

The impact of nuclear accidents on provisioning ecosystem services



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ABSTRACT

Nuclear accidents lead to widespread radioactive contamination of ecosystems and related ecosystem services, with potentially serious consequences for human well-being. Based on an initial exploratory analysis of peer-reviewed articles related to Chernobyl and Fukushima, we identified papers which measured increased Cs-137 levels in provisioning ecosystem services. We used a standardized review-protocol to assess (1) whether peer-reviewed science provides sufficient data density and spatial coverage to provide a coherent and comprehensive map of the global impacts of nuclear accidents on provisioning of ecosystem services; (2) whether such impacts are reported in a standardized and reproducible way; and (3) how different safety thresholds affect the availability of food and fodder for human consumption. Based on an initial analysis of approximately 3000 articles, we identified 121 publications that measured Caesium-137 levels in food, fodder and wood. We found that the comprehensive mapping of the impacts of nuclear accidents on provisioning ecosystem services requires a considerable increase in peer-reviewed assessments, including assessment of existing grey literature. Assessments should follow a coherent protocol, providing consistent information on sampling location and the identification of provisioning ecosystem services. There should be a critical dialogue on maximum allowable radiation levels in provisioning ecosystem services and the impacts of such safe appropriation thresholds on human well-being.

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1. Introduction

Nuclear power plants are primary energy sources for 30 nations (IAEA, 2013). It has been suggested that 45 countries are actively considering embarking upon nuclear energy programmes (World Nuclear Association, 2014). Nuclear power is often described as a more sustainable energy solution than fossil fuels (Sokolov and Beatty, 2009) due to the lower direct emissions of greenhouse gases (IAEA, 2012). However, the potential environmental damage from nuclear power generation is not limited to their normal operations, but also the long-term direct and indirect effects of nuclear accidents (Dangerman and Schellnhuber, 2013; Macfarlane, 2011). Although nuclear accidents are low-frequency events, they can cause long term impacts on a broad spatial scale

that have to be considered in the cost–benefits analysis for nuclear energy use. Therefore, assessments of the “sustainability” of nuclear energy must also consider the full impacts of its generation, critically, including the environmental and socio-economic impacts of nuclear accidents on the environment.

There have been two major nuclear accidents: Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2011) which released Caesium 137 isotopes into the atmosphere (Lelieveld et al., 2012). In response to these accidents monitoring programmes have been put in place to measure ambient atmospheric gamma radiation, for example, the European Radiological Data Exchange Platform (EURDEP) with approximately 3900 monitoring stations in 33 European countries generates hourly measurements (Vries et al., 2005). While such monitoring indicates where potential problems might occur, they do not provide meaningful data regarding the environmental and socio-economic impacts of nuclear accidents. There has been considerable research carried out to evaluate the direct impact of nuclear accidents on human health (e.g. Hoeve and Jacobson, 2012; Baverstock and Williams, 2006; Ilyin et al., 1990),

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but less focus on the indirect impacts on human well-being mediated through changes to ecosystems.

Long-term ecological studies are important for understanding and quantifying the effects of radiation in ecosystems across generations (Garnier-Laplace et al., 2011). Several studies have investigated how radioactive substances affect migration and uptake in food chains and ecosystems (e.g. Beresford et al., 2012; Møller and Mousseau, 2007), but ecological impact assessment studies are limited (Møller and Mousseau, 2006, 2013) and a clear and integrated research agenda on the impacts of nuclear accident on ecosystems from ecological processes through to human appropriation of ecosystem functions has yet to be developed (Wehrden et al., 2012). In particular the long-term impacts on ecosystem services are unknown.

Increased radioactivity within ecosystems following nuclear accidents potentially reduces the availability of those ecosystems to provide ecosystem goods and services that contribute to human well-being. National and international regulations have been implemented to set the maximum permissible levels of radioactivity in food and fodder. Adherence to such legally binding regulations—intended to minimize harm to human health—reduces the ability of humans to use these ecosystem services to increase their well-being.

The Millennium Ecosystem Assessment categorizes services provided by ecosystems into four different types: supporting, regulating, cultural and provisioning services (MEA, 2005). Following nuclear accidents, supporting ecosystem services such as nutrient cycling may be affected by the occurrence of long-lived and persistent nuclides such as Cs-137 through the disruption of ecosystem functions. Regulating ecosystem services such as flood protection from wetlands (Froehlich and Wallich, 1994) may be affected, for instance, by remediation measures to limit radioactive contamination (Davydchuk, 1997). Cultural ecosystem services impacted by nuclear accidents are often associated with cultural practices related to provisioning ecosystem services such as mushroom gathering (Druzhinina and Palma-Oliveira, 2004). Provisioning ecosystem services—the goods obtained by the ecosystems, for instance food, fresh-water, wood, fibre and fuel (MEA, 2005)—are the most directly affected ecosystem services types from nuclear accidents. It has been suggested that provisioning ecosystem services strongly determine human-well-being (Raudsepp-Hearne et al., 2010). It is therefore vital that we can quantify the effects of such thresholds on the availability of provisioning ecosystem services after nuclear accidents.

The composition and interrelations of factors influencing Cs-137 accumulation in ecosystems are site specific, and complex—due to issues such as bioaccumulation (Oleksyka et al., 2002), making broad scale generalization of evolving impacts on flora and fauna difficult (Beresford et al., 2007). As a consequence of these difficulties considerable data is required to accurately assess the impacts of nuclear accidents on ecosystems and their related services.

Here, we focus on assessing the known impact of nuclear accidents on provisioning ecosystem services as identified in the peer-reviewed literature. We acknowledge that there is a large body of grey literature in the form of national monitoring reports on radioactivity levels in provisioning ecosystem services (e.g. MHLW, 2013a; EC, 2009). There are also monographs focusing on the impacts of Chernobyl and Fukushima on food and agriculture (Nakanishi and Tanoi, 2013; Moberg, 1991). However, here we focus on peer-reviewed publications since this literature is not limited by national boundaries; provides reproducible results; additional contextual information regarding the dynamics, interactions and impact of nuclear accidents; and draw conclusions regarding research gaps and shortcomings. There are peer-reviewed studies that report radiation levels in a single provisioning ecosystem service across large spatial scales (e.g. Lavi

et al., 2006; Kalac, 2001; Mietelski et al., 1994), but these studies only provide a partial view of the impact of nuclear accidents on provisioning ecosystem services. We assess the extent to which the peer-reviewed science can be used to quantify the impacts of Cs-137 contamination on provisioning ecosystem services, with a specific focus on food, fodder and wood, after major nuclear accidents.

We addressed three aims: (1) whether the peer-reviewed science provides sufficient data density and coverage to provide a coherent and comprehensive map of the global impacts of nuclear accidents on provision ecosystem services (which we refer to as a coherent impact grid); (2) whether scientific publications are reporting monitoring results in a standardized and reproducible way; and (3) how different permissible radiation thresholds affect the availability of food and fodder and therefore human well-being.

2. Material and methods

We conducted a quantitative and qualitative review of peer-reviewed studies focusing on the sampling of radioactivity in food, fodder and wood after nuclear accidents. First we identified all publications (“full papers” in English and German) via the Scopus database (April 2012) with two search strings (see Appendix A) including “Chernobyl” (all papers since 1986) and “Fukushima” (all papers since 2011). This search returned approximately 3300 papers. A second search on “Fukushima” to include recent papers was conducted in November 2012 returning 76 studies.

2.1. Selection process of peer-reviewed papers

We limited the analysis to studies that measured caesium-137 radioactivity (subsequently Cs-137) as the highest radiation dose to the human population after the Chernobyl and Fukushima nuclear accidents was caused by Cs-137 deposition (Tracy et al., 2013). Moreover, Cs-137 has a half-life of 30 years, allowing long-term impacts of radioactive accumulation on provisioning ecosystem services to be analyzed. We considered only Becquerels (Bq) measurements, because this measure is used to set maximum permissible levels (thresholds) of radioactivity of goods that can be sold. One Bq describes the activity of radionuclides in which one nucleus decays per second on average (Kalac, 2001). We acknowledge that provisioning ecosystem services can be negatively affected by genetic changes as a result of radioactive accumulation in plants (Kuchma et al., 2011; Kovalchuk et al., 2003) and animals (Røed and Jacobsen, 1995). Nevertheless, these impacts were not included in our analyses because more knowledge is needed to understand the evolving consequences of mutations (Kuchma et al., 2011) on provisioning ecosystem services.

We had institutional access to 1873 of the 2050 studies dealing explicitly with monitoring results and measurements on ecosystem services. We only included papers in the analysis (Chernobyl ($n = 118$) and Fukushima ($n = 3$)) that reported actual Cs-137 radioactivity levels—illustrated or mentioned in the text, tables or graphically—exceeding those set by the Japanese authorities after Fukushima for food (MHLW, 2013b) and fodder (IRSN, 2012), as we deemed this to be the lower bound threshold below which the provision of the associated service would not be effected (Table 1). Since no thresholds have been set for wood, we applied the recommendation of 750 Bq/kg for stemwood from the National Ukrainian wood utilization (Davydchuk, 1999) and 100 Bq/kg for other wood samples (bark, twigs, shoots), as assumed by Hubbard et al. (2002) for fuel-wood. Here we should note that we did not limit the analysis to those studies that explicitly referred to the consumption of the flora and fauna under study. Therefore, this analysis relates to

Table 1

Comparison of maximum allowed radioactivity levels in provisioning ecosystem services set in the EU and Japan.

Provisioning services in peer-reviewed articles above current Japanese thresholds	Thresholds for Cs-137 fresh weights in Bq/kg and Bq/l		
	EU*	Japan (till April 2012)**	Japan (current level)***
Meat, fish, mushrooms, berries, other food (vegetable, honey, lentil, rice grain, nuts)	General food 1250	Meat, eggs, fish, grains, vegetables 500	General foods 100
Milk, cheese, cream, milk powder	Milk and dairy products 1000	Drinking water, milk and dairy products 200	Milk 50
Baby food	Infant food 400	n.a.	Infant foods 50
Tea (leaves)	Water/liquid foodstuff 1000	Drinking water 200	Drinking water 10
Fodder (incl. crops)	Fodder (depending on livestock) 1250–5000	Feed**** 500	Feed**** 500
Plants for pharmaceutical use	Minor foodstuff ten times those of general food	n.a.	n.a.
Non-food: wood (stemwood, fuelwood), tobacco	Recommendations in some countries for wood samples	n.a.	n.a.

Allowed levels of total Cs 134 and Cs 137 activity in Becquerel per litre or kilogram of products which will be placed on the market (wet weight) after Chernobyl for the EU (*EEC, 1987a,b, 1989a,b, 1990) and after Fukushima for Japan (**MHLW, 2011a,b, ***MHLW 2013b, ****EC, 2011).

potential, rather than actually appropriated, provisioning ecosystem services. Only papers where the flora studied was explicitly noted as having fodder or pharmaceutical/medicinal use(s) were included in the analysis, only edible mushroom species were considered.

2.2. Data collection—analysis of papers

We refrained from providing a statistical analysis due to stochastic radioactive accumulation in provisioning ecosystem services. The 121 papers analyzed showed considerable variance with regard to their spatial and temporal focus. Therefore, we undertook a mixed qualitative and quantitative analysis based on the following on nine variables extracted from each of the peer-reviewed publications (see [Appendix Table A1](#)):

(1) Which types of provisioning ecosystem services were contaminated by Cs-137?

Ecosystem services were assigned to different provisioning types (e.g. meat, dairy, fodder). If multiple goods of the same type were studied at the same place only the highest radioactivity level of one of the goods was recorded. For example, only rabbit, with a maximum level of 1360 Bq/kg, was taken from the various meat sources sampled by [Fehér \(1988\)](#).

(2) How high was the contamination level of the service? (Min, Max, Mean in Becquerel)

We analyzed all provisioning ecosystem service types above permissible thresholds (see [Appendix Table A1](#)). Where radioactivity levels were only shown over time graphically (e.g. [Kostiainen, 2007; Smith et al., 2000](#)), the highest level was estimated visually from the graph.

(3) and (4) When and where the sample was analyzed? (Year, Country)

If the sampling process of the study was conducted over several years only the highest contamination of provisioning services was recorded. Furthermore, if one provisioning ecosystem service type has been analyzed at several locations in one country, we used the highest contamination level of one sampling location within the country (e.g. [Smith et al., 1993](#)). Thus, we recorded

all countries where studies on provisioning ecosystem services took place. Hence the total number of scientific studies ($n=132$) and the total number of provisioning ecosystem services recorded ($n=173$) is higher than the number of published peer-reviewed papers ($n=121$).

(5) After which accidents did the contamination take place? (Accident)

(6) and (7) Is the sampling location explicitly mentioned (Latitude/Longitude; Exactness of georeference: explicitly mentioned or inferred)?

If a specific georeference was not mentioned we took the information that inferred the approximate site of the sample(s).

(8) Was the sample measured in dry or fresh weight? (Weights)

Radioactive measurements can be reported in dry weights ([Appendix Table A2](#)), whereas maximum allowed thresholds for food refer to fresh/wet weights ([EEC, 2000](#)). Following [Kalac \(2001\)](#) all dry weight becquerel measurements of food samples can be scaled by a factor of 0.1 to estimate fresh weight contamination. Thus, we recalculated the dry weight contamination of mushrooms according to that approach.

(9) How long was the sampling process? (Time scale)

Since radiation impacts differ in time reliable temporal data is required. Here we recorded the duration of the sampling process (up to one month; between one month and a year; more than one year till five years; more than five years to ten years, more than ten years).

All figures were made using the R 2.14.2 software ([www.r-project.org](#)) and ArcGIS 10.

3. Results

121 scientific papers—Chernobyl ($n=118$) and Fukushima ($n=3$)—were analyzed based on nine variables. Results show variations in data collection and reporting. There were no coherent maximum permitted radiation levels implemented in affected countries covering all provisioning ecosystem services.

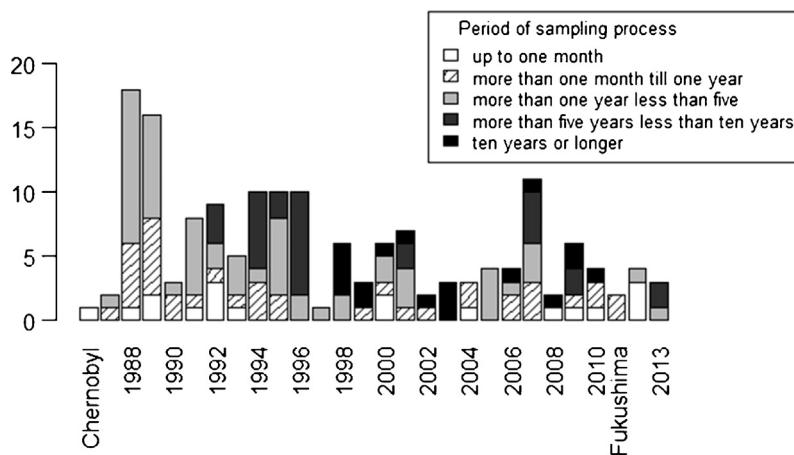


Fig. 1. Distribution of published peer-reviewed articles on the radioactivity in provisioning ecosystem services. Publication year and duration of sampling process of radioactivity in provisioning ecosystem service after Chernobyl and Fukushima.

3.1. Temporal-, spatial- and types of provisioning service coverage in peer-reviewed science

The majority of the monitoring of radioactivity in food and fodder started in the first years after Chernobyl (Fig. 1). A total of 66% ($n = 107$) of all studies ($n = 173$) were conducted for more than one year (Fig. 1), but only 11% for ten years or more ($n = 18$). The overall trend showed declining peer-reviewed publications over time with most studies published in the first ten years, with an increase in the decennial anniversary years (Fig. 1).

Regarding the spatial coverage of the impacts we found that peer-reviewed research was patchily distributed in space (Fig. 2). No coherent global or European impact grid on provisioning ecosystem services could be generated from the peer-reviewed studies. The majority (58%) of the scientific research studies were located in the following six countries: Sweden ($n = 18$), Germany ($n = 14$),

Austria ($n = 11$), Ukraine ($n = 12$), Norway ($n = 11$) and the United Kingdom ($n = 11$) (Fig. 2). Only 39 of the provisioning ecosystem service studies (Fig. 2 explicit location) gave explicit georeferences for their locations. The majority of data ($n = 134$) could not be linked to their specific spatial origin.

The focus on the impact of nuclear accidents on provisioning ecosystem services varied considerably among different provisioning services “types”. The greatest focus was on radioactive accumulation in mushrooms ($n = 43$) and meat ($n = 40$), followed by fish ($n = 28$) and dairy products ($n = 17$). It is unclear if this focus was due to the relatively high radioactivity levels in mushrooms, meat and fish (Fig. 3) compared to other provisioning ecosystem services, or simply because other provisioning services were simply studied less. However, we note that other food and non-food products, for instance berries and tobacco, have also shown high accumulations in some samples (Fig. 4).

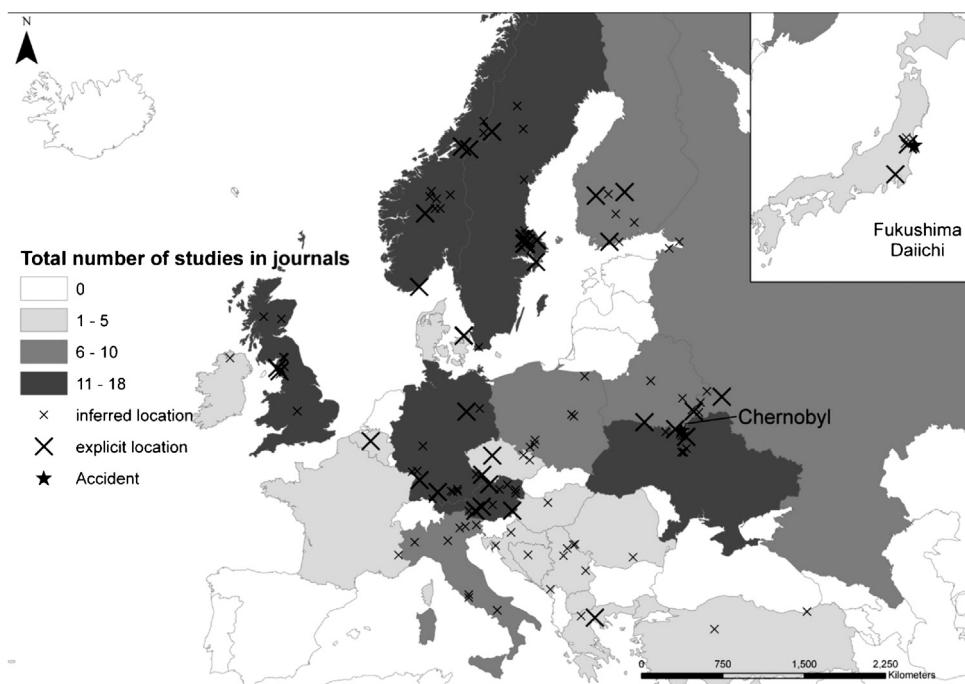


Fig. 2. Overview of the research activities on provisioning ecosystem services in peer-reviewed publications. Studies are included with monitoring results above Fukushima thresholds set in April 2012 (MHLW, 2013a).

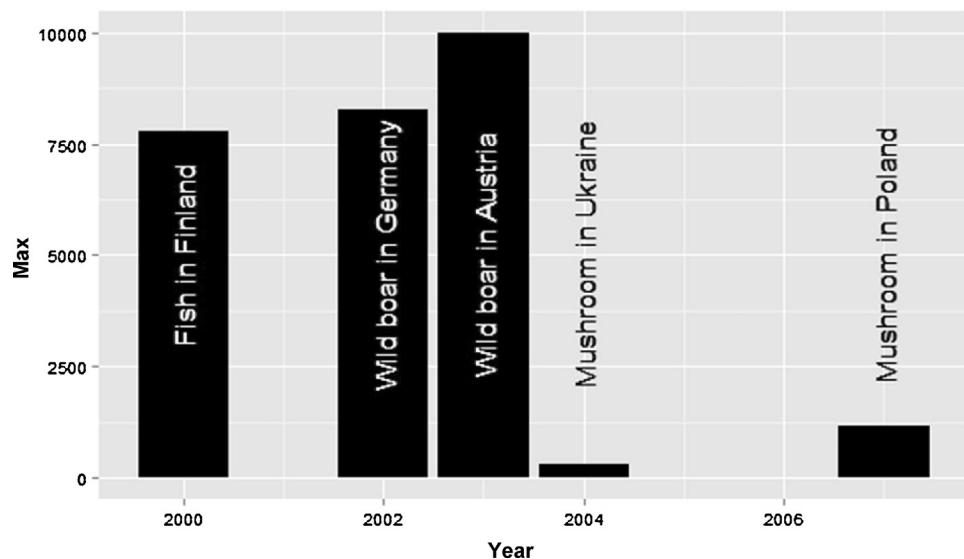


Fig. 3. Examples of long-term radioactive contamination in provisioning ecosystem services. Examples of maximum radioactivity (Bq/kg) in meat, fish and mushrooms (wet weights) based on samples taken more than fifteen years after Chernobyl.

3.2. Impact of threshold schemes on the availability of food and fodder

Maximum permissible radioactivity levels in food and other products regulate market entry. Since there is no common threshold scheme, limits differ across the world (Table 1), influencing the availability of provisioning ecosystem services after nuclear

accidents to different extents. Fig. 4 illustrates the effects of different thresholds for safe consumption of food and fodder on the ability of humans to appropriate provisioning ecosystem services after nuclear accidents. If Fukushima thresholds had been adopted after Chernobyl, a broader range of food and other products would have been prohibited for human consumption (Figs. 4 and 5).

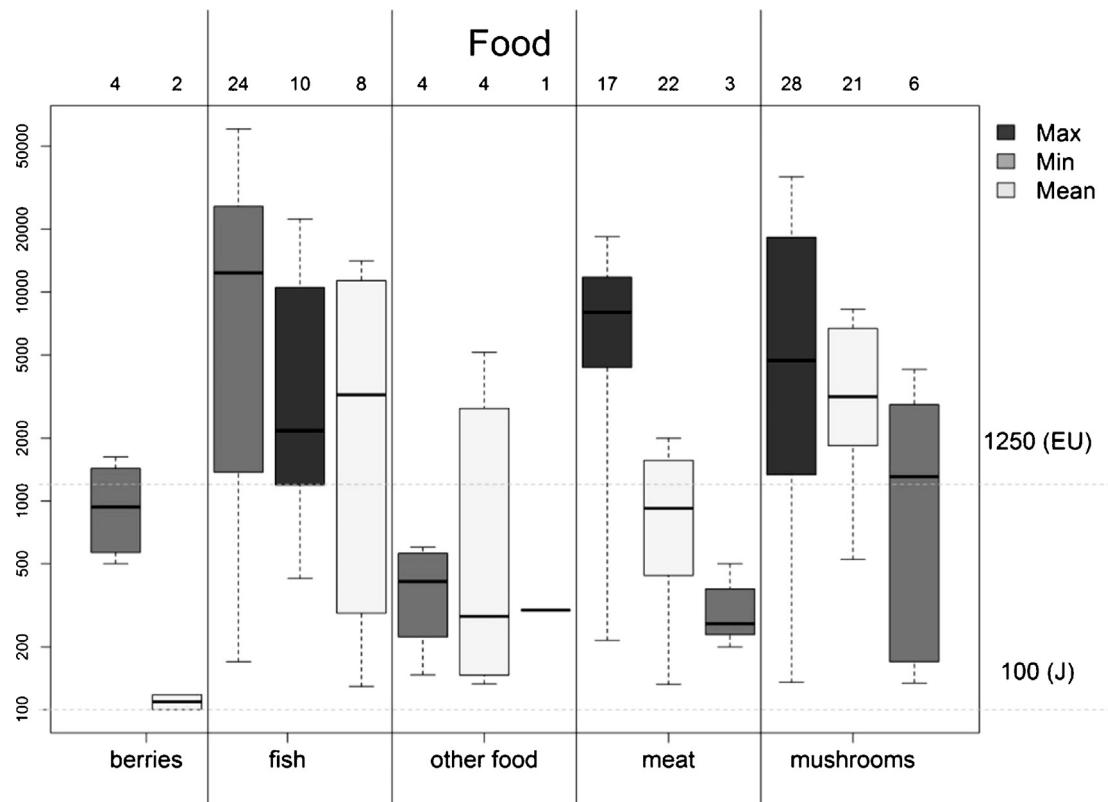


Fig. 4. Overview of radioactivity in food (highest value collected). For comparison safe consumption threshold levels set by the European Union (EU) and the Japanese authority (J) are illustrated (horizontal grey lines). Baby food (one sample) and tea (three samples) were not illustrated. The category other food includes one sample of lentil, spinach, hazelnut, rice bran and two samples of honey. Numbers above individual boxes are the sample sizes. One sample can be included with its minimum, maximum and mean level. Hence, the total number of data here is higher than the total number of samples in the study. Box plots show median, quartiles 25 and 75-percentiles.

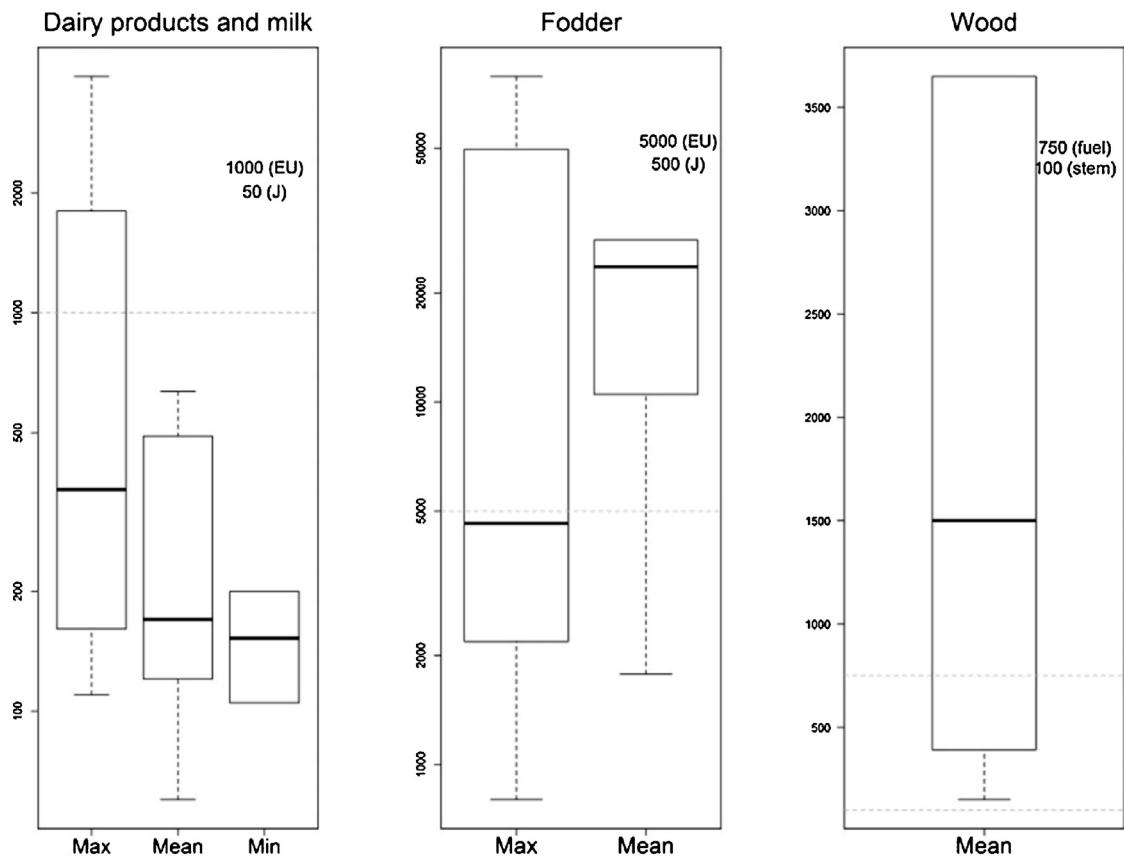


Fig. 5. Overview of radioactivity levels in dairy products and milk, fodder and wood. For wood samples recommended levels have been used ([Davydchuk, 1999](#); [Hubbard et al., 2002](#)). Box plots show median, quartiles 25 and 75-percentiles. For comparison safe consumption threshold levels set by the European Union (EU) and the Japanese authority (J) are illustrated (horizontal grey lines).

4. Discussion

Global peer-reviewed research on the impact of nuclear accidents on provisioning ecosystem services has been conducted in 25 countries. However, these scientific studies do not provide sufficient spatial and temporal coverage to allow for a detailed and coherent assessment of the impacts of nuclear accidents on provisioning ecosystem services. This is crucial for gaining knowledge about relationships between nuclear accidents and their impacts on human well-being.

4.1. Impact grid—variations in temporal, spatial and service types coverage

A total of 121 peer-reviewed papers contained results on Cs-137 radiation contamination (above relevant minimum statutory safety thresholds) in provisioning ecosystem services. This number seems to be rather low given that caesium was deposited over large parts of Europe after Chernobyl. If publications after the Fukushima accident follow a similar temporal trend as found for Chernobyl, we could expect the highest number of studies to be conducted in 2013, followed by a general decreasing trend with decennial anniversary peaks. This temporal sampling dynamic, in part, reflects the half-life decrease of radioactivity, however, increased accumulation levels in flora and fauna are influenced by several factors and can occur even several years after an accident ([Beresford et al., 2007](#); [Pel'gunov et al., 2006](#)).

Although our data cannot provide deep insights into bioaccumulation pattern of different regions, it is an important issue for further investigations. [Avery \(1996\)](#) stated that direct biological

accumulation of Cs-137 from the environment occurs in lower trophic levels whereas higher trophic levels might accumulate Cs-137 due to ingestions of food or inhalation and absorption from the environment. [Rowan and Rasmussen \(1994\)](#) tested several influencing factors on fish and pointed out that among other ecological factors the trophic level of the fish plays a crucial role. [Yamazaki et al. \(2012\)](#) suggested that the contamination of forest soil affects flora and fauna with higher accumulation rates on higher trophic levels. To investigate bioaccumulation in forest soils, animals and food samples long-term monitoring programmes are required ([Yamazaki et al., 2012](#)). Thus, it is important for the scientific community to collect long-term data. Since several sites in Europe are still affected by the fallout from Chernobyl 20 years after the accident ([Fig. 3](#)), it is crucial to use reliable data to gain knowledge on the long-term impacts of nuclear accidents on provisioning ecosystem services.

The spatial distribution of peer-reviewed studies was uneven. The distance to nuclear accidents appears to play no significant role, so there seems to be no higher risk perception, fostering more research, in the Ukraine for instance than in Sweden. Nor do official attitudes towards nuclear power generation appear to play a role in research efforts. Countries phasing out nuclear power (Germany), and countries with no nuclear facilities (Austria) both conducted research. Similarly, countries that repealed phase-out plans (Sweden) or are still discussing the building of nuclear facilities (Norway) invested similar research efforts on the impact of nuclear accidents on provisioning ecosystem services.

Radioactive accumulation of Cs-137 in food and other provisioning services shows a patchy distribution. For example, accumulation levels in fish, differed among species and populations

with variation among years (Hammar et al., 1991). Radioactive accumulation differences depend on many factors such as the amount of soil ingested by animals (Beresford and Howard, 1991) and their movement habits (Karlén et al., 1991). Game using less contaminated habitats has a high tendency to accumulate lower levels of Caesium-137 in their muscles (Lowe and Horrill, 1991). Nevertheless, contamination levels in fauna may be increasing even when ambient radioactivity is decreasing (Pel'gunov et al., 2006). This diversity of influencing factors on a regional scale hinders appropriate generalization of results (Beresford et al., 2007). That is one example of the high level of uncertainty regarding radioactive accumulation in food chains that makes it more difficult to model (Wright et al., 1998). Data sampling on the impacts of nuclear accidents on provisioning ecosystem services requires a higher density of spatial, temporal and species-specific data to create a coherent impact grid and to allow analysis of the interrelated impacts on other ecosystem services.

The small number of studies on the ecological impact of released radioactivity may be a result of very limited funding for large scale research attempting to determine the consequences of radiation exposure (Møller and Mousseau, 2006) and a scarcity of independent scientists able to undertake such assessments (Møller and Mousseau, 2013). While funding seemed to be available in the short-term—the majority of studies were published within the first ten years after Chernobyl (Fig. 1)—long-term monitoring data after nuclear accidents may help to understand the behaviour of radioactive material (Nihei, 2013) and the full impact of such accidents on ecosystem services.

The peer-reviewed research was also patchy with regard to the types of provisioning ecosystem services studied. This patchiness in research effort might be influenced by existence of safe consumption threshold schemes. Since more research is conducted on food products (such as meat, mushrooms, fish and milk) that are regulated than on non-food products (such as tobacco and wood) that are not. The impacts on marine and coastal ecosystems and their services should be a focus of research efforts after the Fukushima accidents, since highly radioactive water has been introduced to the ocean (Buesseler et al., 2011, 2012), but it is not clear this will be influenced by the existent (or not) of safe consumption thresholds.

With a few exceptions (e.g. Merz et al. (2013) and Strand et al. (1987)) official governmental radioactivity measurements of food and fodder are rarely presented in peer-reviewed journals. One challenge to collating Cs-137 radioactive impact data is connected with the fact that some studies on provisioning ecosystem services are not written in English (e.g. Pel'gunov et al., 2006; Skurdal et al., 1987). Some communication of monitoring data does takes place via European reports, (e.g. EC, 2009), and this is an important first step to foster data analysis and transparent communication efforts. However, it is still important to have open data access to governmental monitoring results to enable peer-reviewed analysis of relationships and patterns within and between these large scale governmental monitoring schemes. This would provide a greater understanding of the link between radioactive contamination and its impacts on ecosystem services and the consequences for human well-being.

4.2. Reporting of monitoring results—improvements needed

Clear communication requires transparent and coherent reporting of analyses and results is currently hindered by a lack of translation of original reports into English (Fairlie and Sumner, 2006). Information about the spatial location of studies should be included, and it would be preferable to have specific georeference data for every sampling location. If the location of study samples is unavailable the spatial analysis of underlying patterns, for instance the potential impacts on other related ecosystem

services, is hampered. It is crucial to have a spatially explicit database of these studies since radioactivity after nuclear accidents appears to be patchily distributed over large distances, making appropriate impact assessment challenging. The use, or non-use, of contaminated samples recorded within studies on provisioning ecosystem services should to be mentioned. Otherwise the impacts of nuclear accidents on ecosystem services cannot be assessed with any degree of certainty (i.e. we cannot differentiation between potential health effects due to consumption of contaminated goods from the economic loss due to non-consumption of contaminated goods).

4.3. The impact of threshold schemes on the availability of food and fodder

Maximum permissible levels for radioactive Cs-137 contamination in food and fodder influence the availability of such goods by regulating market entry. When products cannot be sold, livelihoods may be adversely affected. Threshold levels differ in several countries leading to different amounts of available food (Beach, 1990; Skurdal et al., 1987). If contamination levels lead to long-term restrictions, entire farming systems can be disturbed leading to a long-term decrease in availability (Smith et al., 2000; Kerr and Mooney, 1988). The use of contaminated food and fodder differs among countries based on national safe threshold schemes (Fig. 4). Since the behaviour of radionuclides such as Cs-137 does not change regarding national borders, it is neither clear on what basis these scheme should differ, nor the scientific justification for a given threshold level.

4.3.1. Diversity of numbers and recommendations

Since Chernobyl the permissible radiation limits differed within European borders. For example, Sweden established its own limits at 300 Bq/kg for general food and raised the limit for Saami food (reindeer meat, fish and game) up to 1500 Bq/kg (Beach, 1990). Meat intended for import into the EU was not allowed to show higher total Caesium values than 600 Bq/kg, whereas meat for use inside the EU could have levels up to 1250 Bq/kg (Table 1). Different levels have been established in Norway where they decided in June 1986 to allow the selling of dairy products and infant food under 370 Bq/kg and others food up to 600 Bq/kg. In Sweden milk should not exceed 300 Bq/l and in some cases even milk with Caesium levels above 40 Bq/l were not allowed to be transferred to dairies (Karlén et al., 1991). Some countries proposed their own recommendations for forest products, for example, in the Ukraine stemwood with radioactivity above 750 Bq/kg is limited to industrial use (Davydchuk, 1999). In Sweden where large parts of the country is covered by forests the Swedish Radiation Safety Authority suggested no use of wood ashes from the combustion of biofuels as fertilizer when Cs-137 exceed the 5000 Bq/kg, with 100 Bq/kg set as the permissible level for fuelwood (Hubbard et al., 2002).

Threshold schemes vary among countries and include a selection of provisioning ecosystem services that has been widely defined as food and fodder. The European Commission has included plants for medicinal or pharmaceutical use in threshold schemes (EEC, 1989b), while some provisioning ecosystem services are only part of recommendations (e.g. wood). The implementation of thresholds rely on linear effects, although as Møller and Mousseau (2013) pointed out radiation below such thresholds may still have negative effects. Thus, an implementation of maximum allowed radiation levels offers a level of security, but as the response to radiation differs largely among species and traits, there may still be significant radiation risks (Møller and Mousseau, 2013). The negative impact on human health should be considered in conjunction with the socio-economic consequences of loss of provision of ecosystem services. Threshold schemes to tackle the negative

impacts on human health caused by radiation rarely give an appropriate estimation on how long, where and to what extent provisioning ecosystem services are affected, making a full impact analysis of the impacts of nuclear accidents (and the related safe consumption regulations) have on human well-being more challenging. To address this challenge, first, we need reliable impact data to assess where and how single services are affected, and, second, it is crucial to understand patterns of feedbacks and relationships between affected ecosystem services to enable and sustain human well-being. A clear and transparent consideration of acceptable safe radiation thresholds in provisioning ecosystem services is required. Such an assessment should include the potential trade-offs between the direct (health) and indirect (degradation of ecosystem services) effects on human well-being of these thresholds.

4.3.1.2. Linkages and feedbacks—impacts in a complex world

Knowledge about consequences of our actions often lacks an understanding of all the underlying patterns, feedback mechanisms and interrelations between impacts (Weinstein et al., 2013). The total impacts on human well-being after nuclear accidents are yet to be fully analyzed and understood. Ecosystems are affected by increased radiation in their processes and services on a broad scale and long-term perspective (Wehrden et al., 2012). Since these services are interlinked and influence human well-being, impact analysis of ecosystem services from nuclear accidents should play an important role in fostering appropriate decision-making regarding nuclear power. Data on the impact on provisioning ecosystem services are rare in peer-reviewed studies, and knowledge on the interrelations between impacts on all ecosystem services is almost non-existent. Nuclear accident impact analysis could be improved by using existing monitoring data and increasing research efforts in peer-reviewed studies. The impact of increased radiation after a nuclear accident requires research approaches analyzing affected ecosystems based on high data density of radiation measurements. It is important to use a more holistic approach of sustainability assessment on nuclear energy by including all the risks to human well-being from nuclear accidents (Stamford and Azapagic, 2011). This should include information about the potential degradation of ecosystem services due to radiation.

5. Conclusion

We conclude that scientific research conducted to assess the impact on provisioning ecosystem services after nuclear accidents in peer-reviewed studies might be influenced by a “don't-ask-don't-tell” maxim. Hence, we suggest that the impacts of nuclear accidents on provisioning ecosystem services should be put on the agenda of nuclear energy assessments. Global scientific peer-reviewed research on this topic is currently, at best, limited

Table A1

The standardized analysis is based on nine indicators.

Different variables of interest	Content
Group of provisioning ecosystem services	Fish, meat, mushrooms, dairy products, crops, fodder, foodstuff (incl. tea, honey, vegetables, hazelnuts), berries, milk, pharmaceutical use, wood, tobacco e.g. Min: 12,000
Becquerel level: Min, Max, Mean	e.g. 1987
Year	Name of the country today (e.g. German Democratic Republic = Germany; Scotland, Wales, England = UK)
Country	Chernobyl: 2, Fukushima: 3 e.g. 62° 62' N, 17° 07' E
Accident	not specific (no georeference or city → georeference of capital taken): 0, inferred (city or other points have been mentioned of which georeference could be developed): 1, explicit (georeference attached in paper): 2 No: 0, Yes: 1
Latitude/longitude	Up to one month: 0, more than one month till one year: 1, more than one year till five years: 2; more than five years till ten years: 3, more than ten years: 4
Exactness of georeferences	
Dry weight	
Time scale of research study	

and patchy. The degree of information varies regarding sampling location, sampling time as well as use, or non-use, of the studied plants and animals as provisioning ecosystem services. To create a coherent grid of impacts of nuclear accidents on provisioning ecosystem services, we highlight the following aspects. First, there is a need for increased peer-reviewed research regarding the impact of nuclear accidents on provisioning ecosystem services. This can be achieved by reviewing the existing national reports and subsequent publication of the results in English. Further global measurements of short- and long-term results should be collected for an appropriate impact assessment in a central database. Second, research studies need to follow a coherent protocol enabling common information on sampling location and use of the potential provisioning ecosystem services. Third, there should be a critical dialogue regarding the maximum permissible radiation levels in provisioning ecosystem services and what these rules mean for human well-being.

Acknowledgments

Patric Brandt and Tillman Kiehn helped structuring the initial draft. Heike Zimmermann assisted in plotting the graphs. FG was funded by a scholarship financed by Leuphana University. Thanks to the anonymous reviewers for their constructive comments.

Appendix A.

See [Tables A1 and A2](#).

A 3 Search strings

Your query: TITLE-ABS-KEY(chernobyl) AND PUBYEAR > 1985 AND (LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(LANGUAGE, "English") OR LIMIT-TO(LANGUAGE, "German")) AND (LIMIT-TO(SUBJAREA, "ENVI") OR LIMIT-TO(SUBJAREA, "ENER") OR LIMIT-TO(SUBJAREA, "PHYS") OR LIMIT-TO(SUBJAREA, "BIOC") OR LIMIT-TO(SUBJAREA, "AGRI") OR LIMIT-TO(SUBJAREA, "PHAR") OR LIMIT-TO(SUBJAREA, "CHEM")) AND (EXCLUDE(SUBJAREA, "MEDI") OR EXCLUDE(SUBJAREA, "HEAL") OR EXCLUDE(SUBJAREA, "NEUR") OR EXCLUDE(SUBJAREA, "IMMU") OR EXCLUDE(SUBJAREA, "COMP") OR EXCLUDE(SUBJAREA, "PSYC") OR EXCLUDE(SUBJAREA, "MATH") OR EXCLUDE(SUBJAREA, "VETE") OR EXCLUDE(SUBJAREA, "ARTS") OR EXCLUDE(SUBJAREA, "DECI") OR EXCLUDE(SUBJAREA, "DENT") OR EXCLUDE(SUBJAREA, "NURS"))

Your query: TITLE-ABS-KEY(fukushima) AND PUBYEAR > 2010 AND (LIMIT-TO(LANGUAGE, "English") OR LIMIT-TO(LANGUAGE, "German")) AND (EXCLUDE(SUBJAREA, "MEDI") OR EXCLUDE(SUBJAREA, "COMP") OR EXCLUDE(SUBJAREA, "ARTS") OR EXCLUDE(SUBJAREA, "MATH") OR EXCLUDE(SUBJAREA, "HEAL") OR EXCLUDE(SUBJAREA, "NEUR") OR EXCLUDE(SUBJAREA, "NURS") OR EXCLUDE(SUBJAREA, "IMMU") OR EXCLUDE(SUBJAREA, "PSYC") OR EXCLUDE(SUBJAREA, "VETE")) AND (LIMIT-TO(DOCTYPE, "ar"))

Table A2

Articles included in the analysis.

Author	Year	Title	Group
Ahman, B., Wright, S.M., Howard, B.J.	2001	Effect of origin of radiocaesium on the transfer from fallout to reindeer meat	Meat
Ajdacic, N., Martic, M.	1989	Contamination of some important kinds of plants by fission-products	Meat
	1989	Contamination of some important kinds of plants by fission-products	Dairy.product
	1989	Contamination of some important kinds of plants by fission-products	Fodder
	1989	Contamination of some important kinds of plants by fission-products	Baby food
	1989	Contamination of some important kinds of plants by fission-products	Meat
	1989	Contamination of some important kinds of plants by fission-products	Pharma
Amundsen, I., Gulden, G., Strand, P.	1996	Accumulation and long term behaviour of radiocaesium in Norwegian fungi	Mushrooms
	1996	Accumulation and long term behaviour of radiocaesium in Norwegian fungi	Mushrooms
Andersson, I., Lonsjo, H., Rosen, K.	2001	Long-term studies on transfer of Cs-137 from soil to vegetation and to grazing lambs in a mountain area in Northern Sweden	Mushrooms
	2001	Long-term studies on transfer of Cs-137 from soil to vegetation and to grazing lambs in a mountain area in Northern Sweden	Meat
Askbrant, S., Sandalls, J.	1998	Root uptake of Cs-137 and Sr-90 by rye-grass on various soils in the CIS	Fodder
Bangert, K., et al.	1986	Radioactivity in air, rain, soil, plants and food after the chernobyl incident	Meat
Baratta, E.J.	2003	Determination of radionuclides in foods from Minsk, Belarus, from Chernobyl to the present	Dairy.product
Barnett, C.L., Beresford, N.A., Self, P.L., Howard, B.J., Frankland, J.C., Fulker, M.J., Dodd, B.A., Marriott, J.V.R.	2003	Determination of radionuclides in foods from Minsk, Belarus, from Chernobyl to the present	Dairy.product
Battiston, G.A., Degetto, S., Gerbasi, R., Sbrignadello, G.	1999	Radiocaesium activity concentrations in the fruit-bodies of macrofungi in Great Britain and an assessment of dietary intake habits	Mushrooms
Beiriger, J.M., Failor, R.A., Marsh, K.V., Shaw, G.E.	1989	Radioactivity in mushrooms in northeast Italy following the chernobyl accident	Mushrooms
Belli, M., Drigo, A., Menegon, S., Menin, A., Nazzi, P., Sansone, U., Toppino, M.	1989	Radioactivity in mushrooms in Northeast Italy following the chernobyl accident	Mushrooms
Belova, N.V., Emeland'yanova, N.G.	1988	Radioactive fallout from the chernobyl nuclear-reactor accident	Mushrooms
Beresford, N.A., Barnett, C.L., Crout, N.M.J., Morris, C.C.	1989	Transfer of chernobyl fallout cesium radioisotopes in the cow food-chain	Fodder
Bradley, E.J., Wilkins, B.T.	2009	Status of reproductive system of bony fishes of Teterev River and Kiev Reservoir after 20 years of Chernobyl catastrophe	Fish
Bretten, S., Gaare, E., Skogland, T., Steinnes, E.	1996	Radiocaesium variability within sheep flocks: Relationships between the Cs-137 activity concentrations of individual ewes within a flock and between ewes and their progeny	Meat
Brittain, J.E., Gjerseth, J.E.	1989	Influence of husbandry on the transfer of radiocaesium from feed to dairy.product during the winter that followed the chernobyl reactor accident	Dairy.product
Bunzl, K., Kracke, W., Vorwohl, G.	1992	Investigations of radiocaesium in the natural terrestrial environment in Norway following the chernobyl accident	Meat
Constantinescu, B., Galeriu, D., Ivanov, E.A., Pascovici, G., Plostinaru, D.	2010	Long-term trends and variation in Cs-137 activity concentrations in brown trout (<i>Salmo trutta</i>) from Ovre Heimdalsvatn, a Norwegian subalpine lake	Fish
Cooper, E.L., Zeiller, E., Ghodseshphani, A., Makarewicz, M., Schelenz, R., Frindik, O., Heilgeist, M., Kalus, W.	1988	Transfer of chernobyl-derived Cs-134, Cs-137, I-131 and Ru-103 from flowers to honey and pollen	Food
	1988	Determination Of I-131, Cs-134, Cs-137 in plants and cheese after chernobyl accident in Roumania	Dairy.product
Curini, M., Rosati, O., Borio, R., Saetta, D.M.S., Cicioni, R., Forini, N., Rongoni, A., Dipilato, A.C.	1992	Radioactivity in food and total diet samples collected in selected settlements in the USSR	Mushrooms
Derauw, W.G., Vanderstruijs, T.D.B.	1992	Radioactivity in food and total diet samples collected in selected settlements in the USSR	Dairy.product
	1992	Radioactivity in food and total diet samples collected in selected settlements in the USSR	Berries
	1992	Radioactivity in food and total diet samples collected in selected settlements in the USSR	Fish
	1992	Radioactivity in food and total diet samples collected in selected settlements in the USSR	Mushrooms
	1992	Radioactivity in food and total diet samples collected in selected settlements in the USSR	Fish
Dvorak, P., Snasel, P., Benova, K.	1995	Evaluation of Cs-137 activity in plant drugs and in some phytoderivatives from Chernobyl accident up to present (1986–1994)	Pharma
Elliott, J.M., Elliott, J.A., Hilton, J.	1992	Radioactive contamination of food sampled in the areas of the USSR affected by the chernobyl disaster	Mushrooms
	1992	Radioactive contamination of food sampled in the areas of the USSR affected by the chernobyl disaster	Fodder
	1992	Radioactive contamination of food sampled in the areas of the USSR affected by the chernobyl disaster	Dairy.product
	1993	Radioactive contamination of food sampled in the areas of the USSR affected by the chernobyl disaster	Mushrooms
Elliott, J.M., Hilton, J., Rigg, E., Tullett, P.A., Swift, D.J., Leonard, D.R.P.	2010	Transfer of Radiocaesium into Wild Boar Meat	Meat
Elstner, E.F., Fink, R., Holl, W., Lengfelder, E., Ziegler, H.	1993	Sources of variation in post-Chernobyl radiocaesium in brown trout, <i>Salmo trutta</i> L, and Arctic charr, <i>Salvelinus alpinus</i> (L), from six Cumbrian lakes (northwest England)	Fish
Endo et al.	1992	Sources of variation in post-chernobyl radiocaesium in fish from 2 cumbrian lakes (north-west England)	Fish
Elstner, E.F., Fink, R., Holl, W., Lengfelder, E., Ziegler, H.	1989	Radioactivity in mushrooms, mosses and soil samples of defined biotops in sw Bavaria—2 years after chernobyl	Mushrooms
	1987	Natural and chernobyl-caused radioactivity in mushrooms, mosses and soil-samples of defined biotops in sw Bavaria	Mushrooms
	2013	Paddy-field contamination with 134Cs and 137Cs due to Fukushima Dai-ichi Nuclear Power Plant accident and soil-to-rice transfer coefficients	Food

Table A2 (Continued)

Author	Year	Title	Group
Feher, I.	1988	Experience in Hungary on the radiological consequences of the chernobyl accident	Meat
Fielitz, U.	1988	Experience in Hungary on the radiological consequences of the chernobyl accident	Pharma
Fielitz, U., Klemt, E., Strebl, F., Tataruch, F., Zibold, G., Fleishman, D.G., Nikiforov, V.A., Saulus, A.A., Komov, V.T.	1996	Radiocesium in wild animals after the reactor accident in Chernobyl	Mushrooms
Forberg, S., Odsjo, T., Olsson, M.	1996	Radiocesium in wild animals after the reactor accident in Chernobyl	Meat
Gattavecchia, E., Ghini, S., Tonelli, D.	2009	Seasonality of Cs-137 in roe deer from Austria and Germany	Meat
Gilmore, B.J., Cranley, K.	1994	Cs-137 in fish of some lakes and rivers of the bryansk region and north-west RUSSIA in 1990–1992	Fish
Gorur, F.K., Keser, R., Akcay, N., Dizman, S., Okumusoglu, N.T.	1992	Radiocesium in muscle-tissue of reindeer and pike from Northern Sweden before and after the chernobyl accident—a retrospective study on tissue samples from the Swedish-environmental-specimen-bank	Meat
Grabowski, D., Muszynski, W., Petrykowska, M., Rubel, B., Smagala, G., Hakanson, L., Andersson, T.	1988	Cs-137 transfer from forage to dairy-product and its removal by clay treatment	Dairy-product
Hakanson, L.	1987	Radionuclide monitoring in northern-Ireland of the chernobyl nuclear-reactor accident	Dairy-product
Hedvall, R., Erlandsson, B.	2011	Radionuclides and heavy metals concentrations in Turkish market tea	Tea
Heinrich	1994	Activity of cesium-134 and cesium-137 in game and mushrooms in Poland	Mushrooms
Heinrich, E.	1994	Activity of cesium-134 and cesium-137 in game and mushrooms in Poland	Meat
Hessen, D.O., Skurdal, J., Hegge, O., Hesthagen, T.	1992	Remedial measures against radioactive cesium in Swedish lake fish after chernobyl	Fish
Higaki, T., Higaki, S., Hirota, M., Akita, K., Hasezawa, S.	1999	Chernobyl—its Impact on austria	Fish
Hohmann, U., Huckschlag, D.	1997	Radioactivity in straw and energy forestry used for energy production in Sweden	Wood
Horrill, A.D., Kennedy, V.H., Paterson, I.S., McGowan, G.M.	1989	Natural and artificial radionuclides in selected styrian soils and plants before and after the reactor accident in chernobyl	Mushrooms
Ikaheimonen, T.K., Saxen, R.	1988	Chernobyl—its impact on Austria	Meat
Johanson, K.J., Bergstrom, R.	1988	Chernobyl—its impact on Austria	Berries
Jonsson, B., Forseth, T., Ugedal, O.	1988	Chernobyl—its impact on Austria	Dairy-product
Kalas, J.A., Bretten, S., Byrkjedal, I., Njastad, O.	2002	Radiocesium decay in populations of brown trout and Arctic char in the alpine Atna area, south-eastern Norway	Food
Kammerer, L., Hiersche, L., Wirth, E.	2012	Radionuclide Analysis on Bamboos following the Fukushima Nuclear Accident	Fish
Karlen, G., Johanson, K.J., Bergstrom, R.	2012	Radionuclide Analysis on Bamboos following the Fukushima Nuclear Accident	Fodder
Karlen, G., Johanson, K.J., Bertilsson, J.	2005	Investigations on the radiocaesium contamination of wild boar (<i>Sus scrofa</i>) meat in Rhineland-Palatinate: a stomach content analysis	Fodder
Kliment, V., Bucina, I.	1995	The effect of heather burning on the transfer of radiocesium to smoke and the solubility of radiocesium associated with different types of heather ash	Fodder
Kostiainen, E.	2007	Transuranic elements in fishes compared to Cs-137 in certain lakes in Finland	Fish
Koulikov, A.O.	1989	Radiocesium transfer to man from moose and roe deer in Sweden	Meat
Koulikov, A.O., Ryabov, I.N.	1989	Radiocesium from chernobyl in Swedish moose	Meat
Kritidis, P., Florou, H.	1999	Chernobyl radioactivity persists in fish	Fish
Lehto et al.	1994	Radiocesium (137Cs) from the chernobyl reactor in eurasian woodcock and earthworms in Norway	Meat
Lepicard, S., Dubreuil, G.H.	1994	Uptake of radiocesium by different species of mushrooms	Mushrooms
Lettner, H., Griesbner, A., Peer, T.	1991	Seasonal-variation in the activity concentration of Cs-137 in Swedish roe-deer and in their daily intake	Meat
Hubmer, A.K., Pintaric, M.	1991	Seasonal-variation in the activity concentration of cs-137 in Swedish roe-deer and in their daily intake	Meat
Lettner, H., Hubmer, A., Bossew, P.	1995	Transfer of Cs-137 to cows dairy-product—investigations on dairy farms in sweden	Fodder
Strebl, F.	1990	Contamination of food in Czechoslovakia by cesium radioisotopes from the chernobyl accident	Dairy-product
Lowe, V.P.W., Horrill, A.D.	2007	Cs-137 in Finnish wild berries, mushrooms and game meat in 2000–2005	Meat
Lowe, V.P.W., Horrill, A.D.	2007	Cs-137 in Finnish wild berries, mushrooms and game meat in 2000–2005	Berries
Koulakov, A.O.	2007	Cs-137 in Finnish wild berries, mushrooms and game meat in 2000–2005	Mushrooms
Koulakov, A.O., Ryabov, I.N.	1996	Physiological and ecological factors influencing the radiocaesium contamination of fish species from Kiev reservoir	Fish
Kritidis, P., Florou, H.	1992	Specific cesium activity in fresh-water fish and the size effect	Fish
Lehto et al.	1995	Environmental-study of radioactive cesium in Greek lake fish after the chernobyl accident	Fish
Lepicard, S., Dubreuil, G.H.	2013	137Cs, 239,240Pu and 241Am in boreal forest soil and their transfer into wild mushrooms and berries	Berries
Lettner, H., Griesbner, A., Peer, T.	2013	137Cs, 239,240Pu and 241Am in boreal forest soil and their transfer into wild mushrooms and berries	Mushrooms
Hubmer, A.K., Pintaric, M.	2001	Practical improvement of the radiological quality of dairy-product produced by peasant farmers in the territories of Belarus contaminated by the Chernobyl accident—The ETHOS project	Dairy-product
Lettner, H., Hubmer, A., Bossew, P.	2006	Altitude dependent (Cs)-C-137 concentrations in different plant species in alpine agricultural areas	Fodder
Strebl, F.	2006	Altitude dependent (Cs)-C-137 concentrations in different plant species in alpine agricultural areas	Fodder
Lowe, V.P.W., Horrill, A.D.	2007	Cs-137 and Sr-90 transfer to dairy-product in Austrian alpine agriculture	Fodder
Lowe, V.P.W., Horrill, A.D.	2007	Cs-137 and Sr-90 transfer to dairy-product in Austrian alpine agriculture	Dairy-product
Lowe, V.P.W., Horrill, A.D.	1991	Cesium concentration factors in wild herbivores and the fox (<i>vulpes-vulpes l.</i>)	Meat
Lowe, V.P.W., Horrill, A.D.	1988	Ecological half-life of cesium in roe deer (<i>capreolus-capreolus</i>)	Meat

Table A2 (Continued)

Author	Year	Title	Group
Lux, D., Kammerer, L., Ruhm, W., Wirth,	1995	Cycling of Pu, Sr, Cs, and other longliving radionuclides in forest ecosystems of the 30-km zone around Chernobyl	Berries
E.	1995	Cycling of Pu, Sr, Cs, and other longliving radionuclides in forest ecosystems of the 30-km zone around Chernobyl	Berries
Malinowska, E., Szefer, P., Bojanowski, R.	2006	Radionuclides content in <i>Xerocomus badius</i> and other commercial mushrooms from several regions of Poland	Mushrooms
Marouf, B.A., Alhadad, A.K., Toma, N.A.,	1991	Radionuclide contamination of foods imported into Iraq following the chernobyl nuclear-reactor accident	Dairy.product
Tawfiq, N.F., Mahmood, J.A., Hasoon,	1991	Radionuclide contamination of foods imported into Iraq following the chernobyl nuclear-reactor accident	Foodstuff
Matovic, G., Franic, Z., Sencar, J., Bituh, T., Vugrinec, O.	2008	Mosses and Some Mushroom Species as Bioindicators of Radio caesium Contamination and Risk Assessment	Mushrooms
Martin, C.J., Heaton, B., Robb, J.D.	1988	Studies of I-131, Cs-137 and Ru-103 in dairy.product, meat and vegetables in North-east Scotland following the chernobyl accident	Meat
Mascanzoni, D.	2009	Long-term transfer of Cs-137 from soil to mushrooms in a semi-natural environment	Mushrooms
Mascanzoni, D.	1992	Determination of Sr-90 and Cs-137 in mushrooms following the chernobyl fallout	Mushrooms
McGee, E.J., et al.	2000	Chernobyl fallout in a Swedish spruce forest ecosystem	Mushrooms
	2000	Chernobyl fallout in a Swedish spruce forest ecosystem	Meat
	2000	Chernobyl fallout in a Swedish spruce forest ecosystem	Wood
Mehli, H., Skuterud, L.	1998	The influence of fungi on the long-term behaviour of radio caesium in Norwegian sheep	Meat
Mietelski, J.W., Dubchak, S., Blazej, S., Anielska, T., Turnau, K.	2010	Cs-137 and K-40 in fruiting bodies of different fungal species collected in a single forest in southern Poland	Mushrooms
Mietelski JW, Jasinska M, Kubica B,	1994	Radioactive contamination of Polish mushrooms	Mushrooms
Kozak K, Macharski P	1994	Radioactive contamination of Polish mushrooms	Mushrooms
Molzahn, D., Tufail, M., Patzelt, P.	1990	Chernobyl radioactivity in Turkish tea	Tea
	1990	Chernobyl radioactivity in Turkish tea	Tea
Muck, K.	1995	Long-term reduction of cesium concentration in dairy.product after nuclear fallout	Dairy.product
Muck, K., Gerzabek, M.H.	1995	Trends in caesium activity concentrations in dairy.product from agricultural and semi-natural environments after nuclear fallout	Dairy.product
Nakanishi, T.M., Kobayashi, N.I., Tanoi, K.	2012	Radioactive caesium deposition on rice, wheat, peach tree and soil after nuclear accident in Fukushima.	Fodder
Nedbaevskaya, N.A., Sanzharova, N.I., Blinova, L.D., II K, Aleksakhin, R.M.	1991	Dynamics of the radionuclide content in precipitation, grazing vegetation, and dairy.product, in the leningrad region after the accident at the chernobyl atomic-energy plant	Fodder
Palo et al.	1991	Radio caesium Levels in Swedish Moose in	Meat
Papastefanou, C.	2001	Radioactivity in tobacco leaves	Tabacco
Pedersen, H.C., Nybo, S., Varskog, P.	1998	Seasonal variation in radio caesium concentration in willow ptarmigan and rock ptarmigan in central Norway after the Chernobyl fallout	Meat
Pourcelot, L., Steinmann, P., Froidevaux, P.	2007	Lower variability of radionuclide activities in upland dairy products compared to soils and vegetation: Implication for environmental survey	Fodder
Rabitsch, H., Pichl, E.	2008	Lifetime accumulation of Cs-137 and K-40 in the ribs and sternum of an Austrian and 'mountain pastureand' cow	Meat
Randa et al.	1993	Original in Czech but mentioned in review of mushrooms (Kalac, 2001)	Mushrooms
Rask, M., Saxen, R., Ruuhijarvi, J., Arvola, L., Jarvinen, M., Koskelainen, U., Outola, I., Vuorinen, P.J.	2012	Short- and long-term patterns of Cs-137 in fish and other aquatic organisms of small forest lakes in southern Finland since the Chernobyl accident	Fish
Roca, V., Napolitano, M., Speranza, P.R., Gialanella, G.	1989	Analysis of radioactivity levels in soils and crops from the campania region (south Italy) after the chernobyl accident	Fodder
Rosen, K., Andersson, I., Lonsjo, H.	1989	Analysis of radioactivity levels in soils and crops from the campania region (south Italy) after the chernobyl accident	Fodder
Ruckert, G., Diehl, J.F.	1989	Analysis of radioactivity levels in soils and crops from the campania region (south Italy) after the chernobyl accident	Food
Ryabov, I.N., Belova, N.V., Polyakova, N.I.	1995	Transfer of radio caesium from soil to vegetation and to grazing lambs in a mountain area in northern Sweden	Meat
Saxén, R.L.	1987	Increased levels of cesium-137 and cesium-134 in 34 species of wild mushrooms following the chernobyl disaster	Mushrooms
Saxén, R.L., Sundell, J.	1998	Evolution of radio caesium contamination in fishes after the Chernobyl accident	Fish
Sarkka, J., Jamsa, A., Luukko, A.	1998	Evolution of radio caesium contamination in fishes after the Chernobyl accident	Fish
Sarkka, J., Keskitalo, A., Luukko, A.	1998	Evolution of radio caesium contamination in fishes after the Chernobyl accident	Fish
Semizhon, T., Putyrskaya, V., Zibold, G., Klemt, E.	2009	Evolution of radio caesium contamination in fishes after the Chernobyl accident	Fish
Skuterud, L., Gaare, E., Eikelmann, I.M.,	2007	Cs 137 in freshwater and lake water in Finland after the Chernobyl deposition	Fish
Hove, K., Steinnes, E.	2006	Cs 137 in freshwater fish in Finland since 1986—a statistical analysis with multivariate linear regression models	Fish
Smith, J.T., Comans, R.N.J., Beresford, N.A., Wright, S.M., Howard, B.J., Camplin, W.C.	1995	Chernobyl-derived radio caesium in fish as dependent on water-quality and lake morphometry	Fish
	1996	Temporal changes in concentration of radio caesium in lake sediment and fish of southern Finland as related to environmental factors	Fish
	2005	Time-dependency of the Cs-137 contamination of wild boar from a region in Southern Germany in the years 1998 to 2009	Meat
	2005	Chernobyl radioactivity persists in reindeer	Meat
	2005	Chernobyl radioactivity persists in reindeer	Meat
	2000	Pollution— Chernobyl land's legacy in food and water	Fish

Table A2 (Continued)

Author	Year	Title	Group
Smith, J.T., Kudelsky, A.V., Ryabov, I.N., Haderdingh, R.H.	2000	Radiocaesium concentration factors of Chernobyl-contaminated fish: a study of the influence of potassium, and blind; testing of a previously developed model	Fish
	2000	Radiocaesium concentration factors of Chernobyl-contaminated fish: a study of the influence of potassium, and blind; testing of a previously developed model	Fish
Smith, M.L., Taylor, H.W., Sharma, H.D.	1993	Comparison of the postchernobyl Cs-137 contamination of mushrooms from Eastern-Europe, Sweden, and north-America	Mushrooms
	1993	Comparison of the postchernobyl cs-137 contamination of mushrooms from eastern-Europe, Sweden, and north-America	Mushrooms
	1993	Comparison of the postchernobyl cs-137 contamination of mushrooms from eastern-Europe, Sweden, and north-America	Mushrooms
Sonesten, L. Spezzano, P., Giacomelli, R.	2001	Land use influence on (¹³⁷ Cs levels in perch (<i>Perca fluviatilis</i> L.) and roach (<i>Rutilus rutilus</i> L.)	Fish
	1991	Transport of I-131 and Cs-137 from air to cows dairy-product produced in north-western Italian farms following the chernobyl accident	Dairy-product
Steinhausler, F., Hofmann, W., Daschil, F., Reubel, B.	1988	Chernobyl and its radiological and socioeconomic consequences for the province of Salzburg, Austria	Meat
	1988	Chernobyl and its radiological and socioeconomic consequences for the province of Salzburg, Austria	Meat
	1988	Chernobyl and its radiological and socioeconomic consequences for the province of Salzburg, Austria	Dairy-product
	2009	Influence of soil acidification in southern Norway on the Cs-137 exposure of moose? Pages 3905–3908	Meat
Steinnes, E., Gaare, E., Engen, S. Strandberg, M.	1994	Radiocesium in a Danish pine forest ecosystem	Mushrooms
	1994	Radiocesium in a Danish pine forest ecosystem	Wood
Strandberg, M. Strebl, F., Gerzabek, M.H., Karg, V., Tataruch, F.	2004	Long-term trends in the uptake of radiocesium in <i>Rozites cuperatus</i>	Mushrooms
	1996	Cs-137-migration in soils and its transfer to roe deer in an Austrian forest stand	Meat
	2007	Time trends (1986–2003) of radiocesium transfer to roe deer and wild boar in two Austrian forest regions	Meat
	2003	Long-term dynamics of Chernobyl Cs-137 in freshwater fish: quantifying the effect of body size and trophic level	Fish
Sundbom, M., Meili, M., Andersson, E., Ostlund, M., Broberg, A. Svadlenkova, M., Konecny, J., Smutny, V.	1996	Model calculation of radiocaesium transfer into food products in semi-natural forest ecosystems in the Czech Republic after a nuclear reactor accident and an estimate of the population dose burden	Mushrooms
	1996	Model calculation of radiocaesium transfer into food products in semi-natural forest ecosystems in the Czech Republic after a nuclear reactor accident and an estimate of the population dose burden	Meat
Szanto, Z., Hult, M., Watjen, U., Altitzoglou, T.	2007	Current radioactivity content of wild edible mushrooms: A candidate for an environmental reference material	Mushrooms
	2007	Current radioactivity content of wild edible mushrooms: A candidate for an environmental reference material	Mushrooms
Teheranie Thiry, Y., Colle, C., Yoschenko, V., Levchuk, S., Van Hees, M., Hurtevent, P., Kashparov, V.	2007	Current radioactivity content of wild edible mushrooms: A candidate for an environmental reference material	Mushrooms
	1988	Determination of ¹³⁷ Cs and ¹³⁴ Cs radioisotopes in various mushrooms from Austria one year after the chernobyl incident	Mushrooms
	2009	Impact of Scots pine (<i>Pinus sylvestris</i> L.) plantings on long term Cs-137 and Sr-90 recycling from a waste burial site in the Chernobyl Red Forest	Wood
	1995	Sources of variation in radiocesium levels between individual fish from a chernobyl contaminated Norwegian lake	Fish
National Board of Atomic Safety and Radiation Protection of the GDR	1988	Results of radiation monitoring in the German-democratic-republic after chernobyl	Mushrooms
	2005	(Cs)-C-137 concentration in meat of wild boars (<i>Sus scrofa</i>) in Croatia a decade and half after the Chernobyl accident	Meat
Vilic, M., Barisic, D., Kraljevic, P., Lulic, S. Vinichuk, M., Rosen, K., Johanson, K.J., Dahlberg, A.	2011	Correlations between potassium, rubidium and caesium (Cs-133 and Cs-137) in sporocarps of <i>Suillus variegatus</i> in a Swedish boreal forest	Mushrooms
	2010	Accumulation of potassium, rubidium and caesium (Cs-133 and Cs-137) in various fractions of soil and fungi in a Swedish forest	Mushrooms
Yoshida, S., Muramatsu, Y. Yoshida, S., Muramatsu, Y., Dvornik, A.M., Zhuchenko, T.A., Linkov, I.	1994	Accumulation of radiocesium in basidiomycetes collected from Japanese forests	Mushrooms
	2004	Equilibrium of radiocesium with stable caesium within the biological cycle of contaminated forest ecosystems	Mushrooms
Zibold, G., Drissner, J., Kaminski, S., Klemt, E., Miller, R.	2004	Equilibrium of radiocesium with stable caesium within the biological cycle of contaminated forest ecosystems	Wood
	2001	Time-dependence of the radiocaesium contamination of roe deer: measurement and modelling	Meat

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