MINI REVIEW

Consequences of nuclear accidents for biodiversity and ecosystem services

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Abstract

Nuclear energy is a potential solution to electricity demand but also entails risks. Policy debates on nuclear accidents have focused primarily on negative impacts on humans. Although such impacts are important, we argue that policy debates must also consider the consequences for biodiversity and ecosystem services. We reviewed 521 studies conducted after the Chernobyl accident, the most severe nuclear accident in history. Elevated radiation levels have been recorded among a diversity of species, even up to thousands of kilometers away from the meltdown site, and after more than two decades following the accident. Close to the reactor, physiological and morphological changes have occurred. Negative effects on ecosystem services have been observed, including the contamination of water, soils, and wild food supplies. Informed policy decisions on nuclear energy require a greater understanding of the consequences of accidents, including effects on biodiversity and ecosystem services. Based on our review, we recommend to (1) fully incorporate risks for biodiversity and ecosystem services into policy debates; (2) develop a coherent information chain regarding such risks; (3) use proactive planning strategies to be prepared for potential accidents; and (4) develop a coherent research agenda on the consequences of nuclear accidents for biodiversity and ecosystem services.

Introduction

Energy demand is surging worldwide (Asif & Muneer 2007), and is potentially a major contributor to global climate change. In this context, nuclear energy could be an attractive solution because it is largely carbon-neutral and, thus, may help to curb global warming (Davis *et al*. 2010). However, the recent disaster in Fukushima (Japan) has revived safety concerns about nuclear energy. The Fukushima disaster is by no means the only example highlighting the dangers of nuclear energy. The most severe accident before Fukushima occurred in Chernobyl (Ukraine), in 1986. According to the International Nuclear Event Scale by the International Atomic Energy Agency, nuclear accidents have also occurred in Argentina, Brazil, Canada, Czechoslovakia, France, Japan, the former USSR, Switzerland, the United Kingdom, and the United States; and incidents have been recorded in Canada, Czechoslovakia, France, Germany, Hungary, India, Japan, Russia, Spain, Sweden, United Kingdom, and the United States (Sovacool 2010).

The environmental consequences of nuclear accidents, although potentially drastic, are easily marginalized in policy debates—these include fallout of radioactive substances, biological contamination, and even changes to the behavior, physiology, and morphology of species

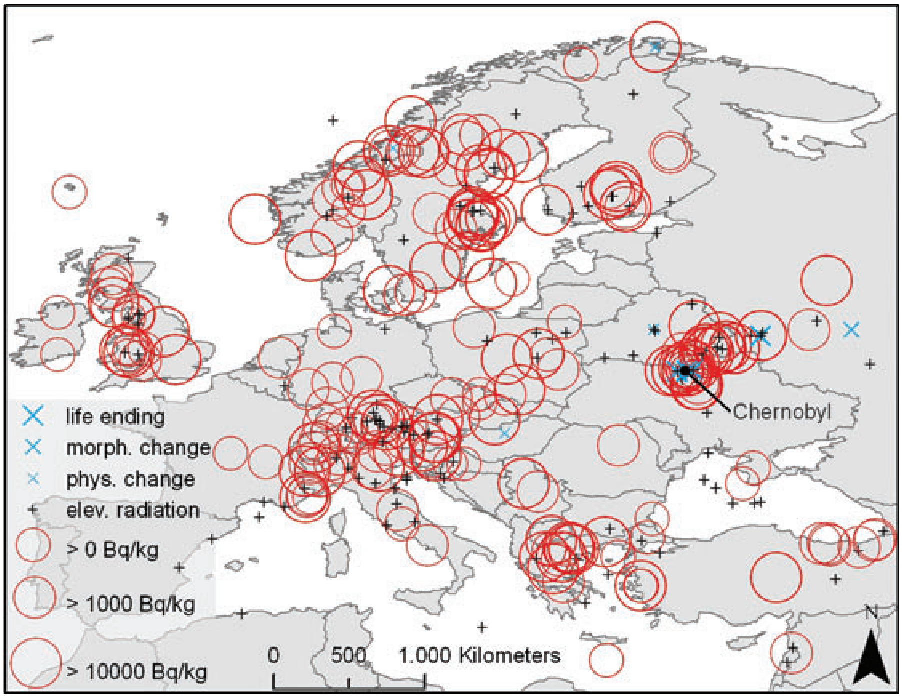

Figure 1 Spatial distribution of the impacts of the Chernobyl disaster described by the 521 studies included in our review (15 studies outside the western Palearctic are not shown). Bq/kg is the most common unit for level of radiation. Thresholds for food items vary across countries but 600 Bq/kg is a common value set by many countries.

(Møller & Mousseau 2006). Overlooking the environmental consequences of nuclear accidents represents a major shortcoming for two reasons. First, the impacts of potential nuclear accidents on a diversity of organisms are worthy of concern in their own right. Second, damage to ecosystems often translates into damage to ecosystem services and, thus, represents an important indirect effect on human well being in present and future.

To characterize and quantify the potential consequences of nuclear accidents for biodiversity and ecosystem services, we reviewed 521 published studies investigating the impacts of the Chernobyl disaster, which, until now, has been the only available baseline event to empirically judge the consequences of catastrophic nuclear accidents (see online Supplementary Material for Methods). Specifically, our study aimed to (1) provide a summary of the spatial and temporal patterns of the documented effects of the Chernobyl disaster on a wide range of organisms, and (2) discuss the implications of nuclear accidents for the provision of ecosystem services, again, drawing on documented evidence in the aftermath of the Chernobyl accident. We conclude with four tangible take-home messages, intended to be directly relevant to debates about the future of nuclear energy.

Consequences or impacts to species

Spatially, the documented effects of the Chernobyl disaster broadly follow known fallout patterns (Figure 1). However, variance in radiation levels is extremely high, not only between but also within sites. At a given study location, radiation levels have been shown to vary from 44,300 to 181,100 Becquerel per kilogram (Bq/kg) for mushrooms in southern Sweden (Mascanzoni 2009), from 3,000 to 50,000 Bq/kg for bats in Chernobyl (Gashchak *et al.* 2010), and from 176 to 587,000 Bq/kg for higher plants in southwestern Russia (Fogh & Andersson 2001); the latter equals almost a hundred times the threshold (600 Bq/kg) set by the European Union for Food that is deemed safe for consumption. High variance in radiation levels means that fallout maps based on extrapolations, models, and climate forecasts are not sufficient to evaluate radiation levels on a fine scale—field data are critically important for this purpose. Furthermore, radiation levels measured in the field and predicted fallout patterns based on meteorological data sometimes do not match (McAulay & Moran 1989), because additional factors, such as dry deposition, are not accounted for by climatic predictors (Arvelle *et al.*

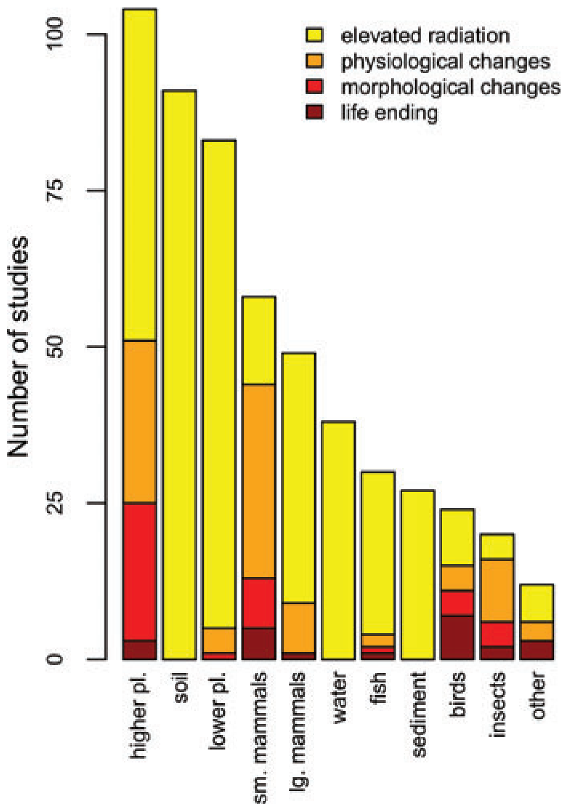

Figure 2 The number of published studies on a given ecosystem component (pl. = plant; other includes amphibians, bacteria, mollusks, reptiles, and shellfish). The majority of studies examining morphological, physiological, or life ending consequences were undertaken in the direct vicinity of Chernobyl (91%).

1990). In addition, some regions and types of ecosystems are systematically underrepresented in studies to date. For example, existing data is sparse for marine and aquatic ecosystems (Figure 1).

Although many measurements were undertaken in the aftermath of the Chernobyl accident worldwide, existing studies are greatly biased toward few taxonomic groups (Figures 2 and 3). Most studies have focused on topsoil measurements and accumulation in the plant layer, which is where radiation can be most easily measured. Despite this bias, it is clear that for most well-studied groups, greatly elevated radiation levels can occur up to thousands of kilometers away from the disaster site. For example, recorded radiation levels in mushrooms were up to 13,000 Bq/kg in Denmark in 1991 (Strandberg 2003) and up to 25690 Bq/kg in Norway in 1994 (Amundsen *et al*. 1996).

The consequences of elevated radiation levels in many parts of a given ecosystem remain poorly understood, but are likely substantial. For example, rats showed changes in sleep behavior after drinking water poisoned with "only" 400 Bq/l (Lestaevel *et al*. 2006), and onions have shown a significantly elevated rate of chromosomal aberrations at levels as low as 575 Bq/kg (Kovalchuk *et al*. 1998).

Although numerous studies have investigated physiological and morphological alterations in the vicinity of the Chernobyl accident site, hardly any studies have quantified the possibility of such alterations at larger distances. This could be a major shortcoming, because radiation levels are known to be greatly increased in some organisms even at large distances from the accident site (see earlier)—physiological or morphological alterations, therefore, are plausible, at least in isolated instances. Where such alterations occur, their long-term consequences on the ecosystem as a whole can be potentially profound (Kummerer & Hofmeister 2009).

The legacies of the environmental consequences of the Chernobyl accident are still prevalent today, 25 years after the event. Although many studies have shown a peak in radiation immediately after the catastrophe and then a continuous decline, radiation levels measured throughout the ecosystem are still highly elevated. For example, radiation levels in mosses (Marovic *et al*. 2008), soil (Copplestone *et al*. 2000), and glaciers (Tieber *et al*. 2009) have remained greatly elevated in several locations around Europe. The long-lasting legacy of the Chernobyl accident was also illustrated by intense wildfires in the Chernobyl region in 2010, which caused a renewed relocation of radioactive material to adjacent regions (Yoschenko *et al*. 2006). The persistence of high radiation levels can be attributed partly to the half-life rates of the chemical elements involved (e.g., 31 years for Caesium-137; 29 years for Strontium-90; and 8 days for Iodine-131).

In addition to elevated radiation levels, morphological and physiological changes are by definition long-term in nature, and can even be permanent if genetic alterations occur. For example, a range of bird species now have developed significantly smaller brains inside the core zone around the Chernobyl reactor site compared to individuals of the same species outside this zone (Møller *et al*. 2011). The consequences of such changes on long-term evolutionary trajectories remain largely unknown.

Lethal mutations following exposure to nuclear fallout have been observed in various plant (Abramov *et al*. 1992; Kovalchuk *et al*. 2003) and animal species (Shevchenko, *et al*. 1992; Zainullin *et al*. 1992), yet research has mainly been conducted within the Chernobyl region. Morphological changes have also been observed in a wide array of species, including plants (Tulik & Rusin 2005), damselflies (Muzlanov 2002), diptera (Williams *et al*. 2001), and mice (Oleksyk *et al*. 2004). In addition, some studies have documented

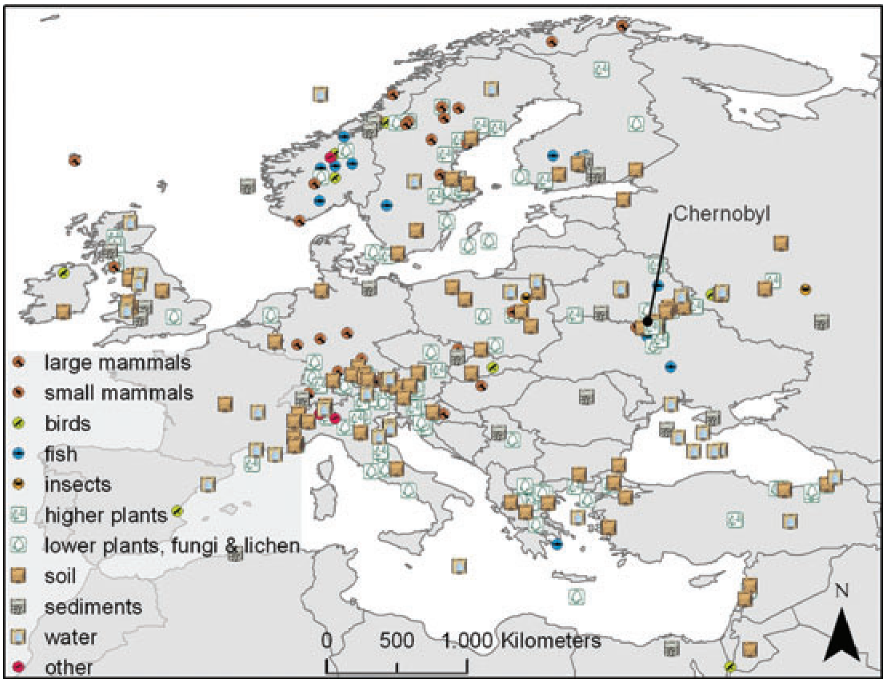

Figure 3 Documented effects of the Chernobyl disaster on specific ecosystem components within the western Palearctic.

physiological effects, such as changes in the leukocyte level (Camplani *et al*. 1999) and reduced reproduction rates (Møller *et al*. 2008). Changes in genetic structure have been recorded in various organisms, including fish (Sugg *et al*. 1996) and frogs (Vinogradov & Chubinishvili 1999). More broadly, elevated radiation can negatively affect the abundance of entire species groups, such as insects and spiders (Møller & Mousseau 2009a), raptors (Møller & Mousseau 2009b), or small mammals (Ryabokon & Goncharova 2006).

How low levels of radiation affect different species is poorly understood; studies have suggested that low levels of radiation can have a persistent influence on mutation rates in *Drosophila* (Zainullin *et al*. 1992), and can weaken immune (Malyzhev 1993) and reproductive systems (Serkiz 2003) of small mammals; but again, most studies have been restricted to the Chernobyl accident area. A more obvious measure of permanent change is widespread death of organisms living in the direct vicinity of the disaster site (Figures 1 and 2).

Food web and ecosystem impacts

In addition to effects on individual species, biological accumulation through the food web can negatively affect some species—particularly those at higher trophic levels and those depending on strongly affected food items. Bioaccumulation poses a risk to affected species because it exacerbates exposure to elevated radiation levels, and hence, leads to increased chances of physiological or morphological alterations. For example, can radiation levels in top predators remain elevated for a long time even when species at lower trophic levels show negligible radiation levels, as demonstrated for the Trench (*Tinca tinca*) in the Kiev Reservoir (Koulikov 1996).

Once an area densely populated by humans, the Chernobyl region was immediately evacuated after the nuclear accident and was declared an exclusion zone. This caused major land-use changes. Vast areas of former farmland were abandoned (Hostert *et al*. 2011), vegetation spread across former urban areas (Gusev 2004), and populations of many wildlife species have increased in response. For example, rare birds like the common crane and eagle owl increased in numbers. In contrast, species bound to farming landscapes, like the White Stork, stopped breeding (Gashchak 2002).

Consequences for ecosystem services

Humans fundamentally depend on the life-support system provided by ecosystems. Major environmental damage may, therefore, translate into a reduction in ecosystem services—the benefits that humans derive from nature (MEA 2005). Provisioning services have been particularly affected by the Chernobyl accident. Contamination from Iodine-131 was initially the greatest concern, but because of its short half-life (8 days), Iodine contamination is unlikely to be a problem for provisioning services beyond months or at most several years in the aftermath of a major accident. In the case of the Chernobyl accident, other than Iodine, most of the radioactive material that escaped was Caesium-137. Given its much longer half-life (31 years), Caesium-137 has affected ecosystem services over a much longer timeframe, and the effects of Caesium contamination are still measurable today. For example, near the disaster site, freshwater and associated fish will not be safe for human consumption for multiple decades into the future. Similarly, former agricultural land within the ~2,700 km^2 exclusion zone around the accident site will remain unsuitable for human use in the foreseeable future (De Cort *et al.* 1998). Even beyond the exclusion zone, agricultural land has been abandoned, or agricultural production remains strongly depressed. Across wide regions of the Ukraine, agricultural productivity remains low, which in part is directly because of the Chernobyl disaster and in part because the financial returns from agricultural production are reduced by high monitoring costs (Prister *et al.* 1993). Shortly after the disaster, crops and timber were contaminated throughout Europe. Notably, methods of disposal were often improvised because protocols for appropriate procedures of contaminated products were lacking.

Far away from the accident site, postmeltdown contamination has rendered ecosystem goods useless in many locations, such as timber in Sweden (Hedvall *et al.* 1996), fish in Finland (Saxen 2007), agricultural crops in Scandinavia (Rosen *et al.* 1996) and wild foods, such as mushrooms, in Poland (Malinowska *et al.* 2006), game meat in Germany (Fielitz *et al.* 2009), and berries in Finland (Kostiainen 2007). The Chernobyl accident also caused a measurable impact on tourism in Sweden (Hultkrantz & Olsson 1997), underlining the complex impact of the catastrophe on a diverse range of benefits that humans ordinarily derive from nature.

Although many ecosystem services have been greatly reduced, especially near the accident site and in the case of provisioning services, some other services seem to have fared more favorably. For example, human depopulation around the Chernobyl site has led to the return of natural vegetation, thereby benefitting some wildlife populations and probably enhancing the regulating service of carbon sequestration (Kuemmerle *et al.* 2011; Hostert *et al.* 2011).

Nuclear disasters and conservation management

Nuclear disasters represent major challenges for conservation management in at least four ways. First, direct conservation action in response to nuclear disasters, for example, via decontaminating and restoring polluted ecosystems (e.g., soils or water bodies) is often technically or financially not feasible. Second, nature conservation measures are often (and perhaps rightly so) considered secondary compared to measures to preserve and restore human health in affected regions (although some of these may also have an impact on conservation, e.g, in the case of removing contaminated topsoil). Third, as our review highlights, conservation managers lack a rigorous scientific basis to understand and mitigate how nuclear disasters affect biodiversity and ecosystem services. Fourth, the effects of nuclear disasters on biodiversity and ecosystem services are spatially and temporally heterogeneous, making it difficult to generalize what constitutes appropriate conservation measures. For example, both increasing and decreasing wildlife populations have been documented after the Chernobyl disaster, triggering a debate to what extent the positive indirect effect of decreasing human pressure may have outweighed more direct, toxicological effects.

Implications for policy and public debate

Debates about the safety of nuclear energy have followed different trajectories in different parts of the world (Eiser *et al.* 1990), but a common feature is that debates are strongly emotional. One key reason for this is that conventional risk management frameworks are difficult to apply to the issue of nuclear energy, leaving policy makers with few objective criteria to work through a very challenging set of issues. Accidents are extremely rare and the occurrence of a particular accident cannot be predicted with a meaningful probability; yet, when an accident does occur, it has extremely high health, social, economic, and environmental costs. Although numerous scientific studies were initiated following the Chernobyl accident and these studies have provided valuable insights, our review showed that these studies cannot fully clarify its actual consequences—especially regarding longer time scales and long-distance effects. What would be needed in response to such disasters is a more comprehensively, systematic, and coordinated research effort to gather data across a range of spatial and temporal scales and from the genetic to the ecosystem level to unravel the effects of nuclear disasters on the environment. However, judging such changes in a normative sense is an ethical problem rather a scientific one; we can, therefore, expect ongoing debates about nuclear energy to remain controversial.

Despite inherent complexity, and although the prompt resolution of existing debates is unlikely, our review

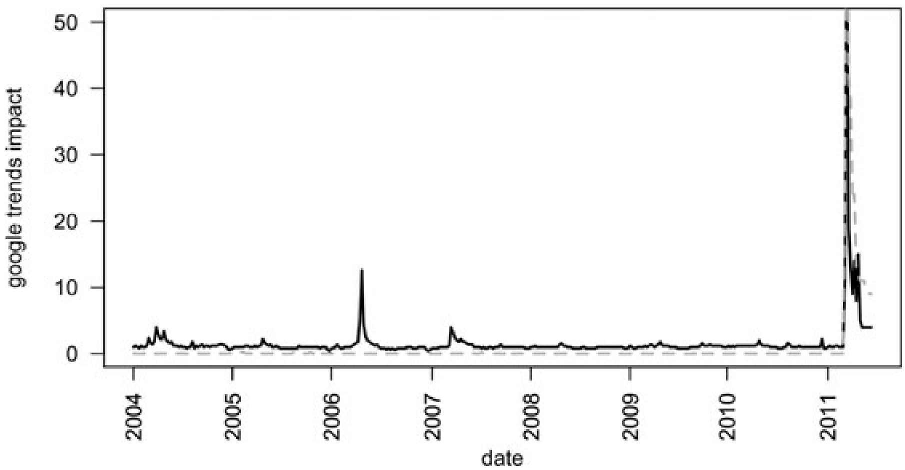

Figure 4 Google trends of the search term Chernobyl (black) and Fukushima (gray). Note the increased search density at anniversaries for Chernobyl and the short-term peak for Fukushima. Data scaling is based on average traffic of the search terms (relative scaling). Note that the short-term peak in March 2011 exceeded the shown scale, with a maximum of 106 (Fukushima) and 81 (Chernobyl).

highlights four important issues that are directly relevant to debates about the safety of nuclear energy.

(1) The focus of debates needs to be augmented to more fully acknowledge that nuclear accidents have measurable (and potentially severe) environmental consequences over large distances and long timeframes. Existing debates of nuclear energy are strongly biased toward human health and welfare, both with respect to waste management and potential accidents. By contrast, considerations regarding biodiversity and ecosystem services have remained marginalized, and are strongly biased toward few parts of the ecosphere.

(2) To facilitate effective conservation responses in the aftermath of nuclear accidents, scientific information needs to be clearly communicated among policy makers, management agencies, and the public. In the case of the Chernobyl disaster, confusion among government stakeholders translated into the media (Otway *et al*. 1988); similarly, the lack of consistent and transparent information was repeatedly criticized in the aftermath of the recent Fukushima accident. Both scientists and government institutions need to play an active role in improving the chain of information from measurable scientific data to accessible information for the public. Consistent protocols to generate reliable data are important in the aftermath of accidents to guide evidence-based policy decisions, and better communication efforts are particularly important because the consequences are long-lived. Communicating the long-term consequences of nuclear accidents for biodiversity and ecosystem services is particularly challenging because (international) public interest following accidents is short lived and triggered by the actual disasters or their anniversaries (Figure 4). For the long-term risks of nuclear energy to be adequately evaluated, both scientists and policy makers need to engage in ongoing discussions about the long-term consequences of nuclear accidents, rather than be reactive to accidents and their anniversaries.

(3) Instead of improvised responses, active consideration of ecological consequences of nuclear accidents is needed, for example through the use of scenario planning. Such an approach (Peterson *et al*. 2003) would help to cope with the severe uncertainty surrounding nuclear disasters and their effects on ecosystem services.

(4) The evidence base regarding long-term consequences for biodiversity and ecosystem services is characterized by extreme uncertainty, which should be reduced through new, well-designed research initiatives. In the aftermath of Chernobyl, management of ecological consequences was rarely based on scientific evidence; in the Soviet Union, research on ecological consequences of radiation exposure was practically nonexistent before the disaster (Golovnin *et al*. 1986). The amount of research has hardly increased after the Chernobyl accident (Møller & Mousseau 2006). However, most studies focused on the immediate impact of the radioactive fallout on ecosystems; and most were descriptive and did not follow a reproducible sampling design, which is a precondition for a long-term impact assessment (Kummerer & Hofmeister 2009). Perhaps most

importantly, studies examining how elevated radiation affects entire communities and ecological interactions remain very scarce, yet existing examples (e.g., on top predators) indicate that such effects could be tremendously important. Likewise, research focusing on the impact of nuclear disaster on the ecosystem service flows is sparse, despite clear suggestions that a wide range of services is negatively affected. Moreover, research efforts have differed substantially between different countries (Figure 1), partly reflecting different political environments and prevailing public opinions. Although research initially focused on quantifying radioactive relocation, studies specifically designed to examine long-term impacts on various ecosystem components are rare, and mostly motivated by few individual researchers (e.g., Anders Møller). Complex interactions of radiation exposure throughout the ecosystem and the long-term impact of low-level radiation remain largely unknown, partly due to insufficient funding for the required monitoring agenda (Møller & Mousseau 2006). Similarly, a substantial amount of data on provisioning ecosystem services was gathered in the aftermath of the Chernobyl accident (Fesenko *et al*. 2007), but very little work has been conducted on other ecosystem services (Savchenko 1997). Data from comparable incidents (e.g., the Kyshtym disaster in the Ural in 1957) are virtually nonexistent, thus hardly any studies for comparisons are available.

The Fukushima disaster, in its vast tragedy, offers the sad opportunity to gain new insights about the consequences of nuclear accidents for biodiversity and ecosystem services—and feed these insights into public and policy debates about nuclear energy. This knowledge will be beneficial to both humans and nature. Radiation levels that occurred in the Chernobyl region are comparable to current levels in the Fukushima exclusion zone (van Hippel 2011). However, the Fukushima accident was smaller in its spatial extent, but was accompanied by a high radiation leakage into the marine environment (Yasundari *et al*. 2011), which poses a further challenge with unclear long-term consequences. Outlining a complete research agenda for Fukushima is beyond the scope of our article. However, it is clear that we need to move beyond uncoordinated individual studies, toward a coherent monitoring agenda (Lindenmayer & Likens 2009). A major monitoring agenda will be costly but necessary if we want to base our understanding of long-term risks of nuclear energy on objective grounds.

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Supplementary Information

Additional Supporting information may be found in the online version of this article:

1. Supplementary Methods

2. Table S1: Articles included in our review based and presented in Figure 1. Literature format follows the output as taken from the ISI Web Of Knowledge

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