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Wildfires Risk Reduction From Forests Contaminated by Radionuclides: A Case Study of the Chernobyl Nuclear Power Plant Exclusion Zone

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Abstract
Insufficient forest and fire management during the last 25 years has resulted in high wildfire hazard in the 260,000 hectares of forests and former agricultural lands of the Chornobyl Exclusion Zone. This area is highly contaminated with long-resident radionuclides of ^{238}Pu, $^{239+240}$Pu, ^{137}Cs and ^{90}Sr. A fire risk classification system based on stand structure and fuel loading was used in conjunction with tree inventory, stand information, and forest growth projections to assess actual and future fire risks. A very bad case scenario was developed in which biomass consumption by fire and release of associated radionuclides into the atmosphere were modeled. A decision-support system for emergency wildfire situations on contaminated lands and a risk reduction system is currently being developed to provide early wildfire detection and warning for local fire fighting forces in order to prevent contamination of populations from radioactivity contained in wildfire smoke plumes. Lessons learned for application to other, future international wildfire and other environmental threats are discussed.
Keywords: Chernobyl, radiation, radioactivity, early warning, fire fighting, wildfire, forest, silviculture, risk.

1. Introduction

An explosion in reactor No. 4 of the Chernobyl nuclear power plant (ChNPP) in northern Ukraine on April 26, 1986 released approximately 1.85×10^{18} Becquerel (Bq) of radioactive material into the surrounding environment (National report 2006, Othman 1990). Residents were permanently evacuated from a 30 km zone around the plant, that later were extended to the area of 260,000 ha. Radioactive material has been incorporated into both the soil and vegetation.

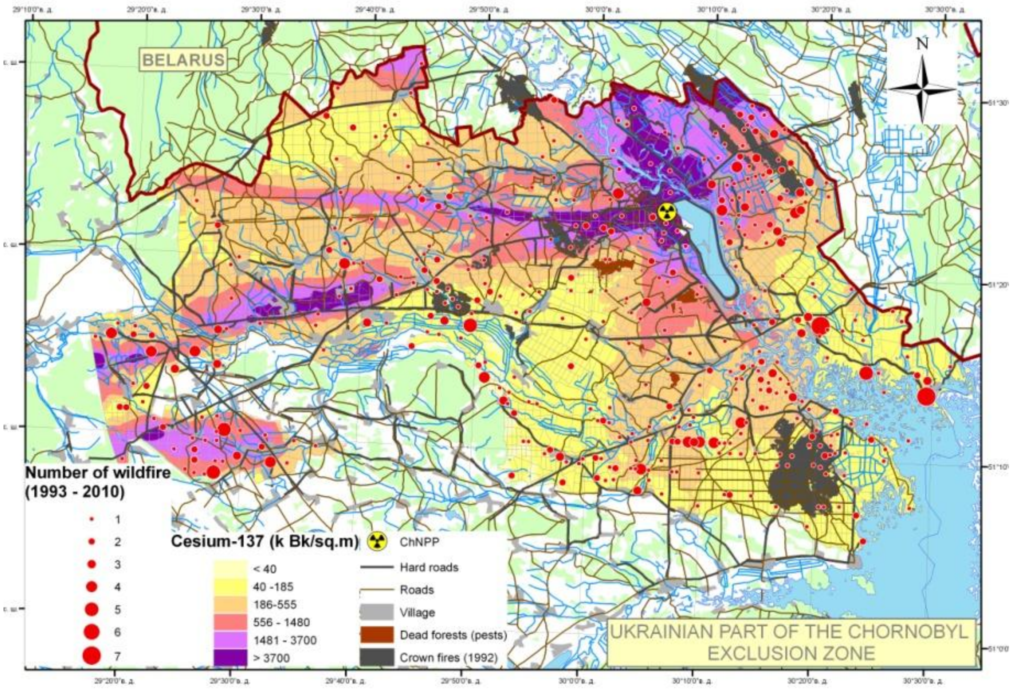


Figure 1— Distribution of wildfires (1992-2010) in different zones of radioactive contamination in the Chernobyl exclusion zone and location of died forests due to impact of fires and pests (map produced by D. Gilitukha, National University of Life and Environmental Sciences, Ukraine, 2011)

Wildfires of up to 17,000 ha (1992) have been occurring periodically in the Chernobyl Exclusion Zone (CEZ) (Figure 1). The effects of radioactive smoke from these fires have been studied (Yoschenko et al. 2006a, 2006b). Preliminary, expert observations by S. Zibtsev (and later Ch. Oliver, J.G. Goldammer, and others) suggested that the forests may also be highly susceptible to catastrophic wildfires based on similar experiences in the western United States. As elsewhere, appropriate silvicultural treatments may reduce this susceptibility. The degree of susceptibility of the CEZ to large and small wildfires and the effectiveness of silvicultural treatments in reducing the wildfire susceptibility needed to be determined. A parallel issue is how harmful are the effects of the irradiation to human health of both the occurring small fires and the potential catastrophic fire. A third issue was one of mobilizing appropriate resources to prevent a potentially international environmental catastrophe.

This paper addresses the three issues addressed above: assessing and preventing a wildfire of catastrophic dimension; assessing the effects of a worst-case scenario if the fire did burn; and mobilizing the political will to take appropriate action.

2. Literature Review

The CEZ is 23% deforested/former agriculture areas and 34% Scots pine (*Pinus sylvestris* L.) forests, with the remaining 23% in softwood forests. The CEZ is largely on droughty glacial outwash, sandy soils. Seasonal droughts and overly crowded pine forests infested by insects and pathogens make these forests highly susceptible to wildfires (Figures 2 and 3).

Figures 2 and 3 —Pine forests inside of CEZ (left) and outside in less contaminated zones. The crowding makes these pine forests susceptible to insect infestations and diseases, dying trees, and high fuel loads for subsequent fires.

Most contaminated area is the CEZ, and the most important radionuclide contaminants throughout it are ^{137}Cs and ^{90}Sr. Within the CEZ, the 10-km zone surrounding the ChNPP has been contaminated by long-term by $^{239+240}$Pu that have decay periods of hundreds to thousands of years. ^{241}Am is expected to increase for the next 100 years because it arises from the decay of ^{241}Pu (IAEA 2006).

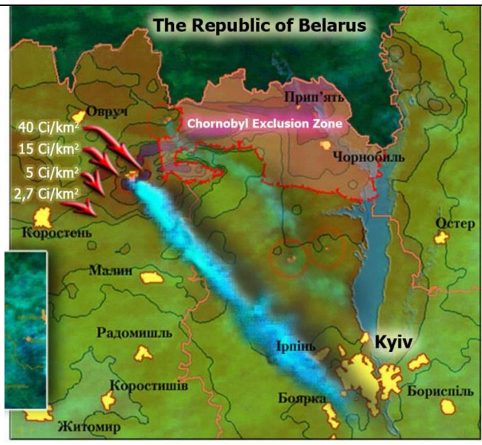
Radioactive fallout was deposited on the plant surfaces during the first month after the disaster—especially on Scots pine stands since deciduous plants had not produced spring foliage. Within 3–4 months, most of the radionuclides had migrated to the ground, accumulating in mosses, forest litter, and soils. The vegetation root systems gradually absorbed the radionuclides in isotope-specific amounts. Within 3–4 years, a period of quasi equilibrium of radionuclides in the ground and vegetation cover occurred and has continued. At the moment, the concentration of each radioactive element varies considerably among the different components of the vegetation. ^{90}Sr, ^{137}Cs, ^{238}Pu, and $^{239+240}$Pu are concentrated mostly in the top soil layers of forests and grasslands (Yoschenko et al. 2006a). The radioactivity of litter is higher than that in living tree foliage, bark, or grasses.

Resuspension of ^{90}Sr, ^{137}Cs, ^{238}Pu, and $^{239+240}$Pu by a wildfire into the atmosphere is occurring in two ways: smoke particles and mineral dust. Construction activity in the ChNPP site and windy conditions are the major causes of dust from contaminated soil. Dust particles are usually large (range: 2–100 μm in diameter, mean: ~10 μm) (Brasseur et al. 1999) and redeposit 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. Fine particles in smoke plumes often form large particles in aged plumes through coagulation and are deposited with cloud droplets downwind from the fires.

Radioactivity of ^{90}Sr, ^{137}Cs, ^{238}Pu, and $^{239+240}$Pu for atmospheric particulate matter near an experimental forest fire and two grassland fires in the CEZ were found to be several orders of magnitude higher than the ambient levels (Yoschenko et al. 2006a). The emitted radionuclides, especially plutonium, were concentrated in fine particles, which would increase the inhalation dosage to firefighters.

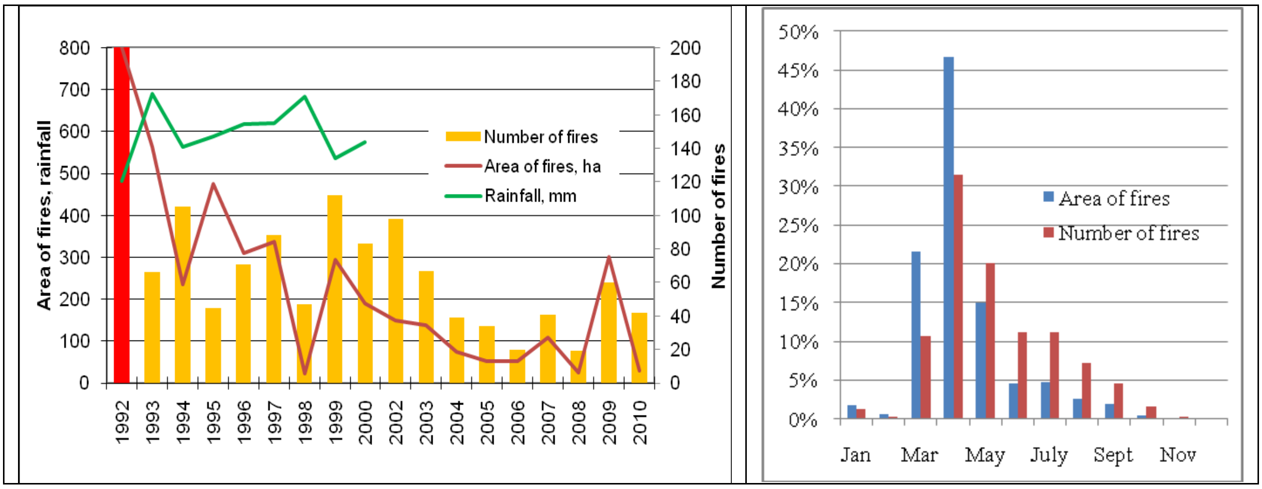
3. The Chernobyl Disaster: Radiological Contamination, Ecological Damages, and Forestry Consequences

Insufficient forest management has allowed the accumulation of fuel in forest stands and a decline of forest health. Forest inventory data shows 15,300 ha of forests in the CEZ are damaged, including 5,300 ha damaged by pests that are now very fire prone. Large forest areas have already died from insects and diseases (*Ocneria Dispar* L., *Fomitopsis annosa* Karst. and others; Figure 4). An estimated 1.4 million cubic meters of dead radioactively contaminated wood has accumulated within the CEZ (data of Ukrainian Forest Inventory Enterprise) that eventually can be burned. Smoke from large size ground and crown fires in contaminated zones moves radionuclids hunred and more kilometers away downwind (Figures 5).



Figures 4 and 5 — Extreme risk of radioactive fire related with fire prone forests (left). During a wildfire burning in contaminated terrain close to the CEZ on 8 May 2003 satellite imagery showed smoke plumes moving toward Kiev. Figure 4: Photo: courtesy of Chernobyl Forest Enterprise. Figure 5: Satellite-derived map courtesy Ukrainian Land Resourse Management Centre, based on a NOAA imagery, 8 May 2003.

Fires are most frequent in grasslands (55%) and forests (33%), but even occur in swamps during periods of drought. Fires have recently been increasing in forests, related to increasing legal and illegal visits to the CEZ by people.



Figures 6 and 7—Annual rainfall, amount and area of wildfires in the Chernobyl exclusion zone (in 1992 17,000 ha of forests were burned) (left) and distribution of number of wildfires in a season (right)

In the extreme drought year of 1992, more than 17,000 ha forests burned in ground, surface and crown fires. A similarly high drought has not occurred, but 980 wildfires of human and natural origin have occurred from 1993-2010 (Figure 6 and 7). There is a general trend of declining numbers and sizes of fires since 1992, coincident with greater firefighting efforts; however, fire occurrence increases during drought years.

Following the catastrophic wildfires in 1992, the specialized Chernobyl Forestry Enterprise was established to carry out fire and forest management to prevent large concentrations of radionuclides from migrating out of the CEZ. However, only 6 to 40% of the planned thinning operations (4–40,000 m^3 per year) were done during 1993-2010 because of restrictions related to radioactive contamination, labor and finance shortages.

The highest risk of fires occurs in spring between March and May. These can be predicted by the Nesterov Index of fire weather classes used throughout Ukraine, and by the Canadian Fire Weather Index (FWI) (Figure 8). The highest probability of catastrophic fires may be the second part of the season — July and August — as happened in 1992. Fires in Russia during the extreme heat wave of summer of 2010 are an example of such a situation.

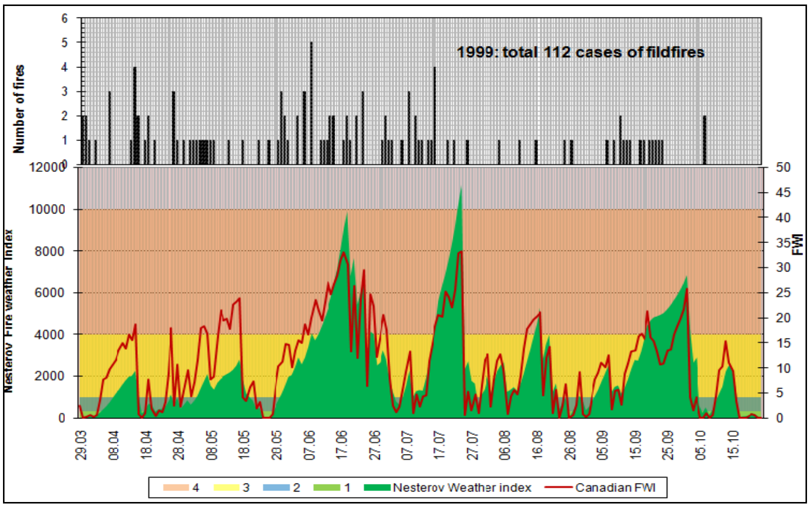


Figure 8—Interrelations of number of fires in CEZ with fire weather (Nesterov Index, WFI) in 1999

4. Fire Risk Assessment

A sample of the CEZ with 26,000 ha was assessed for current and future potential fire risk using Ukrainian forest inventory, the LMS computer platform (Oliver et al. 2009), and both Ukrainian and United States forest fire risk assessments. Forest inventory data was obtained from 1996 assessment for an area of 8,000 ha stands averaging 3.3 ha each for a total of approximately 10% of the CEZ. Results showed 36% of the sampled area in risk class 1 (highest risk of four classes) and 38% in risk class 2 of the Ukrainian fire risk assessment model.

Using LMS, the United States LS variant of the FVS growth model (Wycoff et al. 1982), and the U.S. fire risk classification, current conditions of the stands and their projected changes with and without silvicultural intervention are shown in Figure 9. Silvicultural intervention included thinning some pine stands and converting others to hardwood species, that have lower fire risk.

Both the Ukrainian and U.S. fire risk assessments confirmed initial observations that much of the forest is in high danger of burning. Projections with and without silvicultural manipulations confirmed that the fire risk would remain high without intervention, but could be reduced dramatically with appropriate silvicultural manipulations.

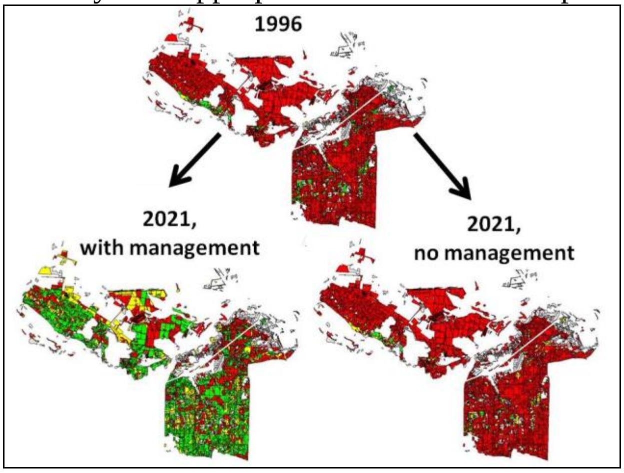


Figure 9—1996 Forest Fire Risk maps of 26,00 ha sample of CEZ forests showing condition in 1996 and projected to 2021 with and without simulated silvicultural intervention. Fire Classes are: Red = High risk; Yellow = Moderate risk; Green = Low risk.

5. Health Effects of the Wildfires from Irradiated Forests

Smoke from the large fires of 1992 redistributed radionuclides in the CEZ. There are a few assessments of radio ecological consequences of this fire for CEZ and its vicinity, e.g. the observation of radioactive smoke plumes containing ^{137}Cs, which were monitored several hundred kilometres downwind from the sites where fires occurred in May and August 1992 (Dusha-Gudym 2005).

The effects on people of smoke from a catastrophic fire in the CEZ was analyzed by assuming a worst-case scenario in which all of the CEZ forests were completely burned and the airborne smoke and particulate matter was blown directly toward Kiev, 100 km away, for 90% of the time. The model was developed as a cooperative effort among the National University of Life and Environmental Sciences of Ukraine, the Global Institute of Sustainable Forestry of the Yale University School of Forestry and Environmental Studies, and the Global Fire Monitoring Center (GFMC) of the United Nations International Strategy for Disaster Reduction (UNISDR) and United Nations University, with financial support by the Chopivsky Family Foundation. The analysis was based primarily on a generic screening model used to assess the impact of discharges of radioactive substances to the environment (IAEA 2001). It consisted of four linked sub-models: a source model, a transport model, an exposure model, and a cancer risk model. It assumed that the 70% of the CEZ classified as deforested/former agricultural areas or pine forests would burn.

The source model used the studies of Kashparov et al. (2000, 2003), Yoschenko et al. (2006b), Sokolik et al. (2004), and Lux et al. (1995) to determine how much radiation of each isotope would be taken up in the smoke assuming a fire that consumed the biomass of pine forests and former agricultural lands and released any associated radionuclides into the atmosphere.

In the transport model, radioactive material from the fire would primarily be discharged and dispersed via a radioactive plume and be deposited on ground and water surfaces. The atmospheric discharge was treated as a point source and its trajectory was modeled using a Gaussian plume model. The wind was assumed to blow towards Kiev at 2 m/s for 90% of the duration of the wildfire.

The exposure model estimated exposure through immersion and inhalation during the fire itself and ground exposure and ingestion in the following year, with different ages and sexes being affected differently. Exposures via inhalation and plume immersion were assumed to cease being factors after the plume has passed. Exposures via surface deposits and ingestion were assumed to occur for a full year afterward. The ingestion (food chain) model assumes that the critical population is exposed to radionuclides through ingestion of crops, meat, and milk products that have been exposed to atmospheric discharges.

The analysis indicated that the greatest effects would be on people working within or near the CEZ and to crop areas that were exposed strongly to the radioactive smoke as far as 150 km away. These crop areas directly in the smoke's path would be too contaminated to grow food for consumption.

Other information, not taken from the model, suggests that the health risk from radioactive wildfires within the CEZ depends of the type of fire (ground or crown) and concentration of contamination where the fire is burning. The highest risk is to the forest fire brigades responsible for the initial attack on the fire. A catastrophic crown fire could also give serious exposure to the professional staff of 2,000-3,000 who are working on the ChNPP and elsewhere in the CEZ. Some risk exists also for people living outside of the CEZ but within its vicinity.

On the other hand, the analysis indicated that people more than 25 km from the fire who did not eat contaminated crops but were exposed to the smoke by inhaling it, being immersed in it, or through surfaces coated with smoke particles would not receive enough radiation to warrant their evacuation. And, there would be no cause for direct panic in Kiev if the smoke came directly there, since any increases in cancers and deaths would be minimal.

The model has been sent out to international experts for peer review. The reviews are currently being compiled and will be available on websites of the Yale University, School of Forestry and Environmental Studies, Global Institute of Sustainable Forestry, U.S.A. and at the National University of Life and Environmental Sciences, Ukraine.

Fires in Ukraine that may send smoke or burn into Byelorussia would require special agreements between the governments to exchange of information and to permit fire fighters to cross the border.

6. Risk Reduction Plan: Prevention, Early Warning System, Silviculture Measures

Many problems, described above, would be created by fires within the CEZ. Fire fighters and other workers within the CEZ would be at risk, as well as surrounding villages. Croplands would need to be abandoned, and international relations may be affected. Although apparently not a serious health risk to people as far away as Kiev (provided they do not eat food from areas where radioactive particles were deposited), a precautionary approach is also to consider a possible risk to these people based on the possibility that the model may be wrong.

A risk reduction plan has been proposed by a joint international project by the National University of Life and Environmental Sciences of Ukraine, the Global Institute of Sustainable Forestry of the Yale University School of Forestry and Environmental Studies, the Global Fire Monitoring Center (GFMC), the USDA Forest Service, and others with financial support by the Chopivsky Family Foundation. The Ministry of Emergencies of the Ukraine and the State Agency of the Ukraine for Management of the Exclusion Zone, as the governmental authorities responsible for wildfire safety in the Chernobyl Exclusion Zone, have considered and support the joint proposed plan.

The proposed risk reduction plan consists of two parts: 1) Installation of advanced and innovative early warning system for the whole CEZ and building an early response system based on an automated fire detection and modelling system; preparedness for initial attacks from helicopters or by the closest ground patrol; development of a decision support system on risk assessment and response for emergency fire situations; development of a smoke management system; and upgrade in the currently antiquated fire fighting trucks and other equipment; 2) Reduction of the fire danger of the most fire prone forests in the CEZ. This would be done by thinning--or clearcut harvesting the forest in some circumstances. Dust inhalation by the woods workers would be minimized by using mechanized machinery (e.g., feller buncher) in which the operator remains within a closed cabin and harvesting trees using a remotely controlled shear on a boom; this would minimize the exposure of forest workers. The machines are designed to ride over the cut tree crowns, pushing them into the ground and thus minimizing their future fire hazard. The harvested logs would be cut by the feller buncher and stacked tightly to minimize their drying and becoming a fire danger—as well as to accelerate their rotting.

The State Agency of Ukraine for Management of the Exclusion Zone included of proposed measures into the draft of "Ukrainian Governmental Social Program for Securing of Fire Safety". A final decision about the financing of the Program will be taken by the Government of Ukraine during the first half of 2011.

7. Conclusions and Recommendations

The high probability and strong negative effects of wildfires spreading radioactive smoke within and beyond the CEZ have led to the decision of the Ukrainian government to initiate measures to prevent them. This decision occurred after over two decades during which these fires could have occurred and created both panic and hardship. A series of activities by Ukrainian and international scientists, global citizens, administrators, and policymakers is leading to a promising outcome. Several positive and negative "lessons learned" can be gained from the experience:

1) The conscientious work by Ukrainian scientists to collect the initial data, the strong leadership of Rector D. Melnychuk, the international cooperation of scientists from many countries in doing and reviewing the analyses, the generous contributions of the Chopivsky Family Foundation, and the contributions of many concerned individuals toward raising the issue show that people can work cooperatively to avert an international environmental crisis before it occurs.

2) On the other hand, there were a few advocacy groups and individuals who tried either to elevate the effects of the radioactive smoke to an alarmist level or minimize the risk of the fires. Groups with neither perspective were scientifically qualified to speak on these subjects. International procedures need to be developed that distinguish the statements of such people and organizations from qualified scientists.

3) In the summer of 2010 when fires in Russia caused high concern in Kiev about irradiated smoke (Goldammer 2010), the Ukrainian and international press behaved responsibly by interviewing members of this team and consequently not sensationalizing the effects of the radioactive smoke. This behavior should be encouraged, since the news media sometimes seeks to sensationalize news inappropriately.

4) Unfortunately, most policy makers, statesmen, and NGOs were not able to do other than sympathize with the issue. Between 2007 and 2010, the World Bank, the European Union (Minister of the Environment), the European Bank for Reconstruction and Development, the United Nations (through the Global Fire Monitoring Center), the Council of Europe through its European and Mediterranean Major Hazards Agreement (EUR-OPA), the Organization for Security and Cooperation in Europe (OSCE), the Environment and Security Initiative (ENVSEC) International Union for Conservation of Nature (IUCN), and representatives of nine countries, including Ukraine, were made aware of the concern, notably by the "Chernobyl Resolution on Wildfires and Human Security: Challenges and Priorities for Action to address Problems of Wildfires burning on Terrain Contaminated by Radioactivity, Unexploded Ordnance (UXO) and Land Mines", which was released in October 2009 (Anonymous 2009; Goldammer and Zibtsev 2009). Many of these were made aware before the second (fire scenario) analysis showed the consequences not to be overly drastic to the citizens of Kiev. Unfortunately, few of these agencies took action; and those that did were stymied by the inaction of the Ukrainian government of those times. This behavior points to a lack of policies that can implement an international emergency strategy while respecting the sovereignty of individual nations.

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