtsev, 2004; Yoschenko *et al*., 2006).

RADIOLOGICAL ZONING OF THE CEZ

For the purposes of forest and fire management, all CEZ forest lands were divided into seven forest ranger districts and into three zones of intensity of forest management and protection:

1. Zone of restricted management (no forest management activities): the most contaminated, core part of the CEZ (23.45 percent of forest lands; defined as the density of soil contamination by ^{137}Cs exceeding 3 700 kBq/m^2, or by ^{90}Sr exceeding 370 kBq/m^2, or by ^{239}Pu exceeding 11.1 kBq/m^2);
2. Zone of limited management (31.20 percent of forest lands, thresholds for ^{137}Cs, ^{90}Sr and ^{239}Pu are 1 480, 111, and 3.7 kBq/m^2, respectively);
3. Zone of normal management (45.35 percent of forest lands).

In every forest ranger district there are lands from all three zones ranging from high-contamination to low-contamination sites (Figure 2). Consequently, all forestry personnel of the Chernobyl Forest Enterprise are required to work in contaminated forest areas. If forest ranger districts were instead delineated on the basis of radiological contamination criteria, it would allow at least a third of current forest personnel to work in relatively clean and safe forests. Furthermore, staff working in contaminated areas need to be trained more specifically on radiation protection, receive special equipment and be part of a special medical surveillance programme.

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3
Example of a 35-year old Jack Pine (Pinus banksiana Lamb.) stand in the CEZ (Korogod forest ranger district) (left) and a 40-year old Scotch Pine (Pinus sylvestris L.) plantation (right) documented in August 2014, both classified as Fire Hazard Class I

FUEL ACCUMULATION

An estimated 1.4 million m^3 of dead, radioactively contaminated wood that could fuel wildfires has accumulated in the CEZ. Forecasts predict that the quantity of contaminated dead wood will increase to 2.4 million m^3 by 2020 (Zibtsev, 2013). Overcrowding of forests is weakening trees and increasing wildfire hazard (cf. next section on fire hazard). As of 2014, 6–20 percent of trees are dead but still standing in middle-aged stands. The dieback of another 8–31 percent is expected over the next 5–10 years. Most of the pine plantations are at a stage of minimum increment due to the competition for space, light and nutrition between trees in stands. The amount of downed and standing deadwood in the CEZ is estimated at 9–26 m^3/ha. The total stock of forest combustible materials in pine stands ranges from 110 t/ha in 22-year old stands to 220-280 t/ha in 44–64-year old stands. Of these, 13–16 percent is ground fuel and 84–87 percent is above ground. Ground fuel is made up of forest litter (89–92 percent), woody debris (8–10 percent), and living forest vegetation (up to 1 percent).

FIRE HAZARD

The level of fire hazard of forest lands in the CEZ is assessed according to the official “Scale for assessment of natural fire hazard of forest lands”, approved by the State Agency of Forest Resources of Ukraine (Rating scale, 2005). The Scale includes five classes (Hazard Class I – maximum; Hazard Class V – minimum) and takes radioactive contamination into account. In particular, Class I fire hazards include all conifer forests less than 40 years old, all conifers on dry and sandy soils, sites affected previously by fires, clearcuts, and grasslands (Figure 3).

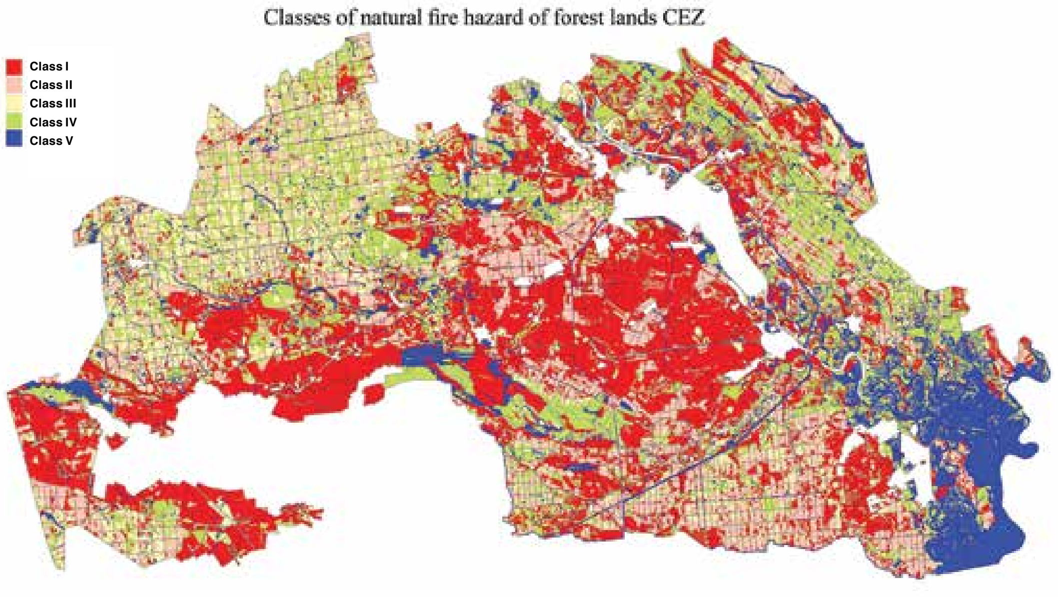
According to official data, 66 percent of the forests belong to Fire Hazard Class I, of which 38 percent are lands contaminated with levels above 555 kBq/m^2 ^{137}Cs, and 13 percent of the forests belong to Class II. Forests with the highest natural fire hazard levels are concentrated in the central and southern parts of the CEZ, including the most contaminated territories west and northeast of the Chernobyl NPP (Figure 4).

WEATHER-BASED FIRE DANGER

For the assessment of weather-based (meteorological) fire danger, a five-grade scale is used in Ukraine with Fire Danger Class V being the highest. The Fire Danger Class determines the level of preparedness of fire brigades and of the intensity of ground/air patrols for forests. However, a comparative analysis of fire history and official Fire Danger Classes based on a modified Nesterov Index reveals that the current early warning system does not reflect a realistic value of the fire-weather danger. A local fire danger scale based on the methodology by Kurbatsky (1963) was therefore developed for the CEZ (Zibtsev and Gilitukha, 2012) (Table 1). It includes a seasonal variation by introducing indices

TABLE 1. Comparative analysis of scales used in the current early warning system and the local scales proposed for the Chernobyl Exclusion Zone (CEZ)

Fire-weather Danger Class	Value of Ukrainian fire-weather indices (modified Nesterov Index)		
	Local scale of fire-weather danger proposed for the CEZ		Current early warning system used in Ukraine
	Spring–summer (10 March–10 June)	Summer–autumn (11 June–30 October)	
I	<250	<1400	<400
II	251–1000	1401–3550	401–1000
III	1001–2100	3551–5400	1001–3000
IV	2101–2800	5401–6400	3001–5000
V	>2800	>6400	>5000



Source: Zibtsev, Borsuk and Gilitukha, 2012.

4
Natural Fire Hazard Classes of forest lands in the Ukrainian part of the Chernobyl Exclusion Zone (Status: January 2013)

for a spring–summer and a summer–autumn period.

As can be seen from Table 1, the early warning system currently used makes a lower assessment of weather-determined fire danger, particularly for Fire Danger Classes IV and V (highest risk classes) during the summer-autumn period, whereas the official scale indicates a fire danger one class lower than that demonstrated by real fire occurrences. The reason is that during the development of the current system in 2011, no data was included from the large forest fires of 1992. Such data, however, will need to be taken into account in developing a new, local early warning system for the CEZ.

FIRE HISTORY

Forest and grass fires are regular occurrences in the CEZ despite the special territorial management regime which restricts access and land use. In 1986, the 10-km and 30-km zones around the Chernobyl NPP were fenced off and checkpoints controlled by police were established on the main access roads around the CEZ. Since then, however, fences have collapsed in some places due to deterioration, wildlife or damage caused by people entering the CEZ illegally. According to the current rules, only professional staff of the CEZ (ca. 300 local managers and researchers) and officially guided tourists are allowed to enter the CEZ).

An analysis of fire history based on statistics available from the Chernobyl Forest Enterprise shows that over 1 147 forest and grasslands fires occurred in the CEZ between 1993 and 2013 (Figure 5).

The time and spatial distribution of the fires shows that they occur more or less regularly over the whole territory of the CEZ, including the most contaminated areas in the 10-km zone with the highest levels of ^{137}Cs, ^{90}Sr, plutonium, and ^{241}Am contamination. It is also clear that in the northern and north-eastern parts, fires have regularly crossed the borders between Ukraine and Belarus. Wildfires have been recorded in grasslands (55 percent), forests (33 percent), former villages and even in swamps during periods of drought. The highest fire occurrence is in spring, between March and May, but the risk of catastrophic fires is highest in the second part of the fire season (July and August), as in 1992. In that year, crown fires burned up to 5 000 ha of forests, particularly in the south-eastern part of the CEZ in the Opachichi forest ranger district. Fires burning in Russia during the extreme heat wave of summer 2010 are another example of such a situation.

FIRE BREAKS

The forestry administration in the CEZ pays higher attention to the establishment of fire breaks than to other standard tools of fire prevention. According to recommendations by the Fire Management Plan (1994), a total of 111.9 km of fire breaks were established during the late 1990s, including 1.6 km of 10 m-wide breaks, 22.5 km of 11-20 m-wide breaks, 44.8 km of 21-30 m-wide breaks, and 43 km of breaks wider than 30 m. Fire breaks were placed mostly along the external perimeter of the CEZ and along main roads. It should be mentioned that since the 1990s, natural fire hazards in the CEZ have changed due to different types of disturbances (fires, wildlife, floods, natural succession, etc.). Most of the above-mentioned fire breaks are no longer maintained by regular removal of fuel and are therefore not able to stop fires. During the past decade, mostly 1.6 m wide fire breaks were built with a total length of 1 750 km. These fire breaks are maintained 2–3 times per year by removing accumulated fuel.

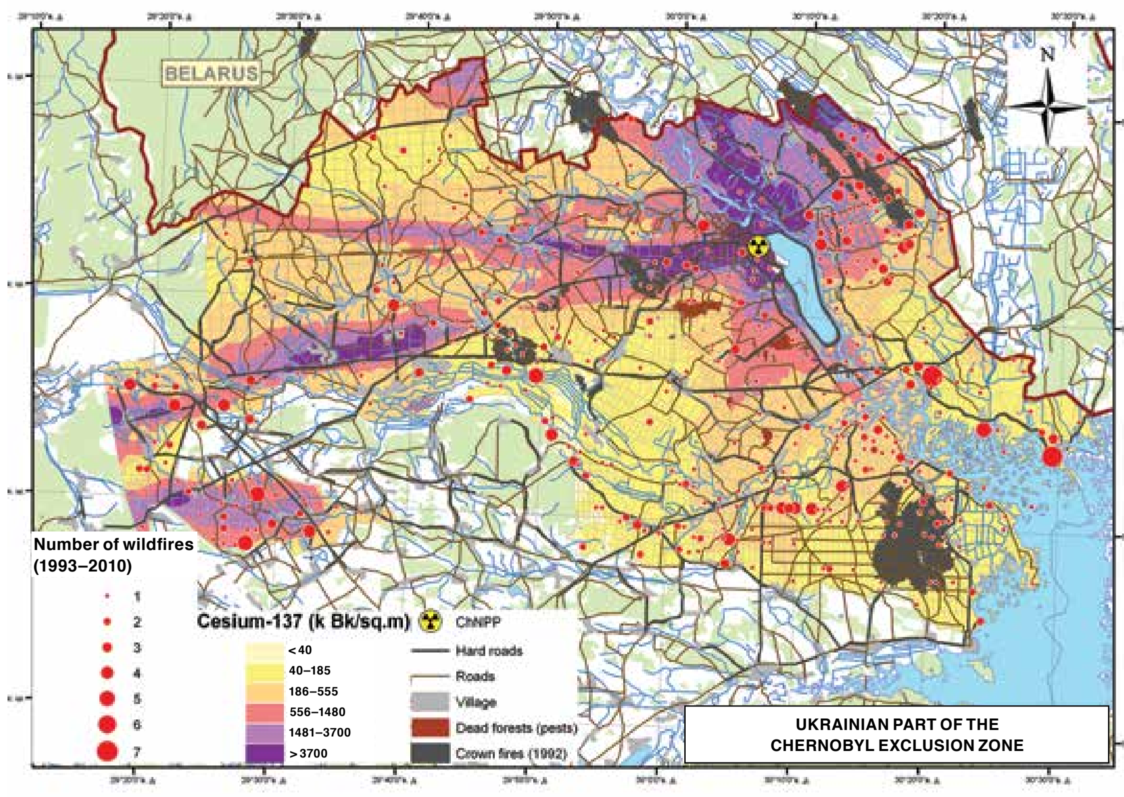
However there is no digital map reflecting the current locations of fire breaks and the main criteria of their establishment is unknown. A special analysis is required to define the effectiveness of the current fire-breaks system to mitigate existing fire risks. This will enable the system to be optimized and reduce the risks of large wildfires.

THREATS TO FIREFIGHTERS AND FIRE MANAGEMENT PERSONNEL FROM RADIONUCLIDES CONTAINED IN SMOKE AND DUST

During forest fires in the exclusion zone, radionuclides deposited in forest fuel in 1986 are released into the atmosphere with smoke. Resuspension of ^{90}Sr, ^{137}Cs, and plutonium is occurring in two forms: smoke particles and mineral dust. Dust particles are usually large (range: 2–100 μm in diameter; mean: ~10 μm) (Brasseur, Orlando and Tyndall, 1999) and redeposited close to the source. In contrast, forest and grassland fires emit fine particles with a bimodal size distribution of 0.04-0.07 μm and 0.1-0.3 μm (Chakrabarty *et al*., 2006). While large particles are usually repelled by the respiratory system, fine particles are inhaled into the lungs. Over time, fine particles in smoke plumes often form large particles through coagulation and are deposited with cloud droplets downwind from the fires.

Data from the Automatic Radiation Monitoring System managed by the Ecological Center state enterprise show a clear increase in the concentration of radionuclides in the air in the CEZ during large wildfires. In particular, during the massive CEZ forest fires in the summer of 1992, an increase in the concentration of airborne radionuclides from 0.017 Bq/m^3 to 1.5 Bq/m^3 was recorded in the town of Chernobyl, not far from the fire. The analysis of available information on the 1992 fire and inventories of radionuclides in the biomass burned showed that the ^{137}Cs-activity released into the air in this period was in the range of 28-130 TBq.[4] Hence, wildfires with areas of up to 1 km^2 in forests with a level of soil contamination higher than 40 MBq/m^2 create a potential threat of air release and long-distance transport of up to 40 TBq of ^{137}Cs. Radioactivity levels in the air of ^{90}Sr, ^{137}Cs, and plutonium near an experimental forest fire and two grassland fires in the CEZ were found to be several orders of magnitude higher than normal levels (Yoschenko *et al*., 2006). The radionuclides emitted, especially plutonium, were concentrated in fine particles, which would increase the inhalation risk

[4] TBq = Tera-Becquerel = 10^{12} Becquerel



Source: Evangeliou *et al*., 2015.

5
Distribution of wildfires (1993-2013) in different zones of radioactive contamination in the CEZ and location of forests killed by fires and pests

for firefighters. The worst case scenario (i.e. a catastrophic forest fire burning all fuel in the CEZ) shows a direct threat to the population and environment across a larger region. Radionuclides could migrate over a distance greater than 100 km, exposing the population to doses in excess of established limits (Hohl *et al*., 2012; Evangeliou *et al*., 2014). The risk of such catastrophic fires increases with climate change and appropriate measures should therefore be considered in emergency planning.

In 2013, an experimental assessment of doses from the resuspension of radionuclides for personnel involved in the establishment of fire breaks was undertaken (Yoschenko *et al*., 2013). The research showed that the effective resuspension coefficient for all radionuclides, calculated for the air inside the cabin of the tractor, is of the order of 10^{-8} m^{-1}. This means that the air-conditioning system reduces the concentration of radionuclides by two orders of magnitude compared to the air outside the cabin. Internal doses to personnel in the cabin of a tractor during the establishment of fire breaks (Figure 6) in the exclusion zone due to inhalation of radionuclides (calculated for a 50-year-old male person, effective dose equivalent) is more than twice as high as the external dose to the body. The inhalation dose is almost entirely due to the intake of transuranic elements. Inhalation doses for personnel located in the plume of dust or in a tractor cabin without an air-conditioning system will be up to two orders of magnitude higher than for staff protected by an air-conditioning system and can reach significant values. All these assessments show the importance and health benefit of cabin air filtering, as the dose contribution through inhalation is the most important pathway.

In the CEZ, the annual dose limit (5 mSv) for personnel involved in the establishment of fire breaks in areas with high contamination levels can be reached within a few weeks. At the moment, not all tractors in the CEZ are equipped with working air-conditioning systems, and air-conditioning systems are not always regularly maintained or new filters provided. In conclusion, doses from inhalation should be taken into account during the planning of fire prevention measures in order to avoid personnel exceeding dose limits. Staying in the plume of dust and using tractors without air-conditioning should be avoided.

FIRE DETECTION

Fire detection on CEZ forest lands before 2009 was based on daily helicopter patrols at midday, detection from fire lookout towers and ground patrols during periods of high fire danger. During the past years, helicopters have no longer been available. Only seven lookout towers (H = 35 m), all established before the failure of the Chernobyl reactor, are now used for fire detection across 260 000 ha of forests lands. However, most of them need repair or replacement. Spatial analysis shows that only 26.8 percent of the CEZ is covered by ground fire detection (Figure 7).

The left map reveals that large areas in the central, northern and eastern parts of the CEZ, which include highly contaminated

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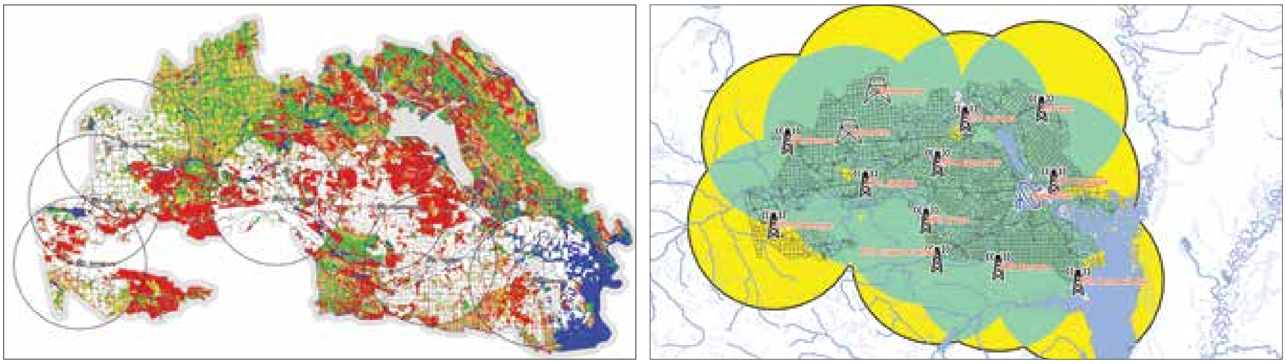
6
Establishment of fire breaks generates radioactive dust that can lead to an increase of inhalation doses for tractor drivers



Note: On the top map only the white-coloured territory is covered by fire detection (26.8 percent of the CEZ territory).
Source: Zibtsev, 2013.

7
Current fire-detection coverage of the CEZ using the existing seven fire outlook towers (left). The proposed fire detection coverage (right) is based on 13 observation towers with a coverage range of a radius of 15 km each, and one receiving station

lands with the highest levels of fire hazard, cannot be monitored from the existing towers. An improved monitoring system for early detection of fires in the CEZ must also include buffer zones to prevent the spread of grass and forest fires from outside the CEZ. In order to reduce the exposure of ground personnel to radiation, the lookout system should be based on automatic detection cameras and one receiving station connected to the dispatch center in the town of Chernobyl. However, a lack of funding, secure equipment and adequate power are the most important obstacles to implementing the proposed fire detection system.

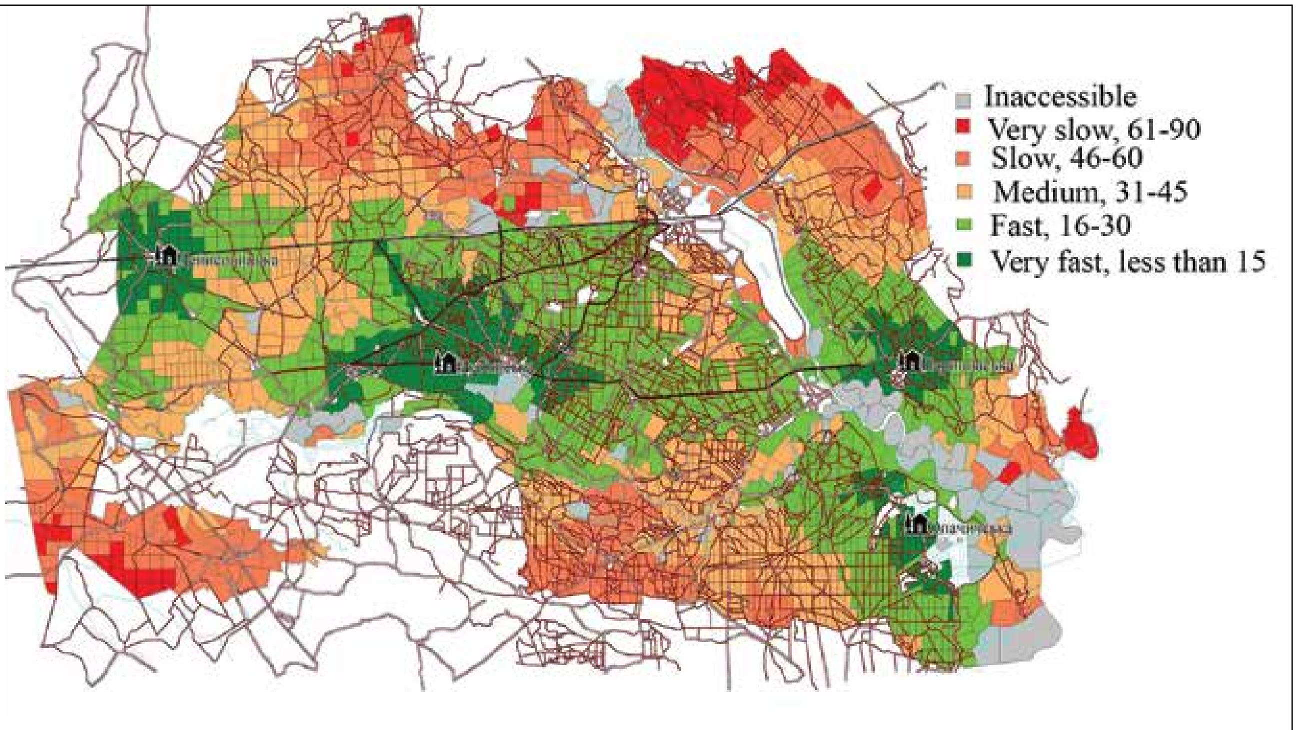
ROADS

In general, the main paved roads in the CEZ connecting the town of Chernobyl with checkpoints and with the Chernobyl NPP are constantly maintained. These roads are used to transport local and international personnel and local villagers who live permanently in the CEZ; to deliver construction materials for Confinement II (new sarcophagus); and for overall nuclear infrastructure and territorial management (power lines, pipelines, etc.). Many of the roads to remote, abandoned villages (Cherevach, Rozsoha, Denisovichi and others), however, are gradually deteriorating and may soon be unusable for wildfire suppression purposes. Most of the abandoned forest roads are now blocked by downed trees and natural tree regeneration (Figure 8).

FIRE SUPPRESSION CAPACITY

The Chernobyl Forest state enterprise is responsible for prevention, patrolling, fire infrastructure maintenance and initial fire suppression in the CEZ. In the case of a fire larger than 5 ha, professional firefighters from the Chernobyl Fire Station could also be involved. Common hand tools, water and the construction of fire lines around the fire are usually used for ground fire suppression. The total capacity for vegetation fire suppression

8
Downed trees and natural tree regeneration make forest roads inaccessible for fire suppression forces



Source: Evangeliou *et al*., 2015.

9
Zones with firefighter and fire truck response times (minutes) to potential fires from currently operating forest fire stations

includes four forest fire stations located in the central and southern parts of the CEZ (villages Denisovichi, Lubjanske, Paryshem, Opachichi) and seven points for hand tool storage which, however, do not coincide with the highest fire hazard areas. In total, only 33 permanent staff (firefighters and drivers), with 15 fire trucks (ZIL 131 with a capacity of four tonnes of water), 19 backpack pumps and hand tools (shovels and fire swatters) are available. The equipment does not even correspond to official Ukrainian minimum requirements for fire stations responsible for regular, non-contaminated forests. Water supply is provided by 16 fire ponds and points for replenishing water tanks.

To assess the effectiveness of the current placing of fire stations in the CEZ in terms of firefighter response time and water supply, a map was drawn up of the road networks reported officially in 2006, which could be used for fire suppression (Figure 9).

On the basis of a statistical analysis of response time from current fire stations, the CEZ can be divided into six main zones (Table 2).

The interpretation of the efficiency assessment needs to take into account that the response time analysis was based on the road network as reported by the Forest Management Plan in 1996. Based on this road network analysis, only 40.9 percent of forest lands in the CEZ could be reached by fire brigades within 30 minutes, whereas to reach other sites, where 60 percent of the fires have occurred during the past decades, it would take up to 90 minutes. In addition, 6.9 percent of forest lands in the CEZ are completely inaccessible to ground transportation. Heavily contaminated lands in the central and northern parts of the zone are also in the category of lands with

TABLE 2. Response times from current fire stations to reach potential fire locations

	Efficiency of response	Time of arrival of firefighters (min)	Average time of arrival of firefighters (min)	Number of fires (1993-2012)	Area of the zone (ha)	Share of total CEZ area (%)
1	Very fast	<15	11	150	23 690	9.9
2	Fast	16–30	23	190	74 315	31.0
3	Medium	31–45	37	259	65 118	27.2
4	Slow	46–60	51	193	48 826	20.4
5	Very slow	61–90	66	28	11 112	4.6
6	Inaccessible	-	-	21	16 627	6.9
Weighted average / total			**33**	**841**	**239 688**	**100.0**

unsatisfactory response times (30 minutes and more). Furthermore, response time may now be much higher in many cases, as a number of roads from that time no longer exist.

RECOMMENDATIONS FOR URGENT STEPS TO IMPROVE FIRE MANAGEMENT

In light of the current state of wildfire risks, threats and fire management capacity in the CEZ, there is an obvious need to take proactive steps to prevent large fires and avoid overexposure of forestry and other personnel working in the CEZ, as well as secondary radioactive contamination of other territories over large distances. To achieve these goals, source risks need to be lowered, which means that fire management needs to be improved. The following plans should be developed and activities undertaken:

1. The CEZ fire management plan should be updated, taking into account current fire hazard, forest health, peculiarities of contamination, road and fire breaks network, fire history and fire response capacity. The fire management plan needs to be economically realistic and feasible.
2. An updated vegetation map of the CEZ should be drawn up, based on remote sensing data.
3. A local early warning system should be in place, as well as reliable automatic fire detection and fast response capacities for the CEZ.
4. A plan for the long-term reduction of fire hazards and fuel management is needed, based on silvicultural and forest utilization methods using harvester/forwarder machines properly equipped with filters to avoid inhalation doses for operators as well as strategically placed and regularly maintained firebreaks. In the long term, a strategy needs to be developed for the management and treatment of harvested, radioactive wood including consideration of special incineration facilities with associated nuclear waste solidification and long-term storage capacities. Without such a long-term strategy, it will be difficult to manage forests and reduce fire risks through removal of dead wood.
5. A decision support system for fire suppression would allow the incident commander to control exposure time of firefighters on the fire line from the point of view of compliance with individual radioactive safety norms.
6. Methodologies should be established to assess fire behaviour and fire intensity, required amount of water, water delivery time and optimized routes for fire trucks.
7. Fire personnel of the Chernobyl Forest Enterprise should be properly trained and equipped to fight radioactive fires. Special fire suppression and incident management tactics aimed at reducing inhalation doses for firefighters as well as radiological health monitoring should be developed. ◆

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Additional information on fire management on contaminated terrain

The following web page of the Global Fire Monitoring Center (GFMC): **http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/SEEurope_1_radio.html** includes an in-depth analysis of wildland fires and human security and a forthcoming (2015) report by the Organization for Security and Cooperation in Europe (OSCE) on firefighting safety on contaminated terrain:

Goldammer, J.G. 2013. Beyond climate change: Wildland fires and human security in cultural landscapes in transition – examples from temperate-boreal Eurasia. In J.G. Goldammer, ed. *Vegetation fires and global change: Challenges for concerted international action. A White Paper directed to the United Nations and international organizations*, pp. 285-311. Remagen, Global Fire Monitoring Center (GFMC) and Kessel Publishing.

Goldammer, J.G., Kashparov, V., Zibtsev, S. & Robinson, S. 2015. *State-of-the-art assessment of best practices on fire suppression in contaminated areas, including recommendations on radioactive and chemical safety of firefighters*. Organization for Security and Cooperation in Europe (OSCE) (in preparation).