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Measuring the radiation exposure of Norwegian reindeer under field conditions

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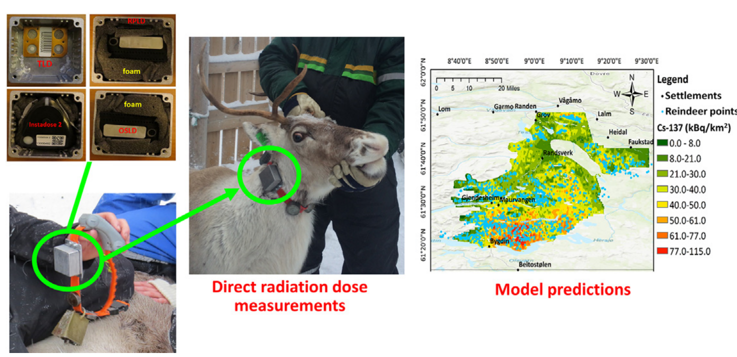
HIGHLIGHTS

- Common radiological environmental assessment models have not been fully validated.
- Dosimeters and GPS units were attached to reindeer at a site contaminated by ^{137}Cs.
- Direct dosimetry measurements were compared to different model predictions.
- Exposure from natural radionuclides and cosmic radiation demonstrated.
- Commonly used assumptions may underestimate the exposure of animals to radiation.

GRAPHICAL ABSTRACT



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ABSTRACT

Models and approaches have been developed to predict radiation exposure of wildlife under field conditions. However, there have been few attempts to directly measure radiation exposure of wildlife in the field and confirm the doses predicted by models. This is a potential issue for stakeholder acceptance of modelling-based assessments. Here is presented a comprehensive study comparing the results of different dosimeters fitted to free-ranging reindeer inhabiting an area that received comparatively high radiocaesium deposition from the 1986 Chernobyl accident. The external dose of reindeer was measured using the four dosimeter types in aluminium box mounted on the GPS collar. The measurements were compared with two model predictions: (i) external dose to reindeer across the entire range area of the herd; and (ii) external doses of individual reindeer predicted using GPS tracking data to determine locations. It was found that although significant differences between the estimates of the various dosimeters were found these were small with no practical implication. Also, the mean predicted external doses using the GPS tracking data were not significantly different to estimates from two of the four passive dosimeter results. The average external dose predicted across the herd area was significantly lower than doses

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Passive dosimeter
Large mammal

recorded by the dosimeters and also estimates using GPS data to determine reindeer location (and hence exposure). For ^{137}Cs the average external dose from the GPS tracking data was about twice that predicted across the herd area, because collared animals favoured the more contaminated area of the study site. This suggests that in some circumstances the assumption of averaging contamination over an assumed home range within assessments may be inadequate though this would need to be balanced against other uncertainties. Natural radiation was the greatest contribution to reindeer exposure and a function of the high altitude.

1. Introduction

Several models and approaches have been developed to predict radiation exposure of wildlife for regulatory assessments(e.g. Johansen et al., 2012; Stark et al., 2015; Vives i Batlle et al., 2011; Vives i Batlle et al., 2016; Yankovich et al., 2010). Direct dosimetry measurements using dosimeters attached to wildlife in the field could be used to validate model predictions of external gamma dose rates. However, there have been few attempts to validate model predictions in this way (Beresford et al., 2008c), even though such validation would likely improve stakeholder confidence in modelling-based assessments. Various dosimetry measurement technologies have the potential to be used in wildlife studies (Aramrun et al., 2018), but deployment methodologies (e.g. collar mounting for large mammals) and dosimeter performances need to be tested under field conditions.

Norway was one of the European countries most affected by radioactive contamination from the 1986 Chernobyl accident. Reindeer (*Rangifer tarandus tarandus*) populations in central Norway have continuing high levels of caesium-137 (^{137}Cs) in their tissues (Jakobsen, 2014). However, despite studies on potential biological effects of the fallout on reindeer (e.g. Røed and Jacobsen, 1995), a total dose estimate for the species including external exposure measurements has never been made. Gamma radiation from ^{137}Cs, natural radionuclides (e.g. potassium-40 (^{40}K)) and cosmic radiation are likely to be the main contributors of external doses to reindeer in Norway.

The ERICA (Environment Risk from Ionising Contaminants-Assessment and Management) Tool is a computerised model for estimating the exposure of wildlife to ionising radiation (e.g. Brown et al., 2016; Brown et al., 2008). It is now widely used for predicting radiation exposure of wildlife for different releases, sources, and various exposure situations (Brown et al., 2016; Černe et al., 2012; Kubota et al., 2015). The ERICA concept for calculating dose to wildlife can be divided into two steps: (i) calculation of activity concentrations in organisms (if not known) from environmental media (i.e. transfer) and (ii) estimation of the dose rate, both internal and external, to organisms (i.e. dosimetry) (Brown et al., 2008). To give confidence in regulatory assessments, predictions of absorbed dose rates of wildlife using the ERICA Tool (and other assessment models) need to be validated by direct measurement in field studies. Whilst comparison of predicted and measured organism activity concentrations (and hence internal dose) have been conducted for a number of sites (Beresford et al., 2008c; Stark et al., 2015; Yankovich et al., 2010) to date it has only been conducted for rodents in a study within the Chernobyl Exclusion Zone (Beresford et al., 2010; Beresford et al., 2008c).

Simple assumptions are generally made regarding animal movement in radiological assessments. For instance, mean activity concentrations over an assumed home range may be used to estimate external (and internal) doses (e.g. Beresford et al., 2005). There is a need to test if this assumption is fit for purpose within regulatory assessments. To best test the assumption, it would be useful to have animals fitted with Global Positioning System (GPS) tracking units and dosimeters, together with data on radionuclide (anthropogenic and natural) contamination surfaces and any other radiation types (e.g. cosmogenic) for the study area.

In this paper, we describe a study conducted to measure the external absorbed doses of reindeer from a herd in Oppland county (Norway) using four types of passive dosimeters (thermoluminescent dosimeter (TLD), optical stimulated luminescent dosimeter (OSLD), radiophotoluminescent dosimeter (RPLD) and direct ion storage (DIS) dosimeter). We estimate total external absorbed doses of the reindeer using these four different dosimeter types and compare to absorbed doses calculated using the ERICA Tool. The hypotheses tested in this study were (i) that the commonly used approach to estimate the external dose rate of wild animals is fit for purpose and (ii) that natural radiation could be an important component of radiation exposure.

2. Material and method

2.1. Study site

The study site was in Vågå, Oppland County in south central Norway (61°40′0″ North, 9°0′0″ East and average altitude is 1.127 ± 0.309 km); the site is part of a reindeer monitoring project (Skuterud et al., 2016). Oppland county is one of the areas of Norway with comparatively high levels of ^{137}Cs in soil as a consequence of deposition from the 1986 Chernobyl accident (Backe et al., 1986). The study area is grazed by a herd of semi-domesticated reindeer, owned by a non-Sami reindeer company; the herd ranges over an area of approximately 1360 km^2 (Skuterud et al., 2005; Skuterud et al., 2016). The ^{137}Cs deposition over approximately 50% of the study area was >15 kBq m^{-2} in June 2011; maximum deposition of up to 70 kBq m^{-2} occurred over an area of approximately 100 km^2 (Baranwal et al., 2011). The Norwegian Radiation and Nuclear Safety Authority (DSA) has been following fifteen Vågå reindeer using collars fitted with Global Positioning System (GPS) units (Telespor AS, Tromsø, Norway). These GPS units report online via the mobile phone network. The movements of the herd are used, together with an aerial survey of the ^{137}Cs deposition in the area, to estimate ^{137}Cs activity concentrations in plants and lichens in the areas grazed (Skuterud et al., 2016)

Monthly average temperatures recorded at a weather station located at the eastern edge of the study area range from approximately −14 °C to 12 °C with minimum and maximum daily temperatures of -40 °C to 25 °C. Monthly precipitation ranges from 0 to 77 mm.

2.2. Dosimeters for external dose measurement of reindeer

Four types of dosimeters were chosen for this study based on our earlier assessment of potential dosimeters for field application (Aramrun et al., 2018): thermoluminescent dosimeter (TLD) (LiF:Mg, Cu,P; standard Harshaw™ type, (Gilvin et al., 2007) generally used for personal monitoring and supplied by Public Health England (PHE), Oxford, UK); optical stimulated luminescent dosimeter (OSLD) (Al_2O_3:C; Nagase Laddauer, Ibaraki, Japan); radiophotoluminescent dosimeter (RPLD) in waterproof plastic capsules (GD-352 M; AGC Techno Glass Corporation, Shizuoka, Japan); direct ion storage (DIS) dosimeter (Instadose+; Mirion Technologies, California, USA).

The dosimeters would have to contend with extreme weather (e.g. snow, rain and low temperatures) and reindeer behavior. Furthermore, for external dose rates we do not want them to record beta radiation (see Beresford et al. (2008c)). An aluminium box (IP68 Deltron, 480 Series Diecast Aluminium Boxes) was chosen to house the four dosimeters because it was durable, waterproof and should provide shielding from beta radiation. The four dosimeters were mounted securely within each box in a consistent geometric relationship (Aramrun, 2018). All dosimeter types in the aluminium box were calibrated with ^{137}Cs, ^{60}Co and ^{226}Ra sources to confirm the linearity of energy responses (over the range of doses anticipated in the field over the 11 month study period using data on ^{137}Cs depositions and natural radionuclide activity concentrations (Baranwal et al., 2011)), angular dependence and flat energy response between ^{137}Cs and ^{60}Co. Tests were conducted using Public Health England (PHE) calibration facilities (https://www.phe-protectionservices.org.uk/pds/). These assessments were conducted with the dosimeter box mounted on a collar as would be used in the subsequent field studies (see Section 2.3). The contribution to the dosimeters of ^{137}Cs incorporated in the deer's body was also assessed by mounting the collar-dosimeter box on a cylindrical phantom containing gel with homogenously dispersed ^{137}Cs (Aramrun, 2018). The phantom was made of 6 mm thick high-density polyethylene (HDPE), and its dimensions are 150 mm diameter, 40 cm long, with a fill cap in the middle. It was determined that the contribution of internally incorporated ^{137}Cs to the recorded dose rate was 0.028 nGy h^{-1} per Bq kg^{-1}.

TLDs, OSLDs and RPLDs recorded accumulated external dose over the study period. The Instadose+ DIS dosimeters were set to record and store doses over 4 h 48-min periods (i.e. five measurement periods each day) by the manufacturer (Mirion Technologies). The dose measurements recorded by the Instadose+ were stored by the unit. The DIS unit also recorded total doses over the complete period of the deployment.

The individual components of the dosimeter box were transported from the UK, and the boxes assembled on arrival in Norway. The dosimeters were carried in hand luggage and declared at airport security checkpoints so that they were not passed through X-ray machines. Three sets of dosimeters were used as controls to measure transit doses between the UK and the Norwegian field site. Three control dosimeter boxes were stored in a lead shielded room at DSA. When the animals were regathered, the dosimeters were recovered and removed from the boxes before transporting back to the UK. During transport back to the UK, dosimeters were again declared at the airport security check points to avoid them being X-rayed. The transit doses were subsequently subtracted from results of the dosimeters attached to the reindeer.

2.3. Mounting the dosimeter box on the reindeer GPS collar

The reindeer collars used were standard livestock collars (OS ID, Oslo, Norway) (Fig. 1) already fitted to the reindeer to mount the GPS units. The collar had a total mass of 490 g which comprised the collar itself, a GPS unit and counterweights. It was essential to ensure that the mounting of dosimeter boxes on the GPS collars would not significantly affect the balance of the collar and therefore the daily life of the reindeer. The dosimeter box was fitted onto the side of the collar opposite to the buckle (Fig. 1); mounting at this point minimised deformation of the collar curvature as this is the flattest part of the reindeer neck. The total mass of the dosimeter box was approximately 150 g.

2.4. Field application of the dosimeters

The herd, approximately 2000 animals, was gathered in January 2016 so that some reindeer could be slaughtered for human consumption. Fifteen reindeer already had GPS collars and these reindeer are routinely measured to determine ^{137}Cs activity concentration using a NaI live-monitor (Skuterud, 2012). When a collar was removed from a reindeer for battery replacement, the dosimeter box was mounted on it before the collar was refitted to the restrained reindeer. Fitting time was 3–4 min, thus minimizing any additional stress caused to the reindeer due to this procedure. A video of this process is available at https://youtu.be/gyW7ty_Zxns.

Dosimeter boxes were recovered when the animals were regathered in December 2016 when the animals were again live-monitored. The dosimeters were removed from the boxes for transport back to the UK. For analysis, TLDs were sent to Public Health England (UK); OSLDs to the Thailand Institute of Nuclear Technology; RPLDs to the Ruđer Bošković Institute (Croatia); and Instadose+ to Mirion Technologies.

2.5. Prediction of average external absorbed dose for the reindeer herd

For the purposes of estimating external dose rates a ‘herd area’ was defined, this was the 1360 km^2 bounded by the known grazing area of the reindeer as described in Section 2.1. The average ^{137}Cs deposition (i.e. 22,037 Bq m^{-2} ± 19,964), potassium (K) in % by weight (i.e. 1.14% ±0.47), uranium (U) and thorium (Th) in ppm concentrations (i.e. U = 0.481 ppm ± 0.362 and Th = 1.838 ppm ± 1.485) over the herd area were calculated using GIS software package (ARCGIS Version 10.3) from data presented by Baranwal et al. (2011). Baranwal et al. (2011) data originate from an airborne gamma survey; the aerial survey recorded five measurements per second resulting in a data spacing of about 6 m. The calculated data was then converted to average activity concentrations in Bq kg^{-1} for ^{137}Cs assuming a soil depth of 6 cm and a soil density at 1600 kg m^3 for ^{137}Cs. To estimate soil activity concentrations of ^{40}K ^{238}U and ^{232}Th, specific activities of ^{40}K, ^{232}Th and ^{238}U of 31.6 Bq g^{-1} K, 4.07 Bq mg^{-1} Th and 12.21 Bq mg^{-1} U, respectively were used (Beresford et al., 2008b). The activity concentrations of ^{238}U, ^{232}Th and ^{40}K were required to estimate the external absorbed dose of reindeer from natural radionuclides in soil. The estimated average activity concentrations in soil and their standard deviations for each radionuclide were input into Tier 2 of the ERICA Tool (Brown et al., 2016) using the tools ‘mammal - large’ geometry (which represents a deer) to predict external absorbed dose rates of the reindeer herd assuming the herd roamed equally everywhere over the study site. Uranium-238 and ^{232}Th series radionuclides with physical half-lives greater than ten days were assumed to be in equilibrium with the series parent (e.g. ^{226}Ra was assumed to have the same soil activity concentration as ^{238}U); daughter radionuclides with a half-life of less than ten days are included in their immediate parents dose conversion coefficient in the ERICA Tool (Brown et al., 2008). The total mean external absorbed dose of the reindeer herd from ^{137}Cs and natural radionuclides was estimated over a period of 11 months (the length of time over which the dosimeters were deployed).

For the cosmic radiation contribution to the dose recorded by the dosimeters, to estimate mean annual absorbed dose of the reindeer herd due to cosmic radiation (Cinelli et al., 2017) ($\dot{\boldsymbol{E}}_{\mathbf{1}}(\boldsymbol{z})$):

$$\dot{\boldsymbol{E}}_{\mathbf{1}}(\boldsymbol{z}) = \dot{\boldsymbol{E}}_{\mathbf{1}}(\mathbf{0})\left[\mathbf{0.21}\boldsymbol{e}^{-\mathbf{1.649}}\boldsymbol{z} + \mathbf{0.79}\boldsymbol{e}^{\mathbf{0.4528}}\boldsymbol{z}\right] \tag{1}$$

where z is the altitude in km; $\dot{E}_1(0)$ is annual dose at sea level, 240 μGy (converted from Sv to Gy assuming a weighting factor of 1). For input into Eq. (1), the mean altitude (1130 ± 309 m) over the study site was calculated using a GIS and data from the U.S. Geological Survey (USGS) (https://earthexplorer.usgs.gov/). The calculated absorbed doses from cosmic radiation were corrected from an annual dose to an 11-month dose and included in the total predicted external doses of the reindeer.

2.6. Estimation of average external absorbed dose of individual reindeer using GPS tracking data

The GPS tracking data of the reindeer between 11th January 2016 and 11th December 2016 were input to a GIS to estimate the time weighted mean ^{137}Cs activity deposition and ^{40}K, ^{238}U and ^{232}Th (using spatial interpolated data on radionuclide activity concentrations calculated from Baranwal et al. (2011)) concentrations in soil for each individual collared reindeer. These activity concentrations were then used to estimate the average external absorbed doses of individual reindeer by applying the external beta-gamma dose conversion coefficients for the mammal - large geometry extracted from the ERICA Tool. Cosmic radiation exposures at ground level of individual reindeer were also estimated using the GPS tracking data and Equation1; the mean altitude estimated for each reindeer was used in this calculation.

2.7. Statistical analyses

The mean external absorbed doses of collared reindeer by direct dosimeter measurements and model prediction were compared using a repeated one-way ANOVA in SPSS v23. Prior to analysis, the normality of the data was tested with Kolmogorov-Smirnov tests. One-trial *t*-tests were conducted to compare between the mean external dose of the reindeer herd as estimated by ERICA and the mean external doses of reindeer as estimated using the GPS tracking data. The mean external dose of the reindeer herd using ERICA was also compare with the mean external doses of reindeer as estimated using OSLDs, RPLDs and DIS dosimeters using one-simple t-test. Where appropriate data for the three reindeer for which DIS (Instadose+) data were not available (i.e. Sigrid Mathilda, Rinda and Guri) were removed prior to statistical analysis. All error values presented are standard deviations (SD).

3. Results

3.1. Physical condition of dosimeters after collection

In December 2016, 12 of the 15 fitted dosimeter boxes were recovered. Two reindeer that had been fitted with dosimeters were within the gathered group, but had lost their collars. The remaining collared reindeer was not within the herd that was gathered in December 2016. The recovered dosimeters were all in good physical condition and there was no water or dust ingress into the boxes. There was no evidence that the fitting of the dosimeter box affected the shape or balance of the collar.

3.2. External absorbed doses measured in the field

The estimated external absorbed doses of the twelve reindeer from the four different dosimeters are shown in Table 1. The external absorbed dose (Gy) was assumed to be the same as the dose equivalent for the whole body as reported for the dosimeters (in Sv); this was justified on the basis of the conversion coefficient of ^{137}Cs at 45° (i.e. the angle between the dosimeter box and radiation source under laboratory conditions) from personal dose equivalent *H*p (10) (Sv) to air kerma (Gy) as described by Aramrun (2018) and from air kerma to average external absorbed dose as described by Ulanovsky (2014).

Table 1
Estimated external absorbed doses for Norwegian reindeer over 11 months using different dosimeter types (note the dosimeter results presented have been corrected for transit dose and the contribution of internally incorporated ^{137}Cs).

Number	Reindeer name	TLD (μGy)	OSL (μGy)	RPLD (μGy)	DIS (μGy)	Mean	SD	%CV
1	Linn	760	820	600	651	708	100	14.2%
2	Ragnhild	735	825	615	625	700	99	14.2%
3	Trinerein	707	717	607	567	650	74	11.4%
4	Prikka	666	546	556	536	576	61	10.5%
5	Sigrid Mathilda	685	595	715	n/a	665[a]	62[a]	9.4%[a]
6	Rinda	620	630	480	n/a	576[a]	84[a]	14.6%[a]
7	Krone	710	670	580	530	622	82	13.2%
8	Guri	798	798	618	n/a	738[a]	104[a]	14.1%[a]
9	Frigg	736	816	686	716	739	56	7.5%
10	Martine EK	713	723	593	733	690	66	9.5%
11	Kari	726	806	716	740	747	41	5.4%
12	Torild	671	651	641	611	643	25	3.9%

n/a – not available.
[a] For these animals, summary values were calculated from TLD, OSLD and RPLD only.

The accumulated doses recorded across all dosimeter types ranged from 480 to 825 μGy (Table 1). The contribution to the dose recorded by the dosimeters due to internal ^{137}Cs activity concentrations in the reindeer, as estimated by live-monitoring (430–880 Bq kg^{-1}), was estimated to range from 100 to 200 μGy with a mean and standard deviation (SD) of 160 ± 27 μGy. Values presented in Table 1 are corrected for contributions from the transit dose of each dosimeter types (270–390 ± 70 μGy) and internally incorporated ^{137}Cs to give the absorbed doses to the reindeer (or dosimeters) from external sources only.

For individual reindeer, the maximum difference between the estimates using different dosimeters was a factor of 1.3 with a coefficient of variation for the four dosimeter measurements of <15%.

For the Instadose+, data were only available for nine reindeer as three of the units failed. For all nine-remaining units, the batteries expired before the Instadose+ were collected and hence a full-time series of data was not recorded. It is likely that the batteries expired due to the cold weather. However, it was still possible to recover a total integrated dose from the nine dosimeters as this is recorded by the Instadose units without the requirement for a battery (presented in Table 1).

3.3. Mean predicted external absorbed dose for the reindeer herd

The total estimated mean external absorbed dose of the reindeer herd based on these radionuclides and cosmic radiation was 471 ± 104 μGy (Table 2). The mean total external absorbed doses of the reindeer over 11 months from the ^{137}Cs and natural radionuclides in soil was estimated to be 174 ± 96 μGy, with ^{137}Cs contributing most to this. The mean cosmic radiation in the reindeer herd habitat was estimated to be 297 ± 40 μGy that is about 60% of the total absorbed dose; the relatively high contribution of cosmic radiation is due to the altitude above sea level of the site (~1100 m).

3.4. External absorbed doses of individual reindeer estimated using reindeer GPS tracking points

Using the reindeer GPS tracking points to estimate the external dose to each reindeer from ^{137}Cs and natural radionuclide activity concentrations in soil and cosmic radiation, the estimated external absorbed doses of the twelve reindeer over 11 months were between 554 and 601 μGy (Fig. 2). Caesium-137 is the dominate radionuclide in the herd area contributing to absorbed external dose of the reindeer. Collared reindeer mostly stayed in the area with the highest ^{137}Cs activity concentrations in soil (Fig. 3(a)). This resulted in the average external doses (194 ± 11 μGy) of the twelve reindeer from ^{137}Cs activity concentrations in soil being about twice as high as the herd average presented in Table 2. For natural radionuclides (i.e. ^{40}K, ^{238}U and ^{232}Th) in soil (Fig. 3(b)–(d)), ^{40}K was the largest contributor to external dose (50–60 μGy). Estimated external doses of individual reindeer from all-natural radionuclides (between 73 and 83 μGy) considered here were about 12–14% of the total estimated absorbed dose. As for the herd average, cosmic radiation was estimated to be the largest single contributor to external absorbed dose. The mean absorbed dose of the twelve-reindeer estimated from cosmic radiation based on GPS tracks was approximately 340 ± 6 μGy, similar to the cosmic radiation predicted for the average reindeer herd.

Table 2
Predicted mean absorbed doses for the herd over eleven months from external sources.

Radionuclide	External dose over 11 months (μGy)	SD
^{137}Cs	103	93
^{40}K	47	19
^{232}Th	9	6
^{238}U	15	9
Cosmic radiation	297	40
Total mean external absorbed dose	471	104

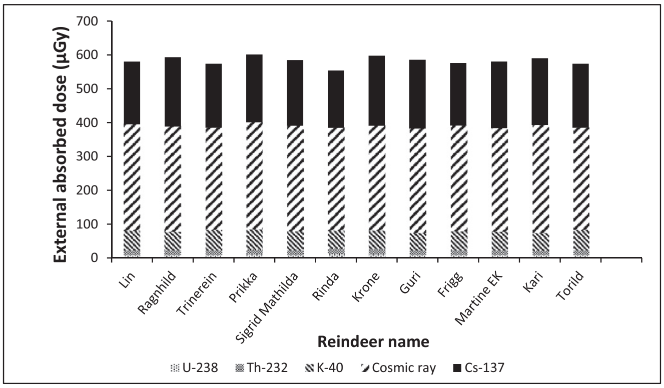

Fig. 2. External doses of twelve Norwegian reindeers over 11 months calculated using the radionuclide activity concentrations in soil, cosmic exposures (estimated from altitude) and GPS tracking data.

3.5. Comparison of model predicted dose and direct dosimeter measurements

Kolmogorov-Smirnov tests showed that the data were normally distributed ($P = 0.20$). Repeated one-way ANOVA indicated significant differences in external dose measured between the different dosimeters and the GPS tracking model ($F_{1,8} = 1985$, $P < 0.001$). Bonferroni-corrected pairwise comparisons indicate that whilst the external dose measured by TLDs did not differ significantly to estimates from OSLDs ($p = 1.00$) and DIS units ($P = 0.10$) it was higher than the external doses measured by RPLDs ($P < 0.05$). The estimated dose from OSLD was significantly higher than doses estimated by RPLD and DIS ($P < 0.05$). The RPLD measurements were not significantly different from DIS measurements ($P = 1.00$). The dose estimated using GPS tracking predictions were not significantly different from the values recorded by RPLDs ($P = 1.00$) and DIS units ($P = 0.86$), but were significantly lower than the external doses measured by TLDs and OSLDs ($P < 0.05$). One-simple *t*-tests showed that the external doses of all dosimeters and the GPS tracking predictions were significantly higher than the average external dose predicted for the reindeer herd ($P < 0.05$).

4. Discussion

External absorbed dose to reindeer in Vågå were measured over 11 months using a variety of dosimeters. This is the first attempt to conduct comparatively long-term dose measurements of large mammals in the field. The method of using an aluminium enclosure to house the passive dosimeters and fitting onto animal collars was successful; the passive dosimeters (i.e. TLDs, OSLDs, and RPLDs) within the aluminium box could record accumulated doses for the collared reindeer under relatively extreme (e.g. cold and snow) field conditions.

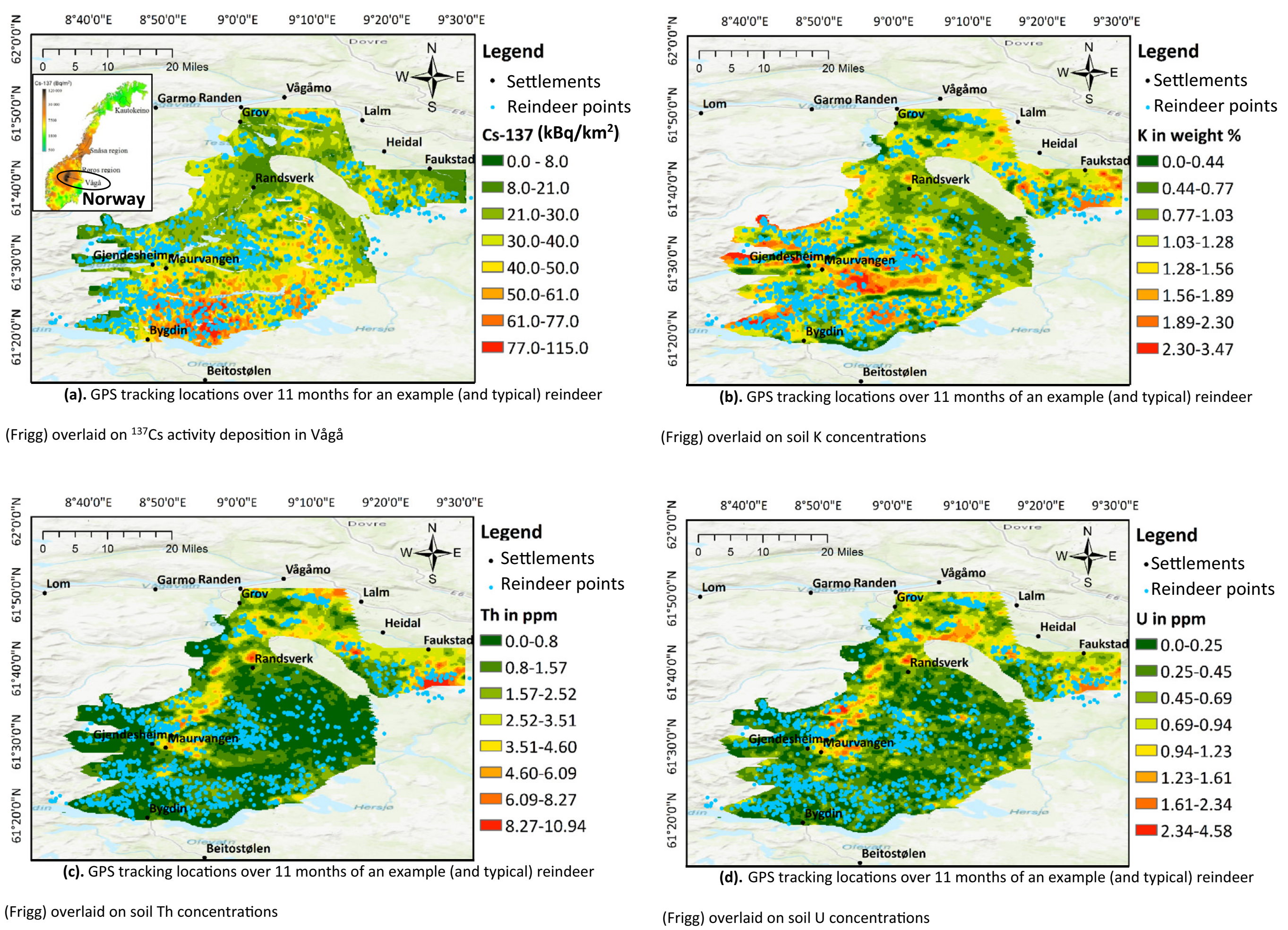

Fig. 3. (a). GPS tracking locations over 11 months for an example (and typical) reindeer (Frigg) overlaid on ^{137}Cs activity deposition in Vågå (sources for the GIS base map: Esri, HERE, Delorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, METI, swisstopo, MapmyIndia, OpenStreetMap contributors and the GIS Use community) (Backe et al., 1986; Skuterud et al., 2016) (b). GPS tracking locations over 11 months for an example (and typical) reindeer (Frigg) overlaid on soil K concentrations (c). GPS tracking locations over 11 months for an example (and typical) reindeer (Frigg) overlaid on soil Th concentrations (d). GPS tracking locations over 11 months for an example (and typical) reindeer (Frigg) overlaid on soil U concentrations.

For an individual reindeer, variation across the four different dosimeters was less than a factor of 1.3 (ratio of highest and lowest estimated doses). Whilst there was a significant difference between the estimates of dosimeters, (i.e. TLDs versus RPLDs; OSLDs versus RPLDs and DIS) the difference of the mean doses between maximum and minimum values was <14% that is trivial compared to other uncertainties in environmental radiological assessments (e.g. Beresford et al., 2008a). Therefore, it is likely that all four dosimeters will give similar results of integrated dose for relatively long-term (i.e. almost a year) dose measurements under field conditions (excluding the issues of extreme cold on the Instadose+ performance). The smaller dosimeters (i.e. TLD, RPLD and OSLD) could also be used with smaller animals providing suitable housing and mounting could be designed (Aramrun et al., 2018). Consideration would need to be given when using the dose conversion coefficient (DCC) for the application of dosimeters to different sized animals. The reported dose would need to be 'corrected' such that they are applicable to the study organism (the external DCC increases as organism size decreases (e.g. see values presented in Vives i Batlle et al., 2007; Vives i Batlle et al., 2011). Ulanovsky (2014) presents relationships that should help in this.

Snow cover of up to 100 cm was present for approximately 4 months during this study (Data from http://www.yr.no/place/Norway/Oppland/Sel/Leirflaten_observation_site/detailed_statistics.html). This will have resulted in attenuation of gamma-emission from radionuclides in soil resulting in lower doses being recorded by the dosimeters over the winter months (Offenbacher and Colbeck, 1991). Therefore, it might be expected that the modelled estimates would overestimate dose, given attenuation from snow was not considered. However, model predictions were similar to or lower than dosimeter estimates.

To compare modelled dose estimates with dosimeter readings we could not simply consider the estimated dose from ^{137}Cs, we also had to consider the contribution of natural background radionuclides and cosmic exposure. Cosmic radiation was the dominant source of exposure for the reindeer, in part, because of the relatively high altitude of the study site. At more highly contaminated sites there may not be a need to consider cosmic radiation or natural radionuclides, because the proportion of external doses predicted from activity concentrations of the anthropogenic radionuclide in soil are likely to dominate. For instance, Beresford et al. (2008c) found relatively good agreement between external doses estimated from TLDs attached to small 'mouse like' mammals and predicted doses based upon soil ^{137}Cs activity concentrations which ranged from *c.* 7 to 100 kBq kg^{-1} dry mass across three study sites in the Chernobyl exclusion zone (approximately 100–200 m above sea level: data from http://www.radioecology-exchange.org/content/chernobyl-exclusion-zone). Mean estimated and measured external absorbed dose rates at these sites ranged from *c.* 2 to 70 μGy h^{-1} and hence the contribution of cosmic radiation or natural background was unimportant. However, if dosimeters were used in compliance monitoring, where anthropogenic radionuclide concentrations are likely to be low, the contributions of cosmic and background radiation would need to be considered.

In interpreting the dosimeter results we also had to consider the contribution of ^{137}Cs internally incorporated in the reindeer to the reading on the dosimeters attached to their necks. The estimated contribution of internally incorporated ^{137}Cs to the dosimeter reading (e.g. 157 ± 27 μGy for the herd average estimate) was similar to the external dose estimated from all of the soil radionuclides considered. Therefore, in any future studies it would be important to estimate the contribution of internally incorporated ^{137}Cs to the dosimeter results to be able to best interpret them. The coefficient we used to relate internal ^{137}Cs contamination to the contribution to the dosimeter reading (i.e. 0.028 nGy per Bq kg^{-1}; Aramrun (2018)) would be applicable to other mammal of a similar size (e.g. wild boar or wolves). However, it could not be used for smaller animals for which the contribution of internal contamination to the dosimeter would be less for a given organism activity concentration.

When considering the modelled ^{137}Cs external dose estimates, those calculated using the GPS tracking locations for the reindeer were approximately twice the ^{137}Cs dose estimated assuming the reindeer grazed equally over the area. This was because the reindeer favoured the more contaminated areas which highlights the need to understand where animals actually spend their time. The habitat quality in the areas favoured by the reindeer was relatively good and better than in other areas of the herds home range. A typical assessment would adopt the approach used here to determine the herd average external absorbed dose rate and hence would underestimate exposure of reindeer in this example. For smaller mammals (mice and vole species) in the Chernobyl Exclusion Zone, (Beresford et al. (2008c)) previously found that using an average of the assumed home range gave reasonable agreement with estimates from attached TLDs.

Uncertainty in external dose estimates also have to be put into context with the total dose received by organisms under consideration; in the case of the reindeer considered in this paper internal dose would dominate the total exposure (based on the live-monitoring data the internal dose of the reindeer would be of the order of 100–202 μGy over the 11 months of the study (Skuterud et al., 2016).

5. Conclusion

There has been considerable debate surrounding the interpretation of studies considering the effects of radiation on wildlife at contaminated field sites (e.g. Beresford and Copplestone, 2011; Beresford et al., in press 2018). One criticism of several field studies considering effects is the lack of proper dose estimates. In this study, we have demonstrated that the use of appropriate dosimeters attached to animals will likely give reasonable estimates of absorbed external dose rates and help resolve this debate.

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Ethical approval (from the Science & Technology Research Ethics Panel, University of Salford) and informed consent (from the Vågå herders) were obtained prior to starting work at the site to ensure that the experiment complied with University of Salford ethical research procedures.

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