



# Exemplifying the “wild boar paradox”: dynamics of cesium-137 contaminations in wild boars in Germany and Japan

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## Abstract

Wild boars (*Sus scrofa*) are notorious for accumulating high contamination levels of <sup>137</sup>Cs in their meat. Publicly available data of <sup>137</sup>Cs contamination levels in wild boars from 2011 to 2019 were used to determine some radioecological characteristics in Germany (affected by Chernobyl-fallout, 1986) and Japan (affected Fukushima, 2011). The effective half-life of <sup>137</sup>Cs in wild boar meat was much longer in Germany (7.3 y) than in Japan (2.6 y), respectively. Wild boars in Germany thus show much more persistent contamination levels than other game or forest animals. This unusual behavior has been termed “wild boar paradox.” In German wild boars, the data sets reveal a distinct geographical and seasonal dependence with higher activity concentrations in winter than in summer. In Japan, contamination levels only exhibit a distinct decline behavior.

**Keywords** Wild boar (*Sus scrofa*) · Chernobyl · Fukushima · <sup>137</sup>Cs · Food · Radiation protection · Game meat · Ecological half-life

## Introduction

The nuclear accidents at Chernobyl (1986) and Fukushima (2011) have caused widespread contamination on a global and national level, respectively. Following major nuclear accidents, protection of the public receives major attention, in particular food safety. In the immediate aftermath of a nuclear accident, it has been shown previously [1–5] that the ingestion of radionuclides with contaminated food is the main additional dose contributor for the public. Of all radionuclides emitted, radioactive cesium, in particular <sup>134</sup>Cs (physical half-life  $T_{1/2} = 2.1$  y) and <sup>137</sup>Cs ( $T_{1/2} = 30.1$  y), plays an important role due to its volatility and high specific activity and persistence in the environment as a result of the long half-life of <sup>137</sup>Cs. The contaminations from Chernobyl and Fukushima, respectively, thus remain relevant for many

decades to come. To a lower extent, fallout from nuclear weapons testing may contribute to the total radiocesium. For Europe, this impact, however, is in the range of only about 10% of the total radiocesium in soil [6]. Fallout from Chernobyl and Fukushima, respectively, thus will dominate the contamination levels in the ecosystems in Germany and Japan, respectively.

Wild game has been identified as a potent accumulator of radiocesium [7–9], in particular wild boar [7, 8, 10–20]. Whereas most forest species have exhibited high contamination levels in the early aftermath followed by decline, strangely, a similar behavior in the dynamics of the contamination could not be observed for wild boars. Wild boars have been shown not only to accumulate radiocesium to a high extent, but also to largely maintain these contamination levels over the periods of years or decades [7, 8, 12, 18, 21, 22].

The continuous intake of radiocesium and the preference for cesium-rich food seems to be responsible for this unique characteristic in wild boars. Especially, the mushroom diet of wild boars is a likely key factor in the contamination of wild boars due to the mushrooms’ cesium-accumulating characteristics [23–31]. Hypogeous fungi such as deer truffle (*Elaphomyces*) have been suggested as the major source of radiocesium in the soft tissue of wild boars [18, 32], rather

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than any physiological anomaly of the wild boar (such as the accumulation in fat tissue [14, 33]). This anomalous behavior warranted for an in-depth analysis of the temporal and spatial contamination dynamics of  $^{137}\text{Cs}$  in wild boar and to elucidate the impact of environmental factors such as the availability of less contaminated foods as well as the impact of the density of forestation. In order to assess these different aspects, the dense and publicly available environmental monitoring data compiled in Germany and Japan, respectively, were harnessed in this study.

## Data and methods

For Germany, data sets of the  $^{137}\text{Cs}$  activity concentration in wild boars, compiled by the German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS) were used, which include samples from January 5, 2012 to March 13, 2019. While data from the last three years is made publicly available [34], older data were provided upon request. The Japanese food data was collected by the Ministry of Health, Labor and Welfare [35], with sampling dates of  $^{137}\text{Cs}$ ,  $^{134}\text{Cs}$  and total radiocesium ( $^{134}\text{Cs} + ^{137}\text{Cs}$ ) activity concentrations in wild boars ranging from May 8, 2011 to July 17, 2018. In cases, where the  $^{137}\text{Cs}$  activity concentration was not reported, it was calculated from the total radiocesium activity concentration as described in [17]. Only the  $^{137}\text{Cs}$  activity concentration was used in the analyses presented here in order to enable a comparison with the German food data. Measurements reported being lower than the detection limit were treated as having a value of half the detection limit in both data sets. Due to the great variance of the measurements, a lognormal distribution was assumed and the geometric mean was considered more representative than the arithmetic mean for most statistical analyses.

## Results and discussion

Cesium-137 activity concentrations in boars show a large variability throughout all years of observation with values ranging from less than 10 Bq/kg to more than 10 000 Bq/kg.

### Spatial distribution

Sampling locations are not uniformly spread throughout the countries, with significant "gaps" in-between (locations from where no samples were reported) (Fig. 1). The figure shows the activity concentrations (geometric means) in the meat of wild boars per municipality (at least one boar per municipality). Geometric means were also used by other authors, e.g., Fuma et al. [10], and were found to reflect the

dynamic characteristics best. In municipalities indicated in gray in Fig. 1, no meat sample was delivered for measurement or measurements were not included in the database. Locations also varied with each year as shown in Fig. 2, making it difficult to assess the combined temporal and spatial distribution of contamination in wild boars in detail. The spatial pattern shown in Fig. 1, therefore, should be interpreted as an overview of "hot spots" only. Especially high activity concentrations can be observed in Northern Bavaria, Germany, correlating with the spread of radionuclides from the Chernobyl nuclear accident in 1986 [36]. Likewise, measurements of high activity concentrations in the Japanese prefectures of Fukushima and Ibaraki roughly match radionuclide depositions reported after the Fukushima nuclear accident [37, 38].

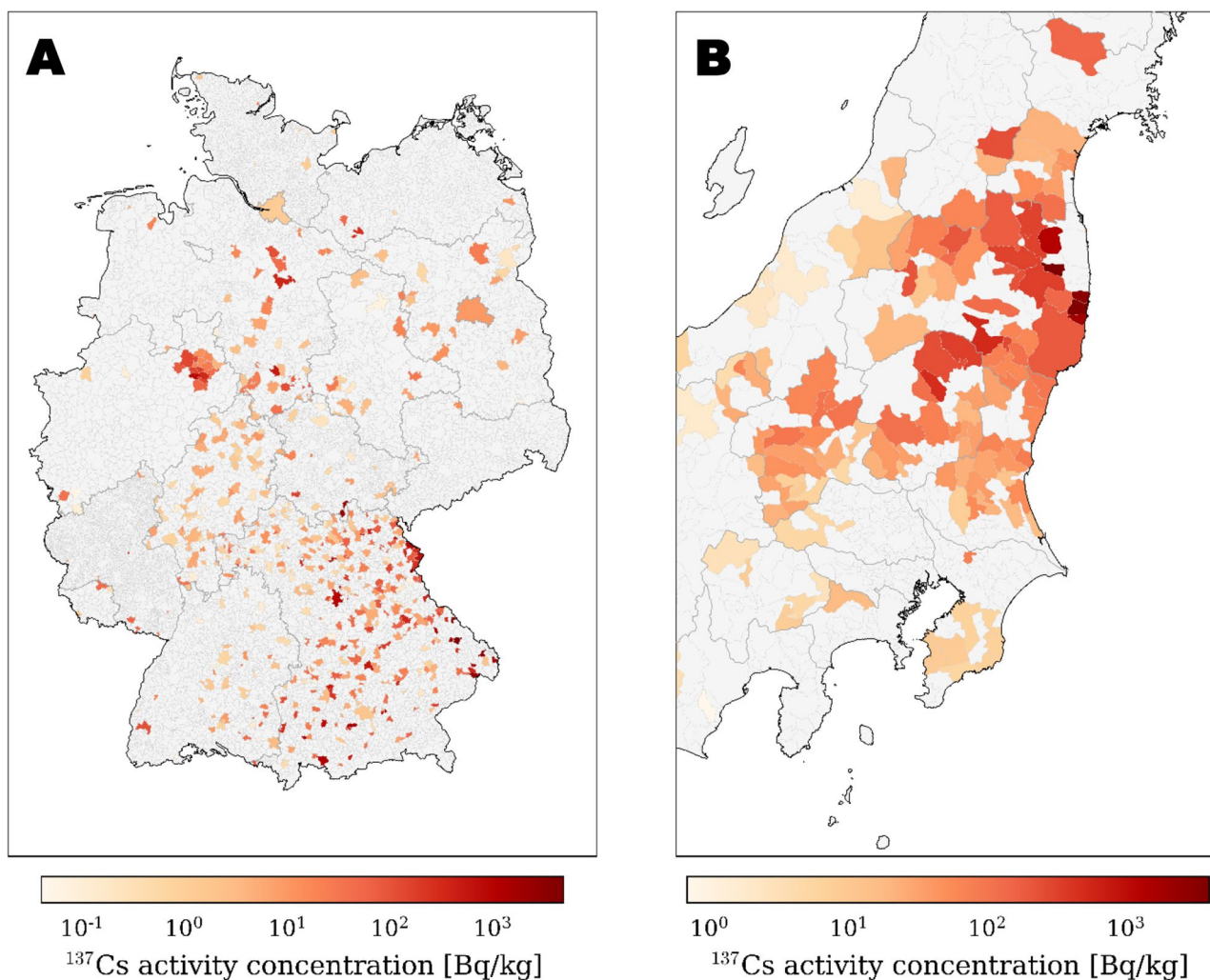
Samples in Bavaria are the most uniformly distributed of the German data set, allowing best for comparison of  $^{137}\text{Cs}$  contamination in boars and land usage in the corresponding area. Data for boars in Germany imply that high levels of contamination are positively correlated with the degree of forestation [39] (Fig. 2, Germany – bottom right). Obviously, the nutrition for boars in forested areas includes a greater load of  $^{137}\text{Cs}$  than for wild boars that supplement their diet with agricultural products for human consumption (e.g., corn).

### Effective and ecological half-lives

The observed declining behavior of radionuclides in plants and animals is calculated by the effective half-life

$$T_{\text{eff}} = \left( \frac{1}{T_{\text{phys}}} + \frac{1}{T_{\text{ecol}}} \right)^{-1}.$$

Here,  $T_{\text{phys}}$  is the physical half-life, and  $T_{\text{ecol}}$  is the ecological half-life, describing the loss of activity in an ecosystem by dilution, excretion or migration (in soil) mechanisms. In Fig. 3, the effective half-life of  $^{137}\text{Cs}$  contamination in wild boars was computed for Germany and Japan respectively. For Germany, a value of 7.3 years was obtained, whereas in Japan the effective half-life amounts to 2.6 years. Note that due to low numbers of samples in each municipality, we had to pool the samples for each country. Here some uncertainty is introduced by some fluctuations in the sample numbers provided each year from municipalities with higher or lower contamination levels. Also note that the effective half-lives in game animals may fluctuate significantly [40]. According to the above equation, the ecological half-lives of  $^{137}\text{Cs}$  in wild boars are 10.2 y for Germany and 2.8 y for Japan, respectively. There are several factors that affect the ecological half-life of radiocesium in a species. Differences have been observed between species and climates. For example,



**Fig. 1** Spatial distribution of  $^{137}\text{Cs}$  contamination in wild boars in Germany (left) and Japan (right). Displayed is the geometric mean of each municipality from 2011 to 2018

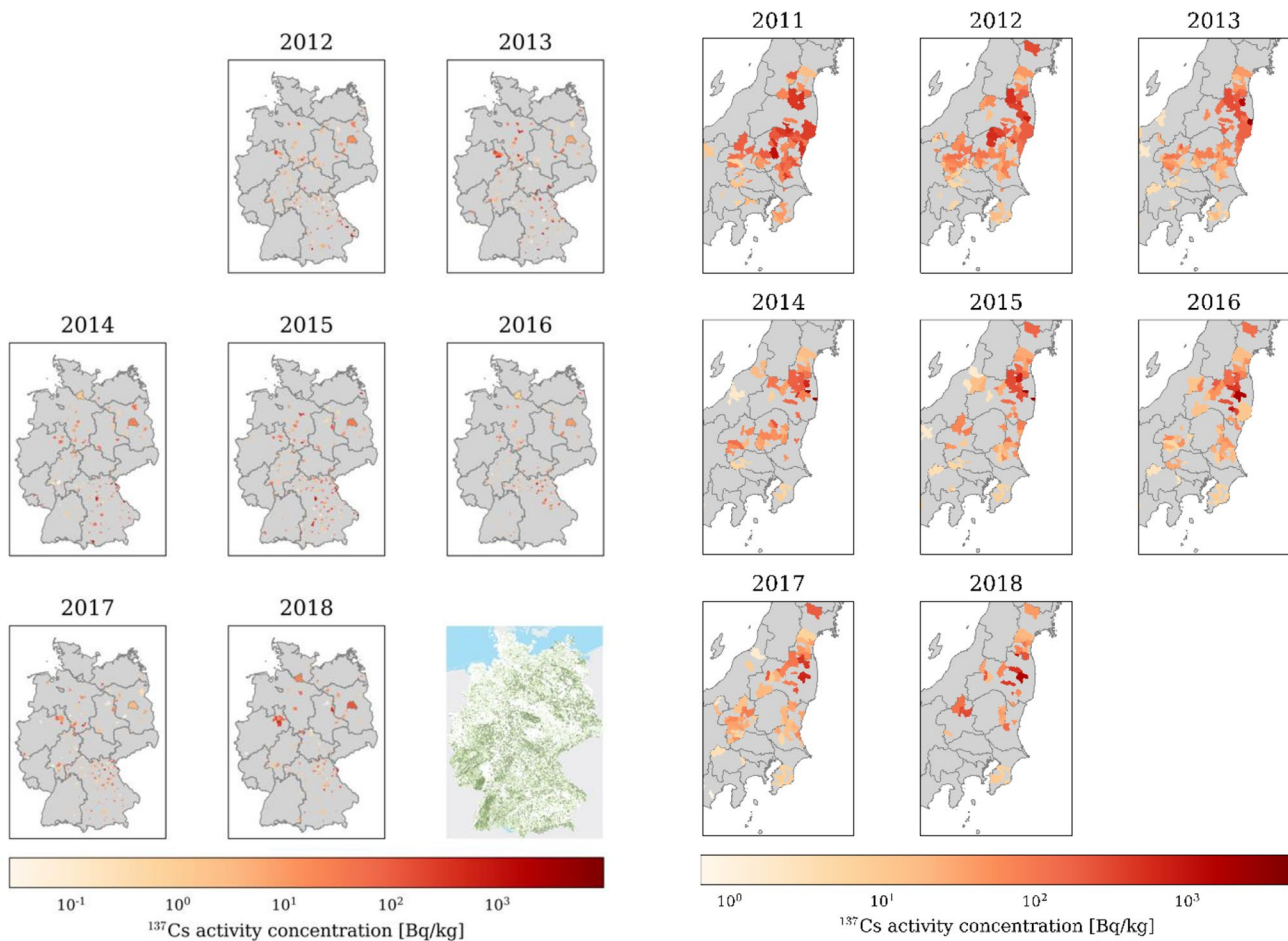
roe deer from central Europe was shown to exhibit ecological half-lives between 7–9 y [7], whereas white-tailed deer from the Savannah River Site exhibited much longer ecological-half-lives of 23.15 y [41]. For wild boar, the variability is even more pronounced. Previous studies found  $10.5 \pm 1.6$  y in Germany [42] or even 62 y [43] or 78 y [44], which leads to an increase rather than a decline of contamination levels (i.e. essentially the “wild boar paradox”). Most recently, an ecological half-life of 16.49 was published for north-east Poland [40].

In any case, the downward trend in activity concentration is more pronounced for Japanese wild boars than for German wild boars. This result is consistent with the aforementioned influence on radiocesium contamination of deer truffles in the boars’ diet, although there could be other confounding factors such as forestation or availability of alternative food sources (which again would relate to the impact

of deer truffles). Unfortunately, deer truffles are difficult to find, which explains why they largely remain an understudied factor in radioecology. Therefore, it is difficult to test the key hypothesis of the paradox directly.

The most common species of deer truffles, *Elaphomyces granulatus*, has been described as widespread and common throughout Germany [32], but they are rare in Japan [45]. The slower decline dynamics of radiocesium in German wild boars (in contrast to Japan) may be caused by the boars’ specific diet and hence may explain our finding of a much longer effective half-life in Germany.

Decline of  $^{137}\text{Cs}$  activity concentrations varies a lot by location (Fig. 4). Especially areas with a higher degree of contamination such as Bavaria, Germany or Fukushima prefecture, Japan show a faster decline than lesser contaminated ones. Some areas even show a slight increase of activity concentrations, which could possibly be attributed



**Fig. 2** Spatial distribution of boars'  $^{137}\text{Cs}$  contamination by year (left: Germany; right: Japan). For each year, the geometric mean of a municipality is shown. In the lower right corner of the left figure, a map that shows the forest coverage of Germany is displayed (taken from ref. [39])

to regionally varying diets of wild boars, leading to differences in radiocesium intake. Similar effects have already been observed in other studies [7, 18].

### Seasonal variations

The data shows substantial seasonal variations over the course of a year in Germany (Fig. 5, top), while in Japan, although fluctuating as well, activity concentrations do not show a noticeable seasonality (Fig. 5, bottom). In any case, a distinct general decline behavior of the contamination levels is obvious for Japanese wild boar, but not nearly as pronounced for German wild boar.

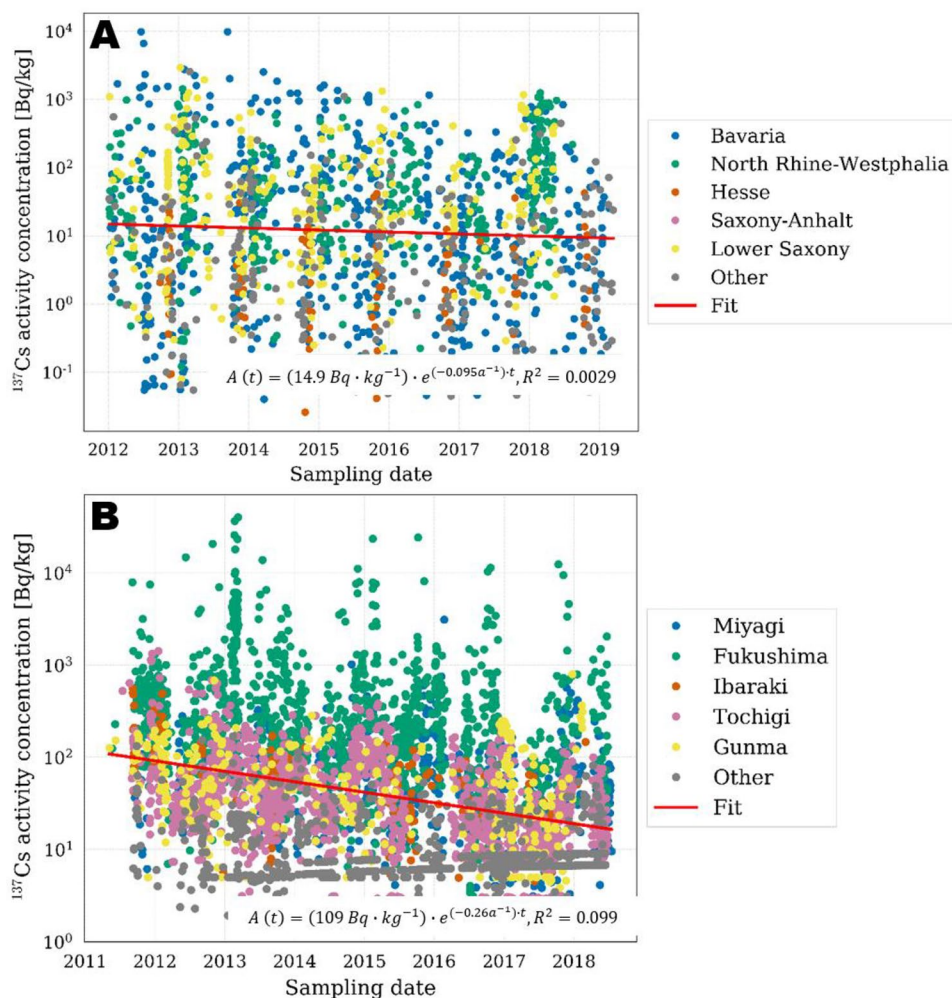
In Germany, activity concentrations tend to be higher in winter and lower in summer in most years. Agricultural products and tree seeds compose a large portion of the wild boars' diet [21]. Availability of these foods falls largely into the late summer months and fall. During winter and early spring, boars are often forced to search for underground food sources like the aforementioned, highly

radiocesium-accumulating *Elaphomyces* fungi. This explanation thus is consistent with our observations for the situation in Germany. In Japan, the situation seems to be different as the seasonal fluctuation of the  $^{137}\text{Cs}$  concentration in boars seems to be much less pronounced. This observation is in line with a previous study that found no distinct correlation between the food items in the stomachs of Japanese wild boar and the contamination level of the respective boar meat [46]. The reason may be that there is no such single food item in Japan that dominates the boars' contamination like the deer truffle in Germany.

The influence of 'mast years' on activity levels in wild boars is another interesting aspect worth of consideration. Mast years are sporadically recurring years with abnormally high production of tree seeds (primarily acorns and beechnuts). These seeds constitute an important fraction of the boars' diet. In Germany, the years 2012, 2016, and 2018 have been classified as mast years in the literature [47]. Figure 6 shows that the arithmetic mean calculated for October of these three years is lower than in the others, albeit not



**Fig. 3** All data points for  $^{137}\text{Cs}$  in meat of wild boars in Germany (A) and Japan (B) by their sampling date. The color specifies the respective state or prefecture (only areas with the highest sample sizes are marked). The red line is an exponential fit of the entirety of data; the obtained parameters and coefficient of determination are given in the box in the lower right corner of each plot

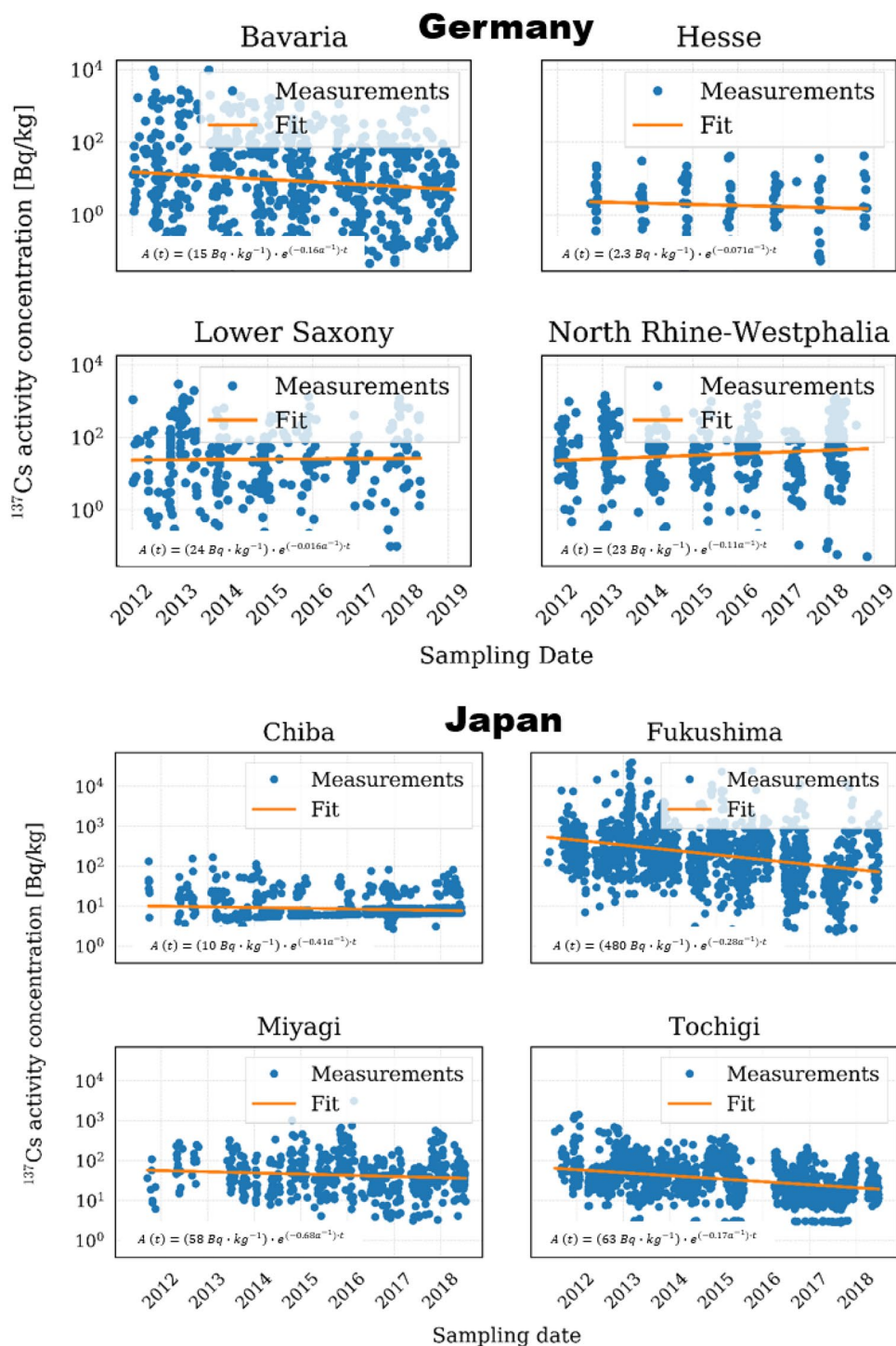


statistically significant ( $p=0.05$ ), as revealed by a Tukey-Kramer test. This distinct feature is also only observable when the arithmetic mean is applied to the data in contrast to the geometric mean that is used throughout the rest of this study (as well as in most of the literature that is available on wild boar contamination). In October, which is the ripening month of acorns and beechnuts, the availability of these seeds reaches a peak and saves the boars the effort of digging for underground fungi. Both acorns and beechnuts are notorious for low radiocesium levels. For example, a 2001 study showed contamination levels as low as  $6.5 \pm 0.1$  Bq  $^{137}\text{Cs}$  per kg for acorns from Croatia [48]. For beechnuts, no literature data are available, but since beech wood exhibits similar contamination levels like oak wood, beechnuts are unlikely at any higher levels than acorns [48]. In contrast, the radiocesium levels in deer truffles are significantly higher, reaching  $5,000 \text{ Bq} \cdot \text{kg}^{-1}$  [49] or even  $25,000 \text{ Bq} \cdot \text{kg}^{-1}$  [50]. In Japan, as discussed previously, mushrooms and underground foods are no dominant contributors to the wild boars' contamination levels [46].

Of course, a mast year would not result in a sudden drop of already existing radiocesium contaminations in the meat, but a decline according to the biological half-life (excretion of radiocesium). However, sudden availability of plenty of low-contaminated, easily accessible fodder would immediately cease the intake of highly contaminated underground food sources. We thus may expect a delayed effect over several months rather than a step function. The seasonal zig-zag pattern for seasonal contamination levels in Fig. 5 is certainly more pronounced in Germany than in Japan.

Comparison on an international scale shows that radiocesium levels in wild boars are in the same range in Poland [40] like in Germany (however, it appears that fewer specimens reach the  $10^4 \text{ Bq} \cdot \text{kg}^{-1}$  range). Polish wild boars also show a distinct "wild boar paradox." In Southern Italy, much less affected by Chernobyl fallout, levels are about two orders of magnitude lower than in Germany or Japan [51].

**Fig. 4** Data is plotted for each of the four areas with the largest sample sizes per country. The orange lines are the individual exponential fits with parameters given in the box in the lower left corner of each plot

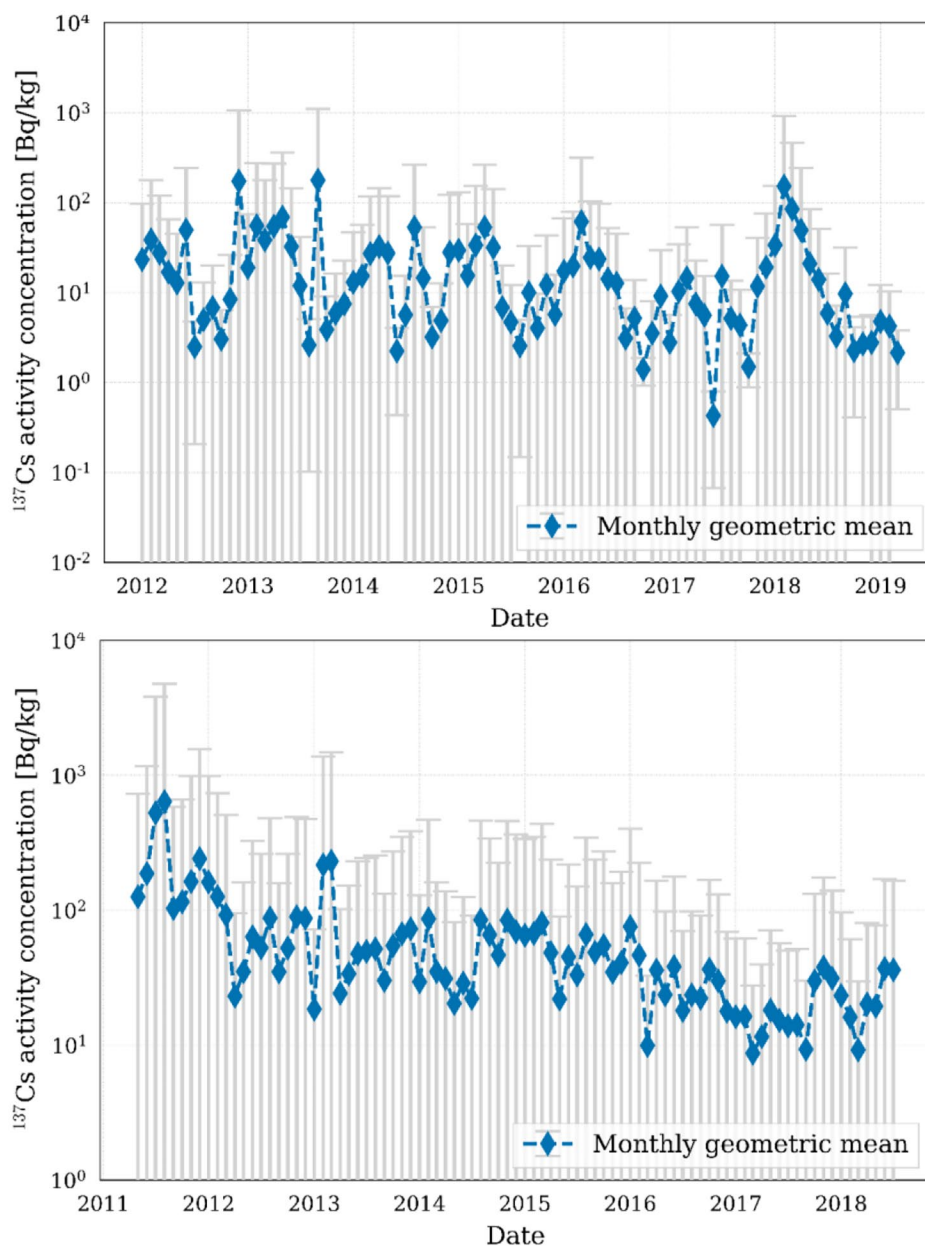


## Conclusion

Radiocesium contaminations in wild boars in Germany and Japan are in line with radionuclide depositions after nuclear accidents. A decline in activity is clearly visible in Japan, while in Germany, activity concentration levels remain rather constant even many years after the Chernobyl nuclear

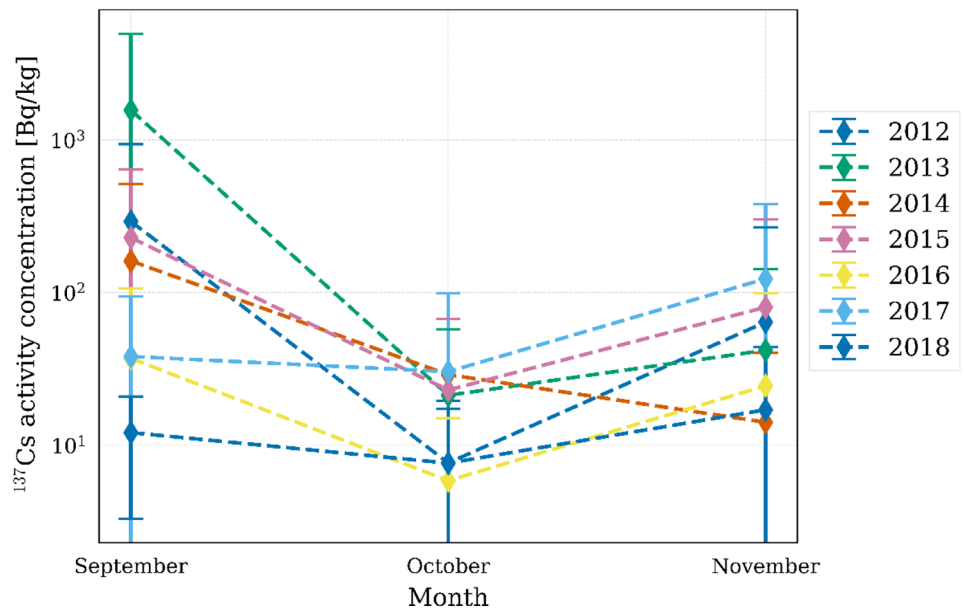
accident. These unique decline dynamics could be caused by a fungus in the wild boars' diet, the radiocesium accumulating deer truffle. In Germany, the contamination shows a distinct dependency on seasons, with generally lower activity concentrations in summer and autumn, indicating a notable influence of seasonally available food sources on contamination. Greater availability of tree seeds in mast

**Fig. 5** Seasonal variation of  $^{137}\text{Cs}$  contamination in wild boars in Germany (top) and Japan (bottom). The geometric mean for each month of the sampling period is plotted at the respective month's start date. Error bars represent the geometric standard error. Due to the y-axis being logarithmically scaled, most of the lower bounds are not visible. Dashed lines only guide the eye and have no further implication



years is noticeable in lower activity concentration levels in the month of October but no level of statistical significance was reached for these effects.

**Fig. 6** Arithmetic means of contaminations of German wild boar meat of September, October and November for each year. Error bars represent the standard error; dashed lines are only meant to guide the eye



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