Activity of caesium deposited on the territories and associated ambient dose rates following the Fukushima Daiichi accident

The evolution of the activity of radiocaesiums[1] deposited on the territories (Bq/m^2) and of the resulting dose rates in the air (μSv/h), are decisive elements in guiding post-accident strategies regarding the management of populations (in particular their return) and decontamination. The evolution of the radiological situation since 2011 has been characterised by multiple campaigns and associated measurement actions, the results of which can be consulted on the Japanese Nuclear Regulation Authority website[2].

The different types of measurement

Airborne measurements

Ten airborne and/or helicopter-borne campaigns were carried out between April 2011 and September 2015. These campaigns enabled the obtention, at close intervals, of mappings of the estimated dose rate at ground level (at 1 m) as well as an associated estimation of the residual radiocaesium activity. These campaigns, the results of which are reproduced in figure 1 within an 80 km radius of the site, named A1 to A10, show an overall decrease in dose rates which, for the most part, is the result of the radioactive decay of caesium-134. These mappings are pertinent as they provide an overall picture of contamination and ambient radiation across all of the territory affected by radioactive fallout, including zones that are relatively difficult to access such as forests, which are predominantly found in this region (covering almost 75% of the surface area) or hilly areas. The estimations of dose rates and ground activity can nevertheless be accompanied by a quite significant degree of imprecision, due to the approximations required in order to interpret a measurement carried out at altitude[3]. These estimations can also have shortcomings due to their lack of spatial resolution, the flight paths being relatively spaced out (around 2 km for campaigns A1 to A6, then < 1 km in the most contaminated areas from campaign A7 onwards), and the fact that a measurement produced at altitude has a tendency to smooth out any heterogeneity on the ground (within a diameter of between 300 to 600 m for these campaigns). Airborne means still remain a key element of the measurement programme to be deployed in a post-accident situation, and essential for the establishment of zoning of the radioprotection management of populations.

High-resolution airborne campaigns have been carried out in the vicinity of the damaged site since 2013 with the help of a drone flying at low altitude. The use of this device made it possible to

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[1] These radiocaesiums are caesium-134 and caesium-137.

[2] http://radioactivity.nsr.go.jp/en/

[3] The conversion of the signal measured at altitude into dose rates and estimated activity on the ground depends on simplifying hypotheses that are only rarely borne out in Fukushima: absence of aerial contamination during the flight campaigns, absence of relief and dense plant cover (i.e. forest) in the regions flown over, absence of snow cover, homogeneity of deposits and of their penetration depth into the soil, etc.

obtain maps with a higher spatial resolution (80 m) revealing contamination lobes that the traditional airborne device had been unable to detect (figure 2).

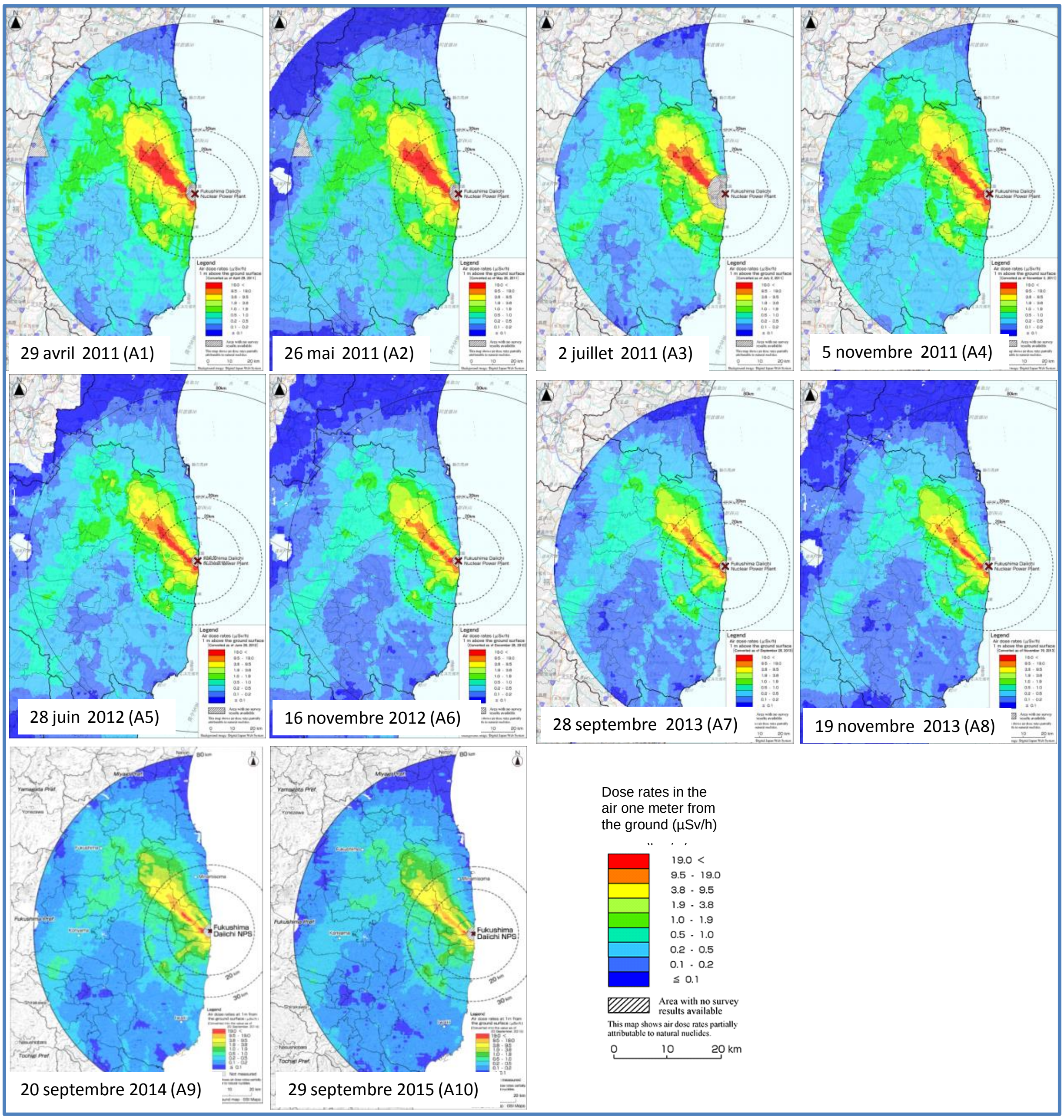

Figure 1: Mappings of dose rates in the air one meter from the ground (µSv/h) established from airborne measurements (campaigns A1 to A10). The spatial resolution of the airborne measurements has been refined in the most contaminated zones (dose rates > 0.2 µSv/h) since summer 2013 (campaigns A7 to A10).

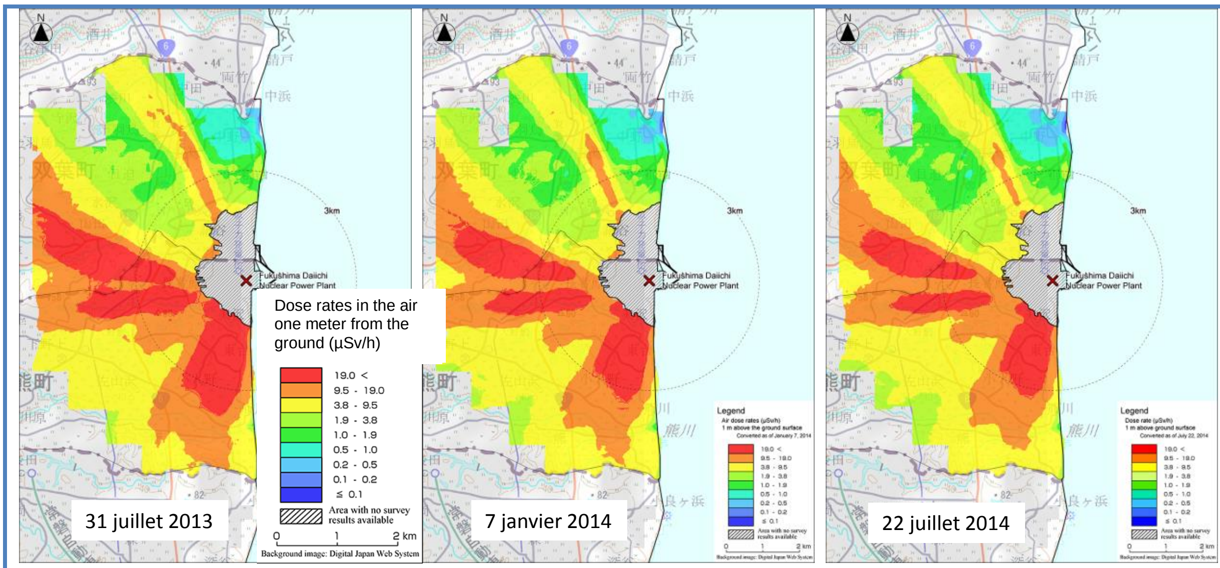

Figure 2: Mappings of dose rates in the field close to the Fukushima site carried out using a drone, between July 2013 and July 2014.

<u>Road network measurements</u>

The Japan Atomic Energy Agency (JAEA) has carried out measurement campaigns along the road networks on a regular basis since June 2011. As with the previous campaigns, these enable the obtention of mappings of the dose rate measured at 1 m from the ground using a detector loaded onto the vehicles, covering large areas in a short time. They also therefore provide essential information for the spatial characterisation and monitoring over time of the contaminated territories, which complements airborne means. Due to the contribution of the road surface in the radiation measured, these measurements may however not reflect the radiological atmosphere encountered in environments next to the road network. In theory, this skew is even more significant when measurements are carried out late after the accident since, as a general rule, the decontamination of roads takes place more quickly than that of natural ground surfaces (as a result of leaching by the rain in particular). The conversion of the dose rates measured into surface radiocaesium activity in surrounding environments is therefore somewhat risky. Moreover, the Japanese have not undertaken this exercise. During the road campaigns the JAEA also proceeded to carry out, but only on an occasional basis, measurements of dose rates on neighbouring soil plots left unoccupied since the accident. These measurements clearly demonstrated that irradiation levels increased the further they were from the road.

Measurements *in situ*

Dose rate measurements carried out with the help of static or mobile detectors, placed 1 m from the ground, certainly provide the most pertinent results on a small spatial scale, typically that of a plot of land. The Japanese authorities have organised three major campaigns of this kind, focussing on inhabited zones within an 80 km radius of the damaged site. In order to improve the representativeness of the measurements, they were carried out solely on large soil plots, with little slope, and with little vegetation (public parks, school yards, etc.). The knowledge about dose rates acquired during the first campaign in June 2011 was considerably refined during the third campaign in December 2012, where the number of dose rate measurements was increased to 6,100 sites compared to 2,200 for the first (figure 3a). These dose rate measurements enable a reasonably reliable estimation of radiocaesium activity in the soils, thanks to knowledge about the characteristic vertical migration depth of these radionuclides. Specific analyses were carried out for this purpose during winter 2012 through soil samples on 85 sites. They showed that the radiocaesiums had migrated little depth-wise and remained on average confined to the top 3 centimetres of soil. The mapping of the resulting radiocaesium activity is reproduced in figure 3b.

The main limitation of the maps obtained in this way is that they do not necessarily reflect the situation encountered in types of environment other than those investigated, such as agricultural and forest land or man-made surfaces.

For agricultural areas, the relation between the dose rate at 1 m and the activity measured in soil samples was the subject of a specific study conducted between October 2011 and January 2012, and which was published in 2014. This study, which was carried out on 3,500 agricultural plots, showed that the estimation of radiocaesium activity using ambient dose rates could be refined if the soil and crop types encountered were taken into account (paddy fields, pasture, orchards and other crops). The utilisation of these results, together with the map of dose rates from the fourth airborne campaign (November 2011), enabled the obtention of a first mapping of radiocaesium deposits on agricultural land.

Massic activity measurements in soils

During the first campaign (June 2011), five soil samples were taken from a square of 9 m^2 for each site, with a view to measuring massic activity (Bq/kg). These samples revealed a significant variability between samples, linked to the natural heterogeneity of the initial deposits and potential horizontal redistribution via micro-runoff, hence the difficulty in reconstituting surface activity (Bq/m^2) at plot level. Moreover, the correlation between the dose rate measured and estimated mean massic activity for each site proved to be fairly average. The Japanese have not carried out any more campaigns of this type, except for the campaign on agricultural plots presented earlier.

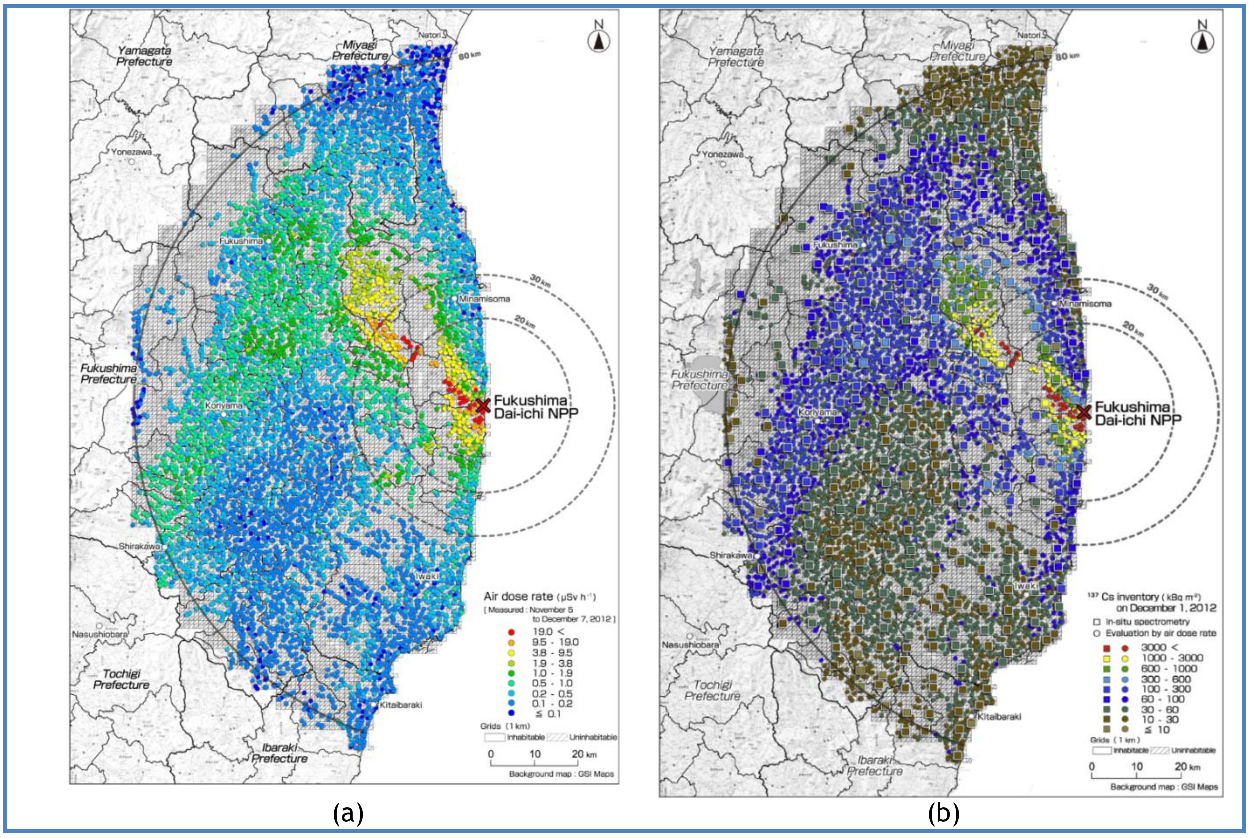

Figure 3: Mapping: (a) dose rates in the air (μSv/h) and (b) surface activity (Bq/m^2) in caesium-137 in inhabited zones on undisturbed soil plots (December 2012 campaign).
Activities are distinguished according to whether they were estimated from dose rate measurements via gamma spectrometry in situ (400 stations) or portable NaI probe (6,100 stations).

Spatial comparison of the different dose rate mappings

The dose rate mappings established at the end of 2012 are reproduced in figure 4 for each of the methods deployed by the Japanese. This comparison makes it possible to confirm that, despite metrological specificities and uncertainties, there is a relatively good overall coherence between the predictions, at least in the scale range over 10 kilometres. These maps essentially differ by way of the extent of their spatial cover. The road campaigns and, to a lesser extent, the ground campaigns in inhabited zones, only provide a small amount of information on the Abukuma forest massif, located to the west of the damaged site, as well as the volcanic range located to the extreme west of the area studied. Nevertheless, a more careful comparison makes it possible to observe that the dose rates estimated along the roads are, in general, lower than those estimated by the other methods, notably on bare soils in inhabited zones where the difference is around 50%. In addition, an IRSN study showed very significant local differences between airborne measurements and measurements on bare soils (up to factor 3). At the level of highly-urbanised regions, such as the Abukuma valley that shelters the towns of Fukushima and Koriyama, dose rates estimated by airborne methods from October 2011 onwards proved much lower than those measured *in situ* on soil plots. This most likely results from an accelerated decontamination of urban surfaces compared to soils, due to the combined action of natural leaching by rain and a progressive rehabilitation of the urban environment during the weeks or months following the accident. Conversely, higher levels of activity than on bare soils were revealed to the south of the Abukuma massif, predominantly covered by conifer forests. These anomalies were interpreted as being dry deposit zones since, in the absence of rainfall, forest canopies capture airborne contamination more effectively than a neighbouring plot of bare soil.

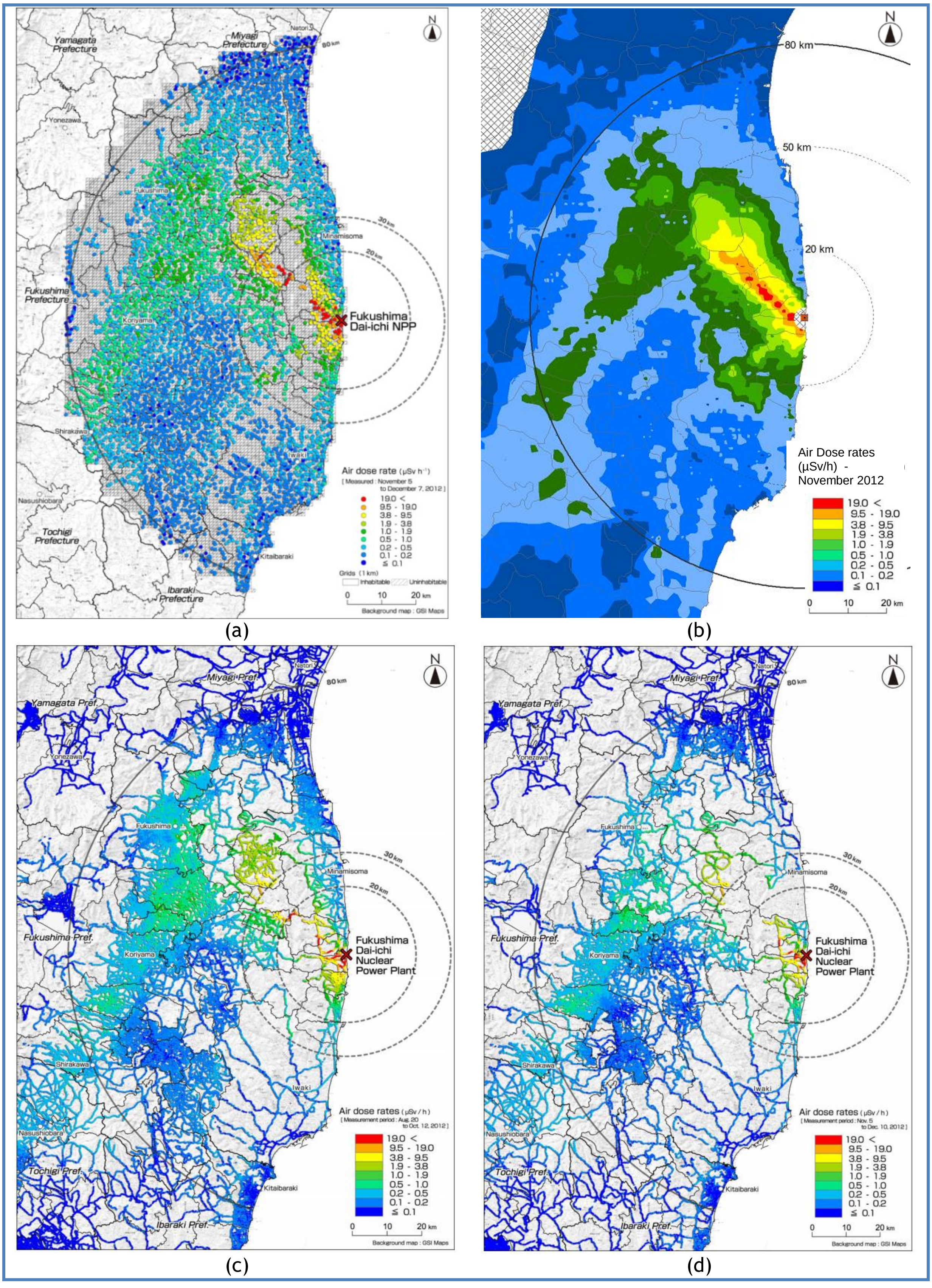

Figure 4: Mappings of dose rates (μSv/h) measured or estimated at 1 m from the ground: according to (a) the campaign on soil plots in inhabited zones in December 2012, (b) the November 2012 airborne campaign, (c,d) the road campaigns of September and November 2012 respectively.

Evolution over time of dose rates and activity of deposited caesium

As figure 5 illustrates, all of the measurement campaigns - irrespective of the method used - indicate that the dose rate in the air decreased by an average of factor 2 to 3 between mid-2011 and end-2013 in the 80 km around the damaged plant. This decrease was relatively sustained during the first two years, and took place at a quicker pace than expected through the radioactive decay of caesium-134 (period of two years) - the radioactive decay of caesium-137 (30 years) being almost insignificant over this period. This decay has slowed since 2013, more or less complying with the expected theoretical evolution.

In the case of airborne measurements, the decrease was in the region of 40% between November 2011 and November 2012, only half of which is explained by radioactive decay. Numerous natural or anthropogenic mechanisms have been put forward in order to explain this decrease, such as the effect of leaching by rain, migration into the soil, the effect of ploughing and decontamination measures. The contribution made by these processes is most certainly significant in urban and agricultural environments. Nonetheless, none of these mechanisms make it possible to explain the fall in dose rates at forest surface level, which do however cover almost 70% of the territory. An IRSN study has demonstrated that the progressive decontamination of coniferous canopies could noticeably modify the signal measured at altitude, notably due to the screening effect applied by the vegetation to radiation emitted at ground level. To find out more about the forest environment, see the specific information sheet.

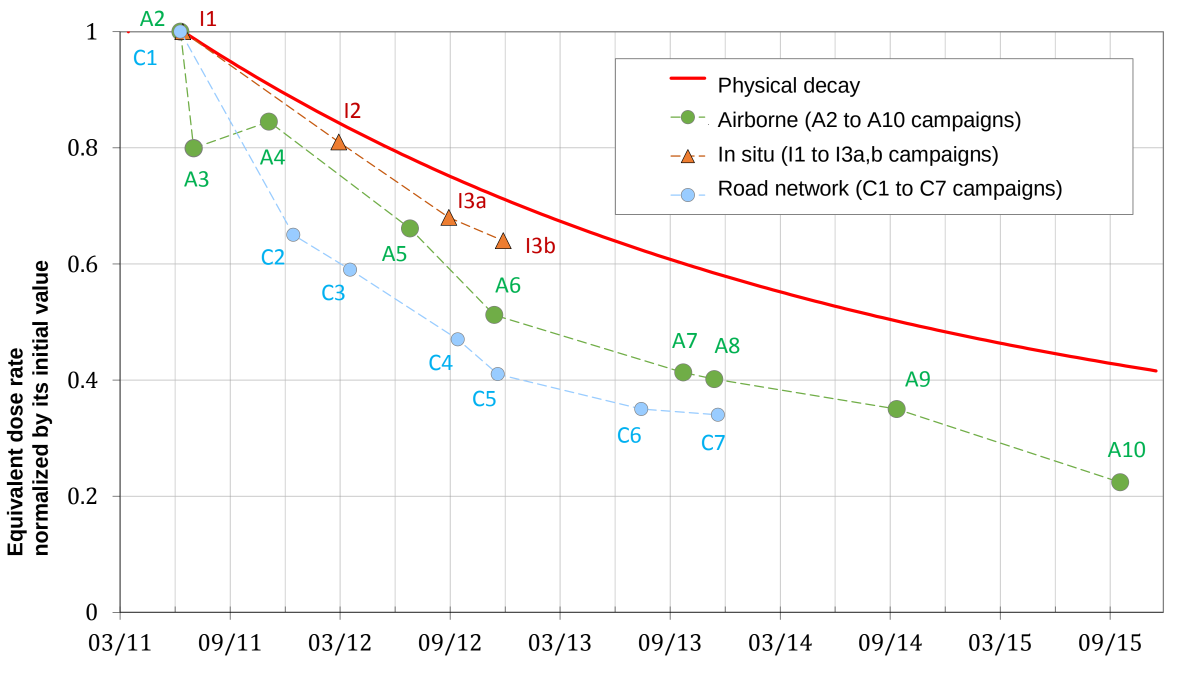

Figure 5 - Evolution over time of dose rates measured by all of the methods deployed and expected evolution through the physical decay of the caesium. The values represented are average values within an 80 m radius from campaigns A2 to A10, standardised by the initial level observed in June/July 2011 (campaign A1 in figure 1). The negative anomaly observed for the airborne campaign A3 is the result of detector calibration problems.

The accelerated decrease in dose rates observed along the road network very probably results from increased decontamination of asphalt surfaces through leaching by rain and road traffic. With the first road campaign only having been conducted in June 2011, there is every reason to believe that this decrease had already begun during the first three months following the accident.