# Measuring regional scale distribution of radiocaesium


David Sanderson

Scottish Universities Environmental Research Centre

East Kilbride, Glasgow G75 0QF, UK


Caesium workshop : Fukushima recovery – understanding, modelling and managing radioacaesium decontamination, CORASSE, Fukushima, Japan

September 30 – October 3rd 2013

University of Glasgow

SUERC Scottish Universities Environmental Research Centre

## Outline

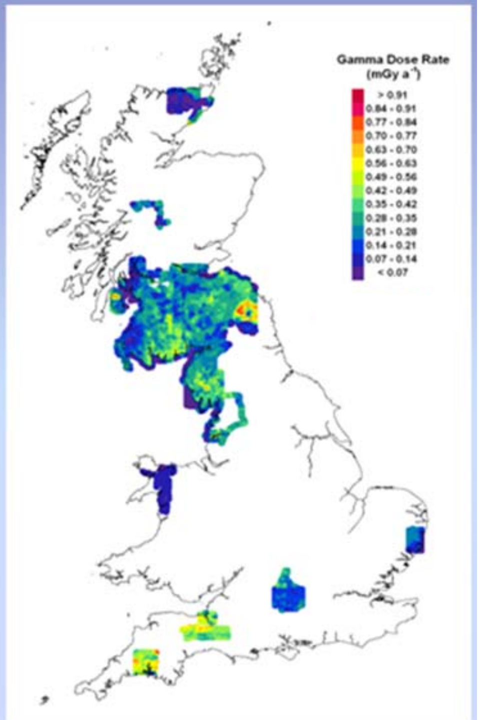
- Airborne and mobile gamma spectrometry
- Measurement technologies and small footprint systems
- Mapping radiocaesium (UK and European examples)
- Spatial resolution and reproducibility at regional and local scales
- International validation and ground to air comparisons
- Work conducted in Japan in 2012/13
- Future opportunities and needs


University of Glasgow

SUERC Scottish Universities Environmental Research Centre

# Airborne & Mobile Gamma Spectrometry for mapping radioactivity

- AGS is capable of rapid radiometric mapping of large areas
  - Sensitive gamma-ray detector mounted on aircraft
  - High volume NaI (or combined NaI/Ge system)
  - Low altitude survey flights (30-100m)
  - Large survey areas, high sampling density
  - ~1000's of observations per hour
  - $10^4$-$10^5$ $m^2$ fields of view
- Mobile Gamma spectrometry
  - Geocoded gamma spectrometry operated from backpacks, small vehicle, UAV's, boats, hovercraft etc
  - More confined field of view – suited to detailed surveys of eg urban areas
  - Data capture rate $10^2$ -$10^3$ per hour
  - 10-$10^2$ $m^2$ fields of view




University of Glasgow

SUERC
Scottish Universities Environmental Research Centre

# SUERC AGS multispectrometer

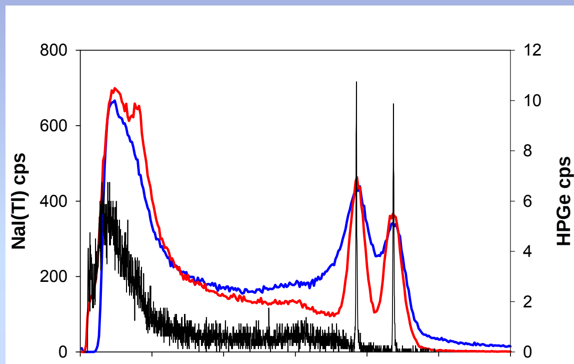
- AGS system used in ECCOMAGS Exercise
- Fully validated performance
  - 17 spectral input channels, multi-sensor capable
  - High volume NaI arrays, HPGe detectors
  - Stabilised power supply
  - Upgraded (2005/6) to more powerful computers, larger displays, revised power systems
  - Software upgrades (2008-2010)
    - ERS Format spectral input/output
  - HPGe analysis
    - Full spectral regridding
    - Disjoint spectral windows
- Real time mapping with differential "rainbow plots"
- Alarms
    - Gross & stripped count rate
    - Significance from differential analysis
    - Intelligent digital filtering
- 5Hz, EGNOS enabled GPS

SUERC
Scottish Universities Environmental Research Centre

# Digital Systems

## Digital systems have advantages

- Increased data throughput
  - Resolution maintained in high radiation fields (but could use HPGe)
- (But summing multi-compton losses in detector arrays)

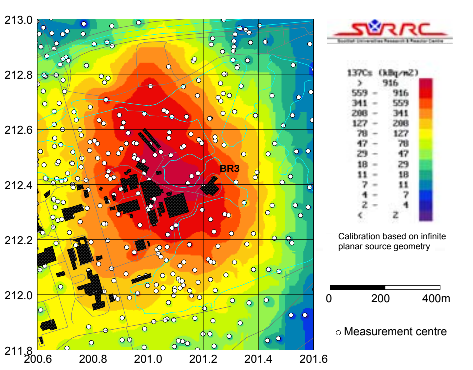


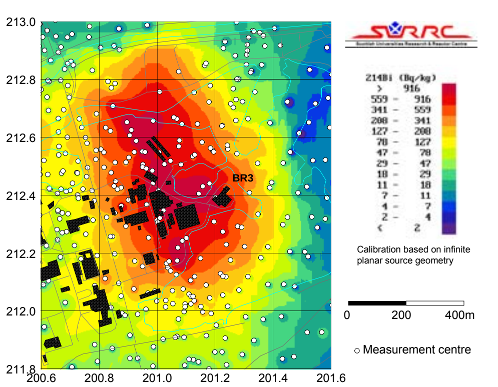

- Simple, compact systems
  - Self contained HV supply and DSP chips
  - USB connectivity
  - Ideally suited to weight limited platforms
  - Alternative detector geometries?

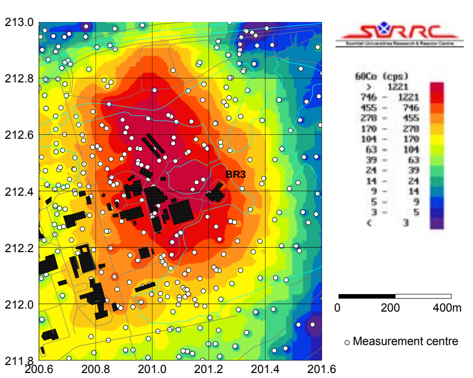
University of Glasgow

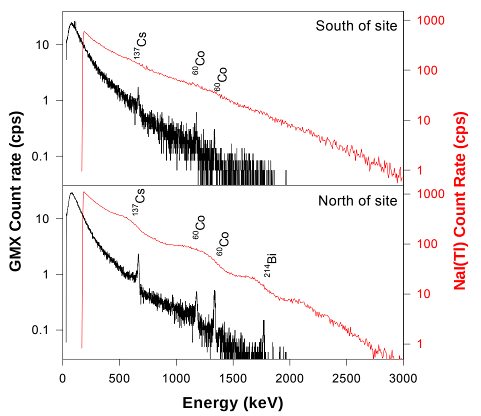
Scottish Universities Environmental Research Centre

# Belgoprocess Site 2



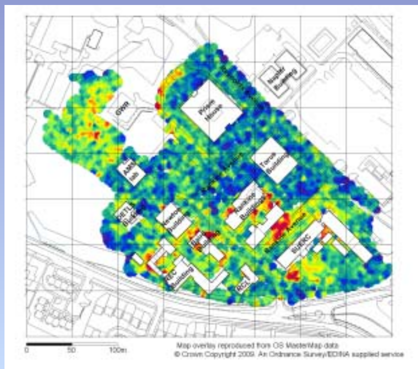



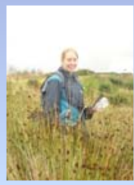

- $^{137}$Cs, $^{60}$Co activity from stored materials
- $^{214}$Bi activity from $^{222}$Rn discharges from stored uranium & radium

- NaI Spectra show spectral distortion and coincidence summing

Scottish Universities Environmental Research Centre

# Backpack System

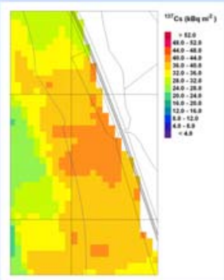


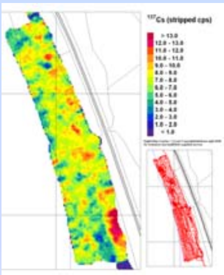


Avril Weir and Catherine Mitchell survey the Scottish Enterprise Technology Park, in 2009 for their MPhys project

"Demonstrating lightweight gamma spectrometry systems in urban environments", Journal of environmental radioactivity, 2013, 124, 22-28

**March 2000 AGS** **June 2010 Backpack**





High resolution survey of Irish Sea beach in 2010

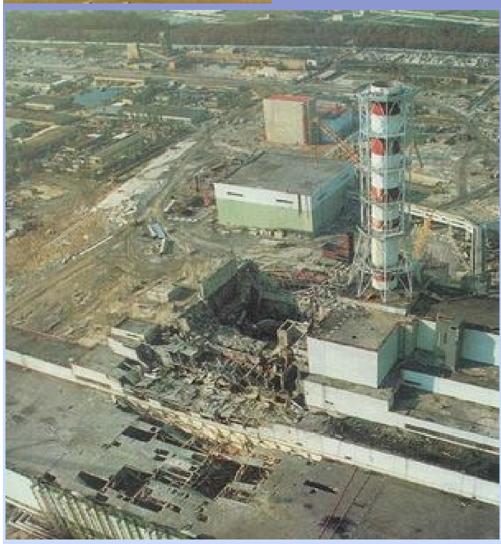
"Evaluating airborne and ground based gamma spectrometry methods for detecting particulate radioactivity in the environment: A case study of Irish Sea beaches" Science of the Total Environment 437 (2012) 285–296

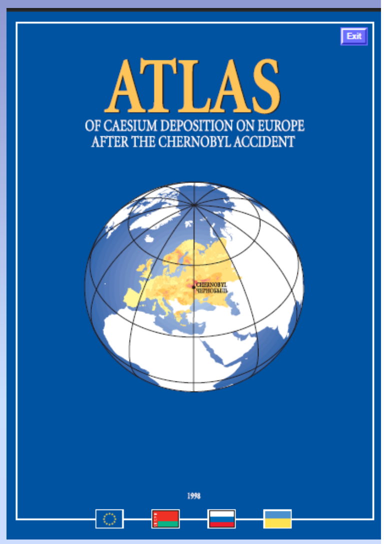
**3x3" NaI(Tl), digiBASE™, netbook, EGNOS enabled GPS**

University of Glasgow

SUERC
Scottish Universities Environmental Research Centre

# Regional scale mapping following the Chernobyl accident on 28th April 1986





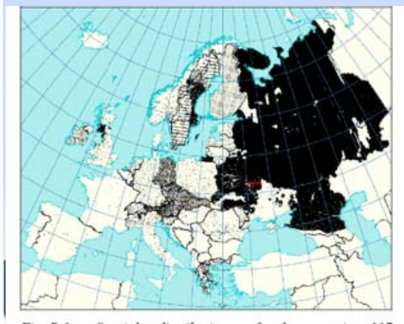
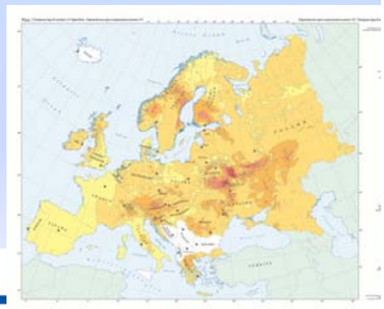
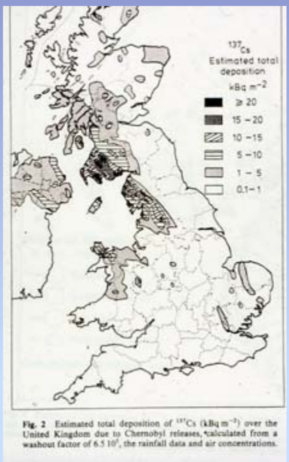



Fig. B.1: Spatial distribution of the caesium-137 deposition data used for the Atlas



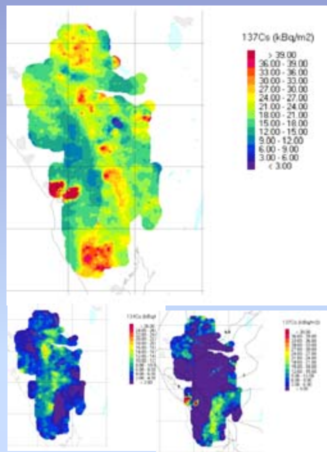
Scottish Universities Environmental Research Centre

# Chernobyl 28th April 1986



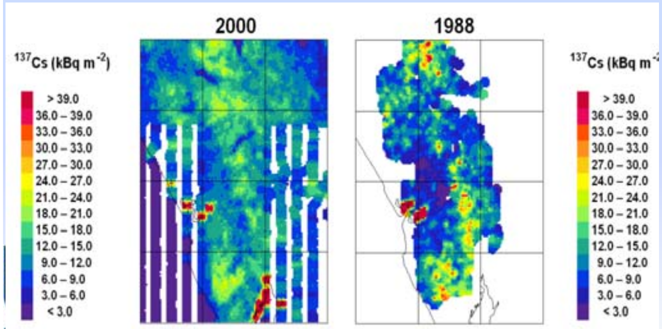

- 28th April Chernobyl
- UK fallout arrives early May
- Initial deposition estimates based on limited ground sampling and meteorological modelling
- Early SURRC surveys – SW Scotland, Western Isles, West Cumbria, North Wales
- Later repeat surveys show long term migration of radionuclides

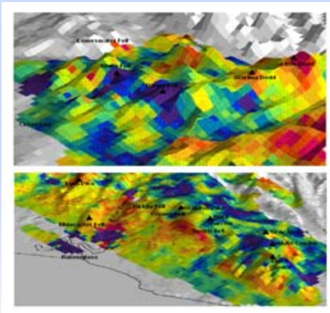
1988 MAFF Survey West Cumbria



Sanderson D.C.W., Cresswell A.J., White, D.C., Murphy, S., McLeod J. 2001, Investigation of Spatial and Temporal Aspects of Airborne Gamma Spectrometry. DETR Report DETR/RAS/01.001.

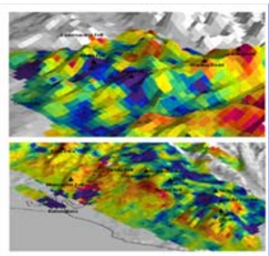
Sanderson D.C.W., Scott E.M.,1989, Aerial Radiometric Survey In West Cumbria In 1988, MAFF Report N611 120



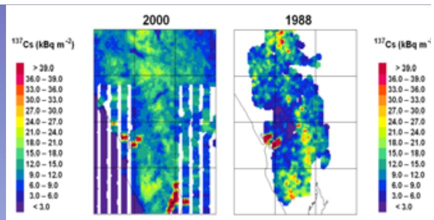



2001 DETR study "Spatial and Temporal Aspects of airborne gamma spectrometry

Scottish Universities Environmental Research Centre



# West Cumbria – Changes Between 1988 and 2000 - Livestock restriction zone



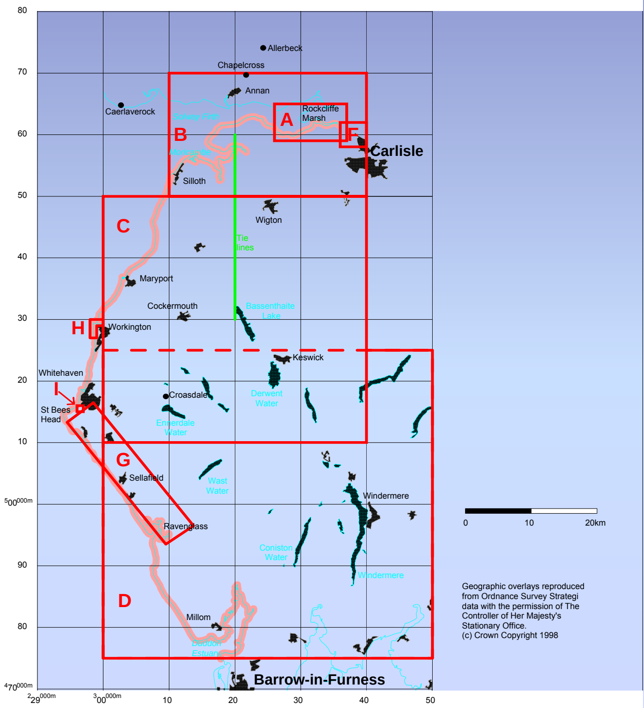
| | 1988 | 1988 (decay corrected) | June 2000 |
|---|---|---|---|
| Total Area (TBq) | 9.35±0.02 | 7.01±0.02 | 7.22±0.02 |
| Black Combe (GBq) | 496±3 | 372±3 | 319±1 |
| Corney Fell (GBq) | 704±3 | 528±3 | 469±2 |
| Loweswater Fell (GBq) | 636±3 | 477±3 | 453±1 |
| Lowlands (GBq) | 851±16 | 638±12 | 732±8 |

- Total activity in area agrees to within 3% after decay correction
- Movement of activity from high to lower lying ground due to hydrological and colluvial processes

University of Glasgow

Scottish Universities Environmental Research Centre

# Investigation of Spatial and Temporal Aspects of Airborne Gamma Spectrometry




**Inner Solway**

The Solway Firth has extensive areas of salt marsh

Contaminated by discharges from Sellafield

**Survey areas**

6x11km, encompassing Rockcliffe and Burgh marshes and the tidal inlets of the Esk and the Eden

30x20km, including Annan, Silloth and part of Carlisle

**Survey dates and flight lines**

April 1999: 50 and 250m line spacings ; June 2000: 250m line spacing,

February 1992: 500m line spacing

**West Cumbria**

Upland areas and coastal plain

Contaminated by Chernobyl and Windscale fire

**Survey areas**

Coastline and Sellafield area (March 2000)

40x40km (500m), northern Lakes and lower lying areas (June 2000)

50x50km (2.5km), Lake District high ground (June 2000)

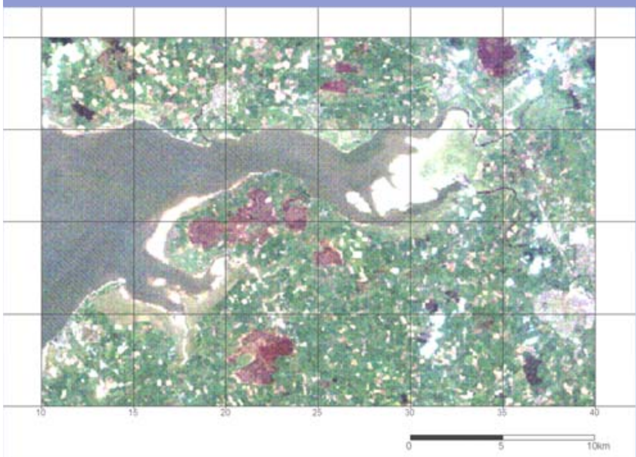
Older data : Aug/Sept 1988: 500m line spacing; Sept 1990: Sellafield area

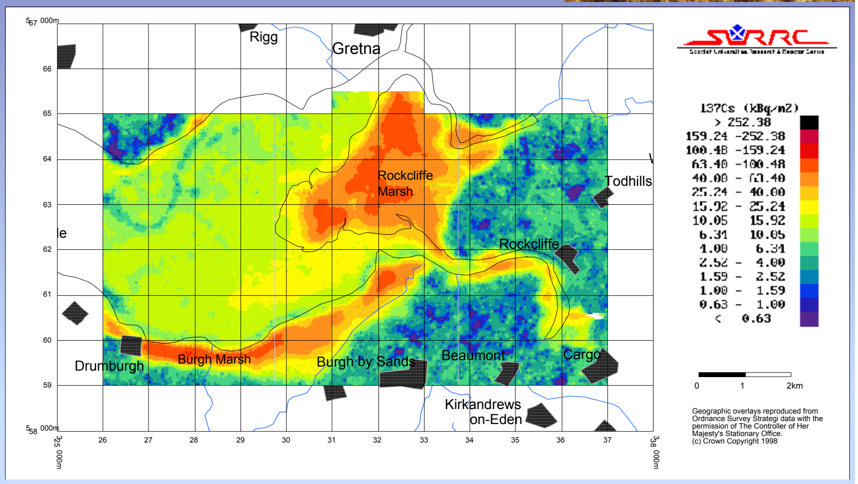
- Analysis of line spacing and environmental change
- How reproducible is AGS?
- How to measure change

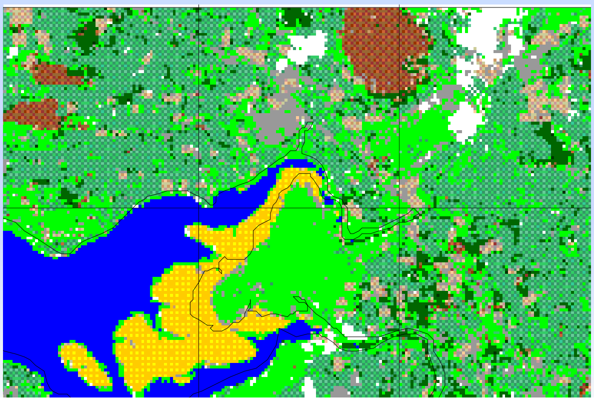
University of Glasgow

SUERC
Scottish Universities Environmental Research Centre

# Inner Solway $^{137}$Cs Distribution and the landcover setting



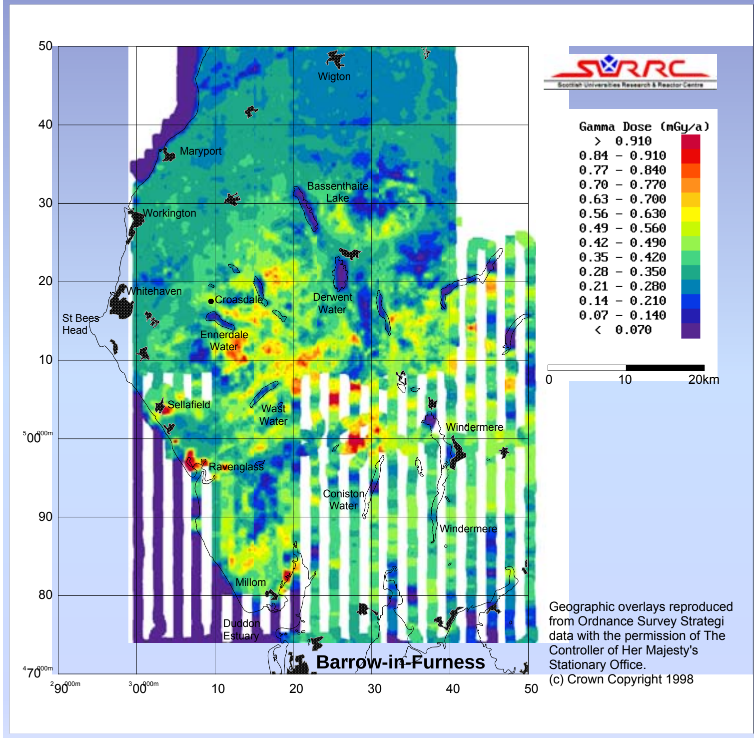



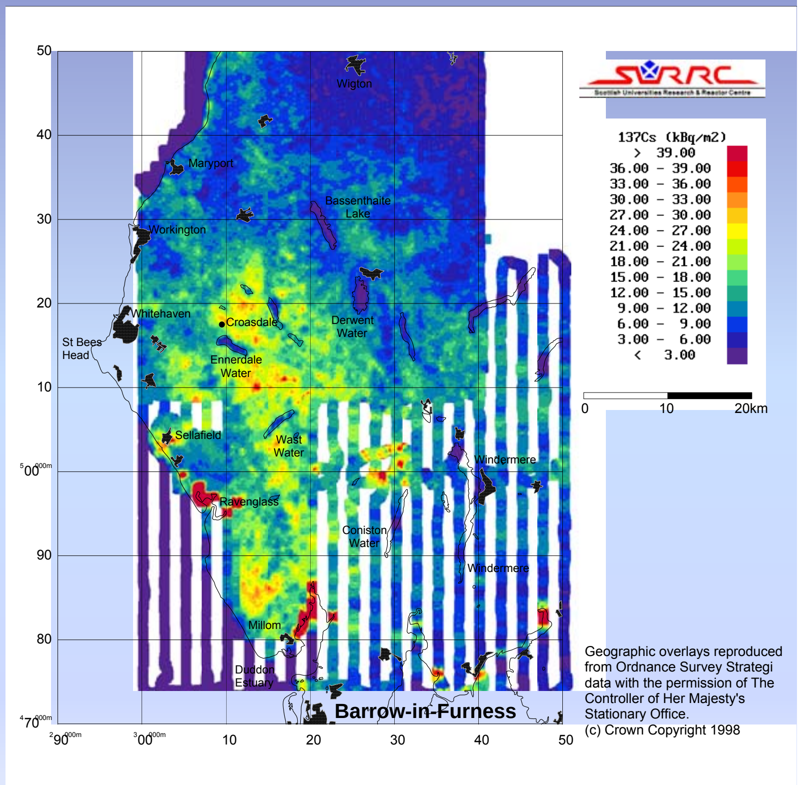



University of Glasgow

SUERC
Scottish Universities Environmental Research Centre

# Sparse data for West Cumbria

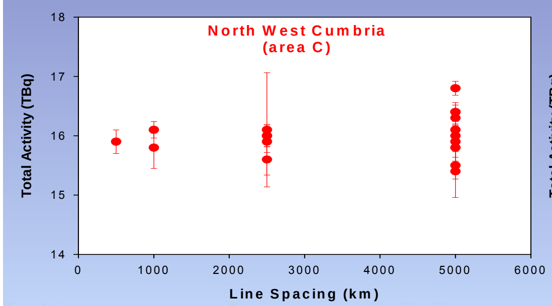


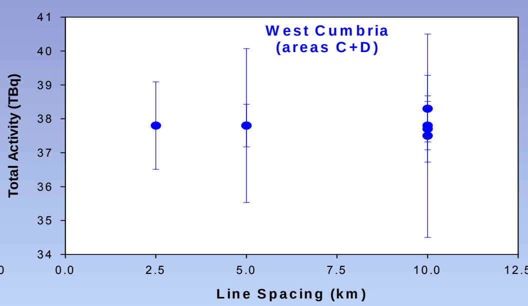




University of Glasgow

Scottish Universities Environmental Research Centre

# $^{137}Cs$ Activity for Areas C and D



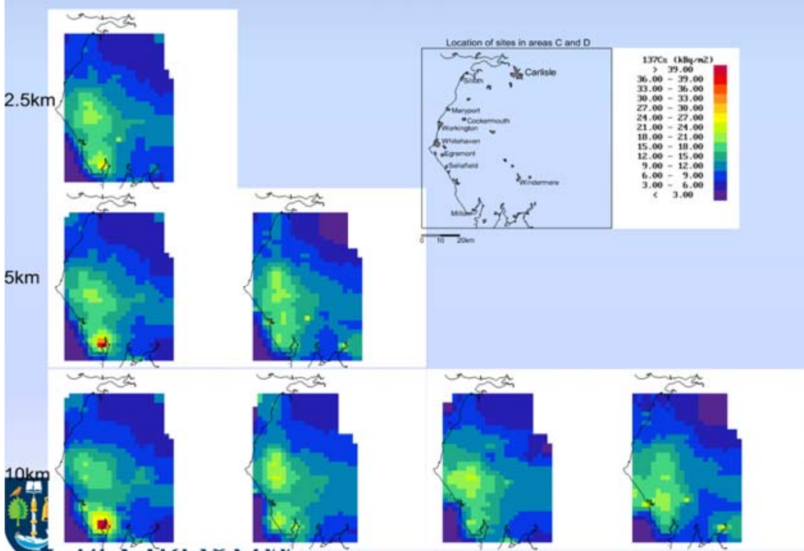




**Inventories of large features relative to line spacing are robust (shapes less so)**

**for dimensions perpendicular to lines >2x line spacing**

**smaller features subject to significant uncertainties for wider line spacing**

**Even 10km line spacings show broad distribution pattern and inventory of Chernobyl derived activity on uplands**



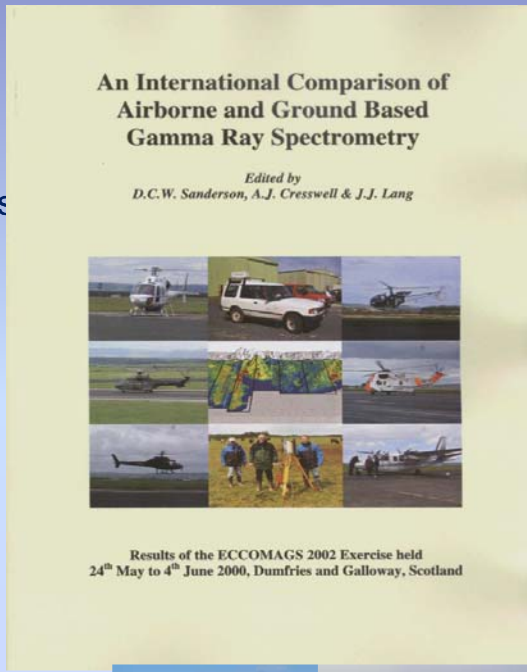

Sanderson, D. C. W., Cresswell, A. J. and White, D. C. (2008) 'The effect of flight line spacing on radioactivity inventory and spatial feature characteristics of airborne gamma-ray spectrometry data', International Journal of Remote Sensing, 1 – 16 DOI: 10.1080/01431160701268970

University of Glasgow

Scottish Universities Environmental Research Centre

# ECCOMAGS

- Protocols for dose rate and radionuclide deposition mapping using AGS
- Exercise design documentation
- Unique data base of airborne & ground based measurements
- Exercise report – 387p  book published
- Journal articles
- European Capability for AGS *Radiation Protection Dosimetry*
- *Vol. 73, Nos 1–4, pp. 213–218 (1997)*
- European Bibliography *Journal of Environmental Radioactivity*
- *53 (2001) 411-422*
- International validation of deposition and dose rate determination under conditions of cooperative trials *Radiation Protection Dosimetry (2004), Vol. 109, Nos 1-2, pp. 119-125*









University of Glasgow

SUERC
Scottish Universities Environmental Research Centre

# Exercise Aims and Outcomes

- Aims
  - Validation of AGS protocols for deposition and dose rate quantification
  - Traceable comparisons between AGS, in-situ spectrometry, field dose rate measurements and laboratory analysis of core samples
  - Demonstration of composite mapping capability
- Venue
  - SW Scotland May 24th-June 3rd 2002
  - Pre-characterisation fieldwork in November 2001
- Organisation
  - International steering Committee (ISC)
  - National Organising Committee, (NOC)
  - Design and Evaluation Group (DEG)

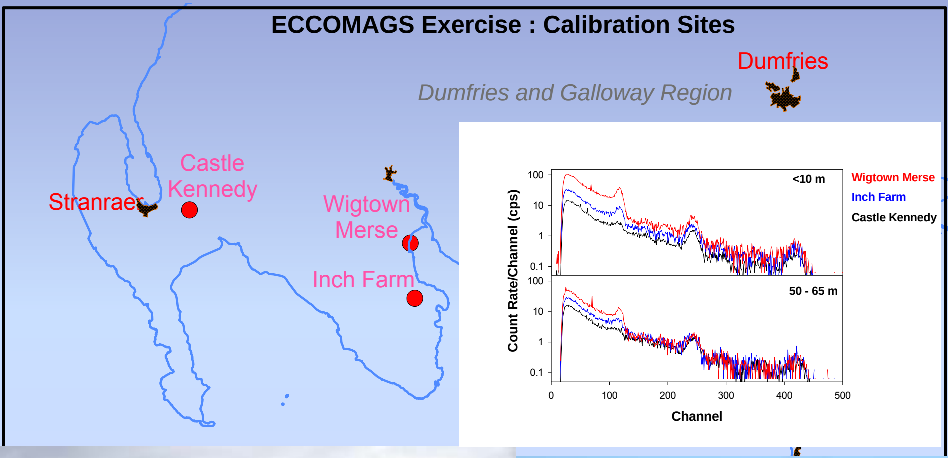
Outcomes

Participants
150 participants from 18 institutions in 10 countries
Observers and visitors
Activities and achievements
AGS >120,000 measurements in common areas and composite mapping zones
~150 In-situ and field dose rate measurements from calibration sites and 42 common area sites
>750 laboratory gamma spectrometry results from ~130 core samples and reference materials
CGS data from 3 teams

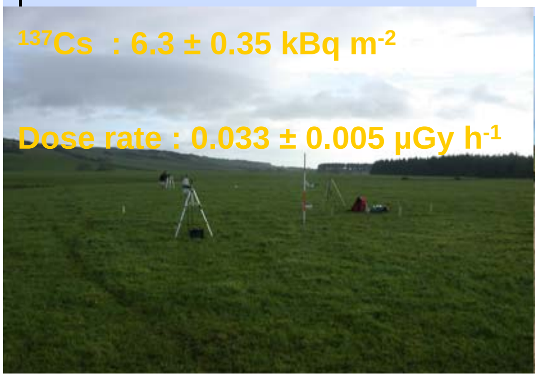
University of Glasgow

SUERC
Scottish Universities Environmental Research Centre

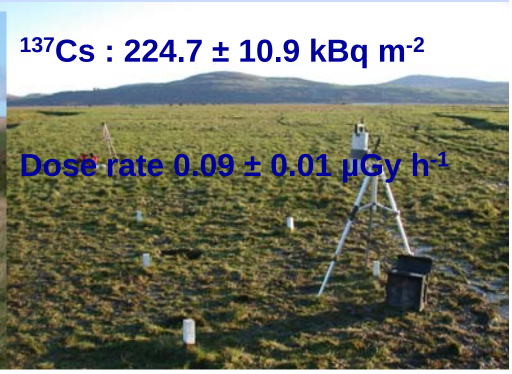
# Calibration sites




- Sampled in November 2001
- Reference values distributed to participants
- AGS hover manoevres and in-situ measurements used for data levelling
- In-situ checks for environmental change

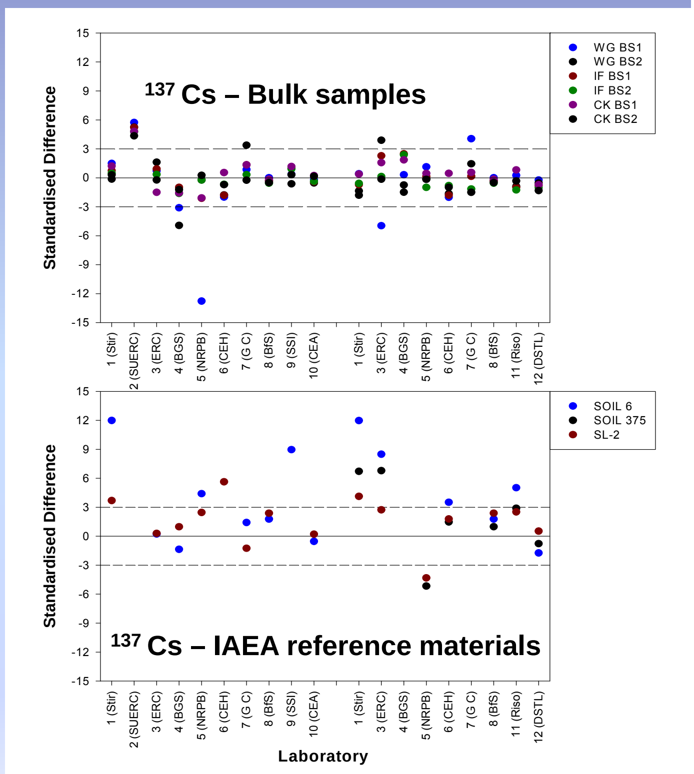







# Ground Based Data sets – Key points for ground to air comparisons

- Laboratory Gamma spectrometry
  - Laboratory performance
  - Different behaviours observed between IAEA reference materials and common bulk samples
  - Results provide basis for ground to air comparisons
- In-situ data
  - Necessary to re-standardise data sets to common mass-depth profiles
  - Also to re-level them to the Inch Farm site
  - Relationships between in-situ and cores bring mass-depth into play
- Dose Rate measurements
  - Field instruments showed considerable differences
  - Dose Rates re-estimated from in-situ spectra and cores
- CGS biased by field of view differences

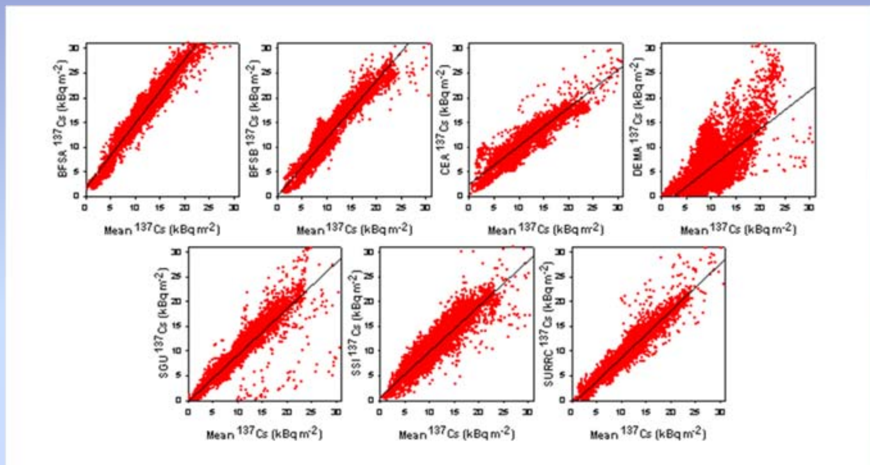



University of Glasgow

SUERC
Scottish Universities Environmental Research Centre

# Main Common area AGS findings

- All teams identify the main radiometric features
- Data levelling between teams using single common measurement point
  - Applicable to emergency response
  - Further corrections and analysis lead to only minor changes
- Considerable agreement between teams
  - Definition of spatial features
  - Point to point regressions

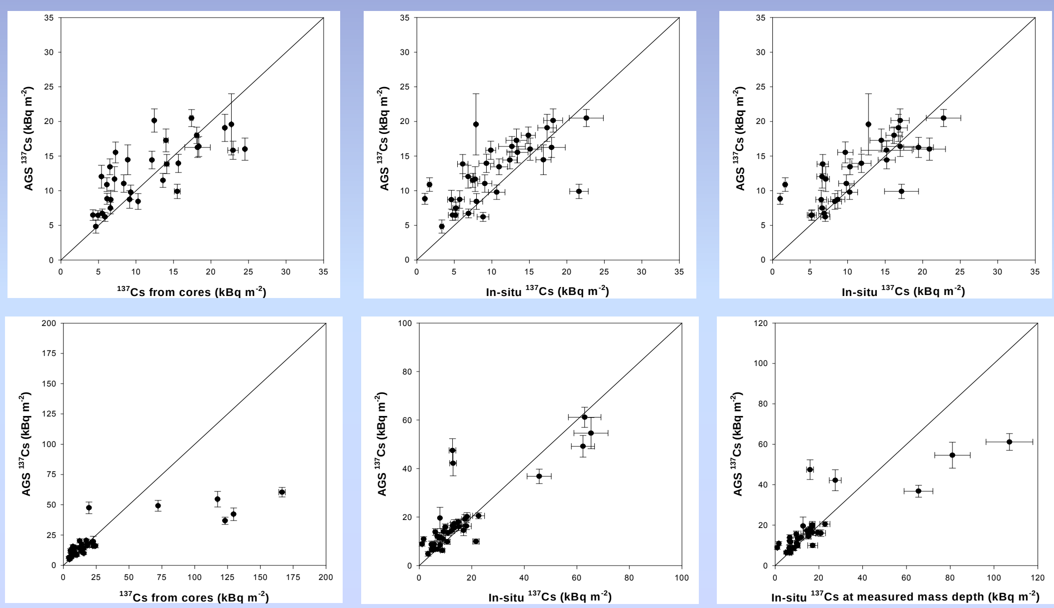



University of Glasgow

Scottish Universities Environmental Research Centre

# Ground to Air Comparisons

- Ground to air comparisons
  - Agreement is broadly consistent with the internal consistency of each data set
  - AGS and in-situ sensitive to depth distribution
  - AGS observations are consistent with ground based results
  - But are spatially more numerous and representative
  - The data sets provide a basis for protocol validation



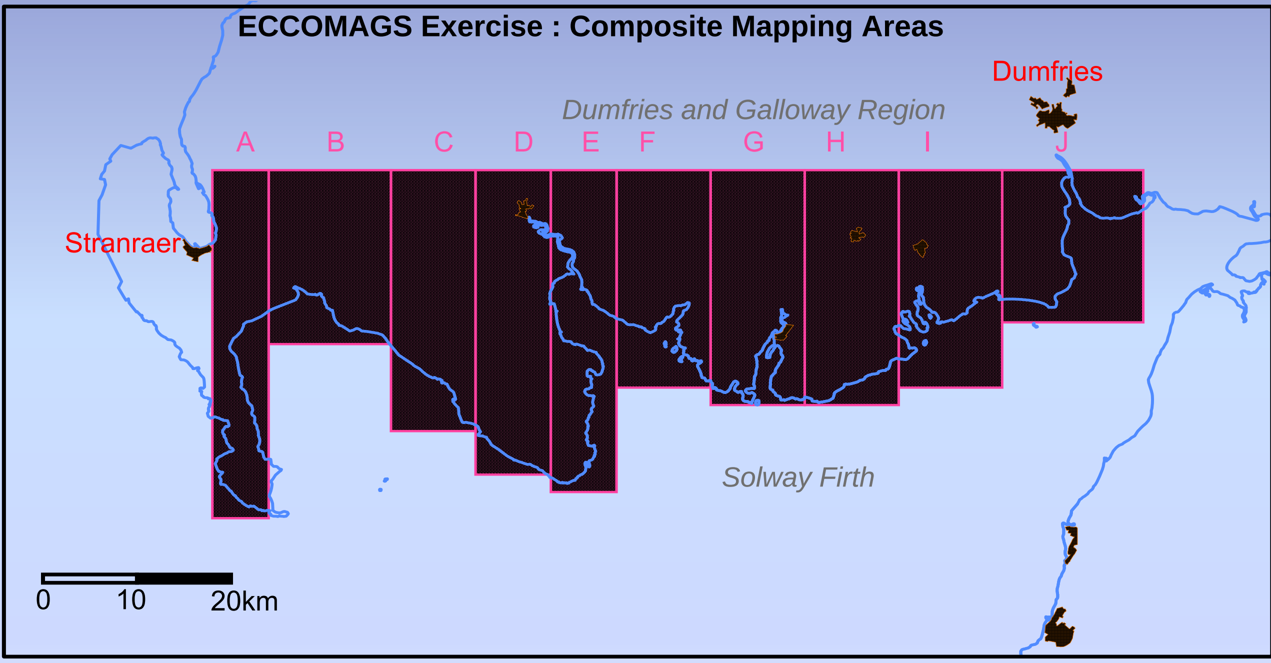

Assuming 8.5 g cm-2 relaxation depth

Assuming measured depth profile

University of Glasgow

Scottish Universities Environmental Research Centre

# AGS Composite mapping task




- 10 contiguous areas of approximately 250-270 km$^2$
- Each presenting diverse environments from topographic and radioecological perspectives
- Allocated to individual AGS teams to demonstrate collective mapping abilities

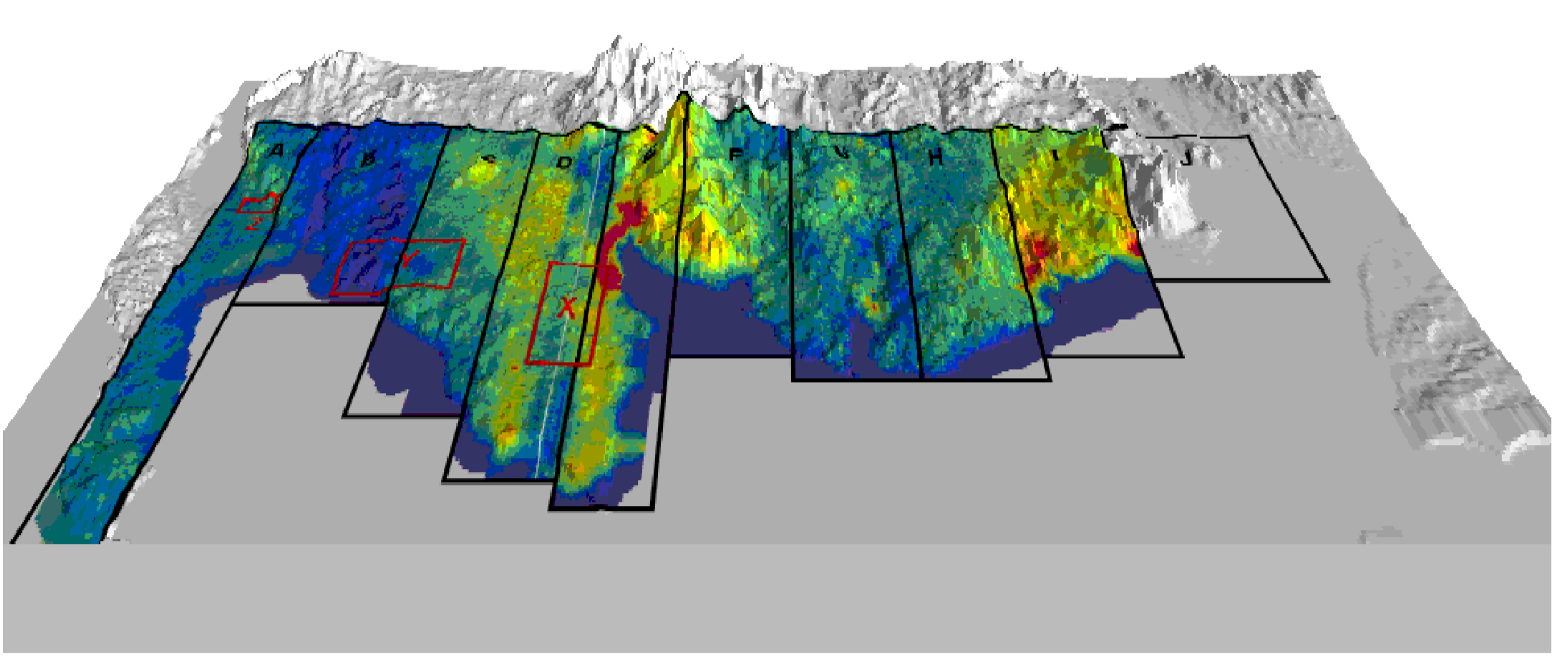
University of Glasgow

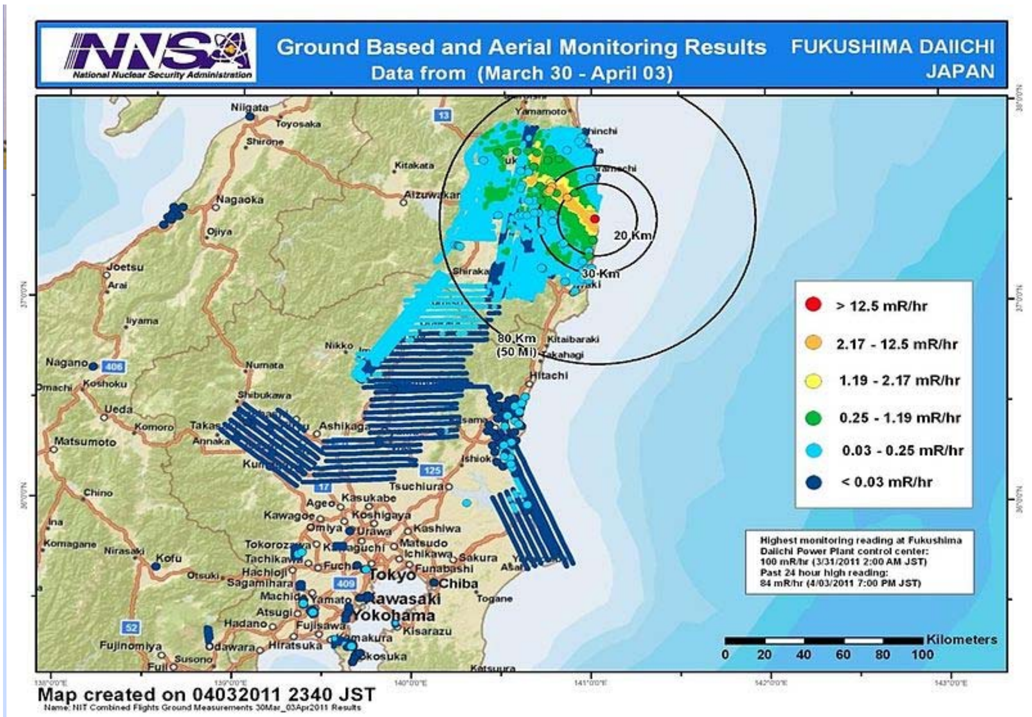
Scottish Universities Environmental Research Centre

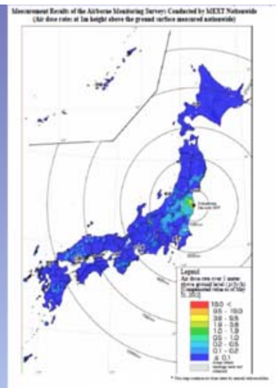
# $^{137}$Cs Map with terrain model

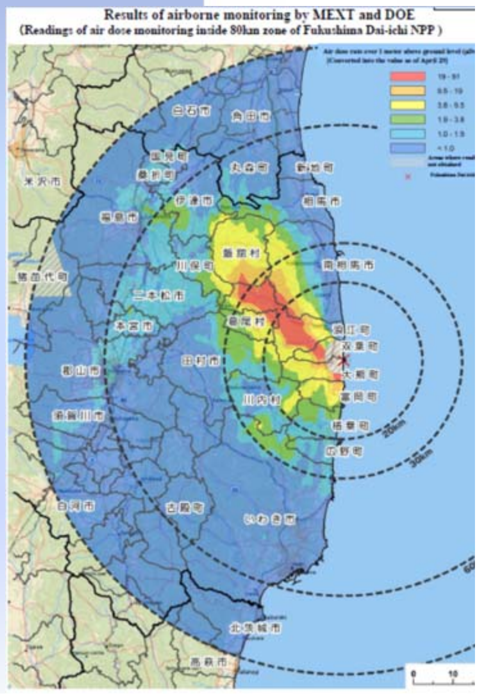
ECCOMAGS exercise composite mapping task 2002

90x40 km area; 69000 spectra; data acquired in 3 days, published on-line within a week





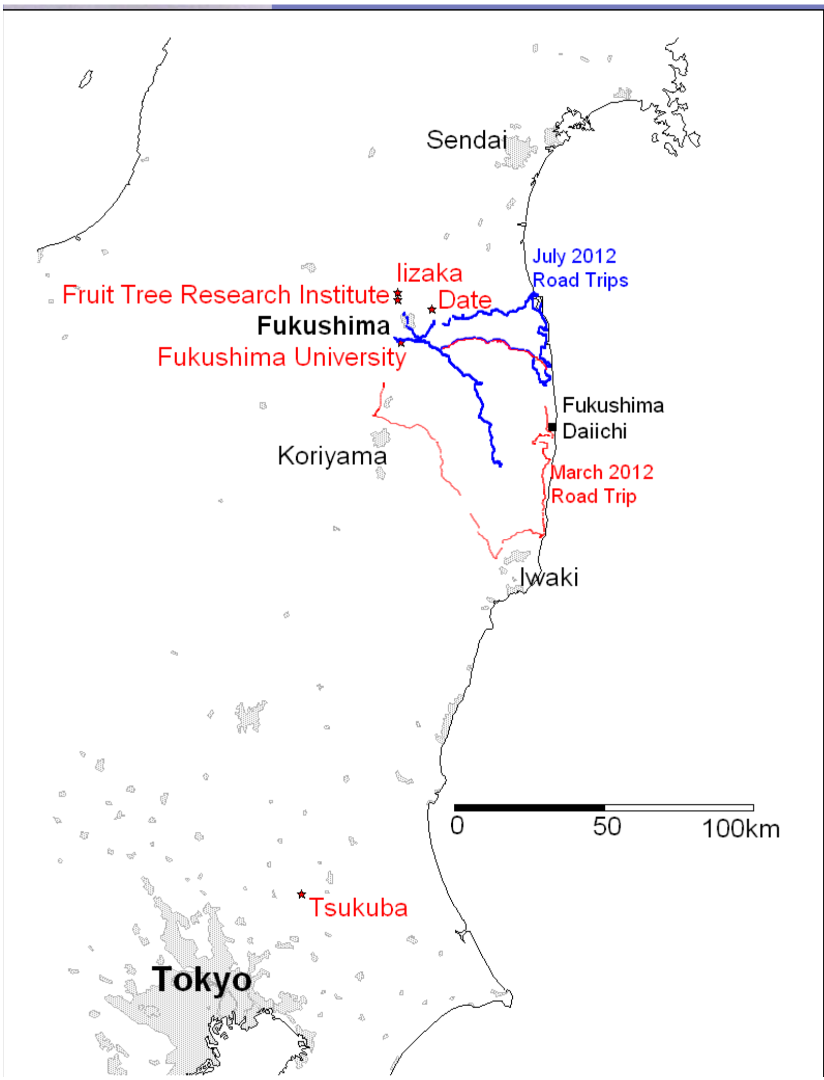






## Airborne Gamma Spectrometry maps

- US DOE team (March), MEXT/JAEA teams April
  - Ground clearance 300m initially
  - Dose rate maps, followed by apportioned Cs maps

University of Glasgow

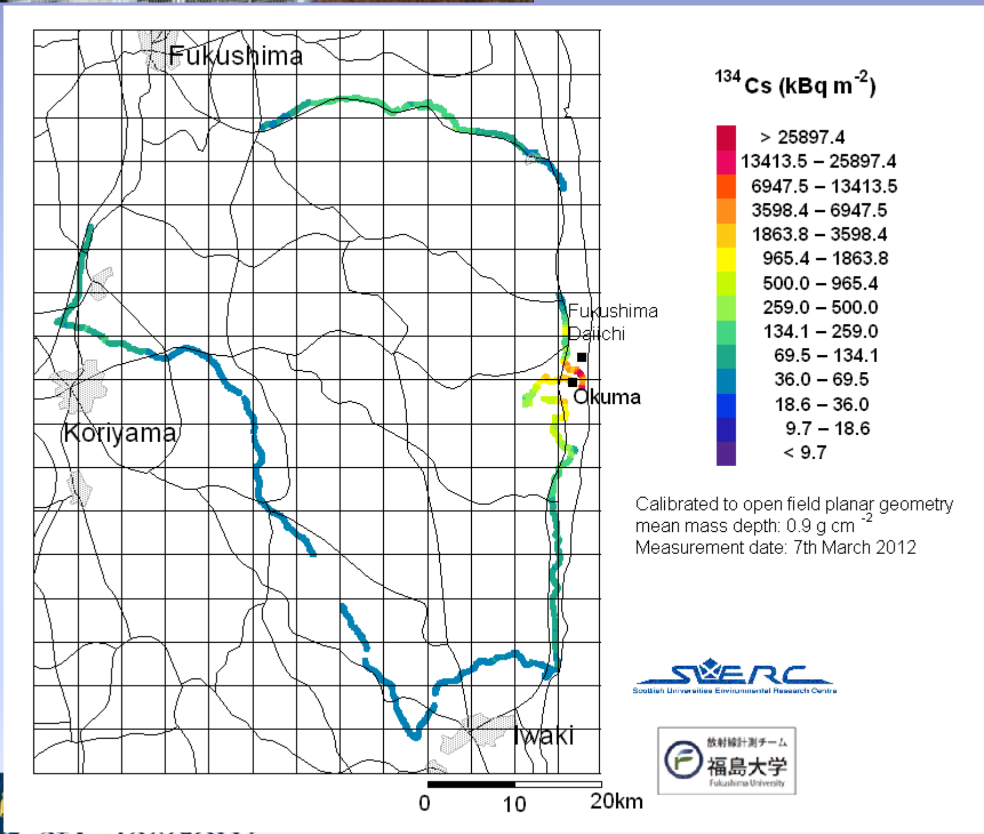



Visits to Japan 2012/13

- March 2012 – Tsukuba, Fukushima, Exclusion zone, Prefecture research institutes, JAEA, UK Embassy, EU delegation (DS/YT)
- May 2012 – SRRCE inaugural conference Fukushima Izaka (DS)
- July 2012 Fukushima (AC, BS)
- September 2012 (SF,XS) visit AMS labs
- Oct/Nov 2012 UK Nuclear Safety workshop (FCO) (DS)
- Jan 2013 Biomass investigation Iwaki (AC DS)

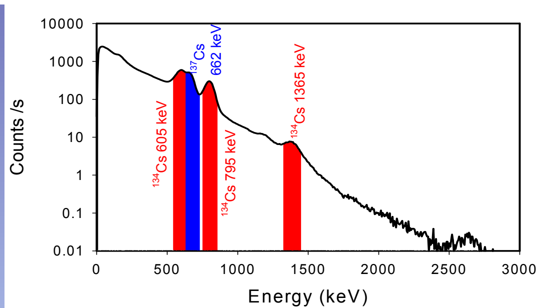
SUERC
Scottish Universities Environmental Research Centre

# 7th March 2012 Road Trip

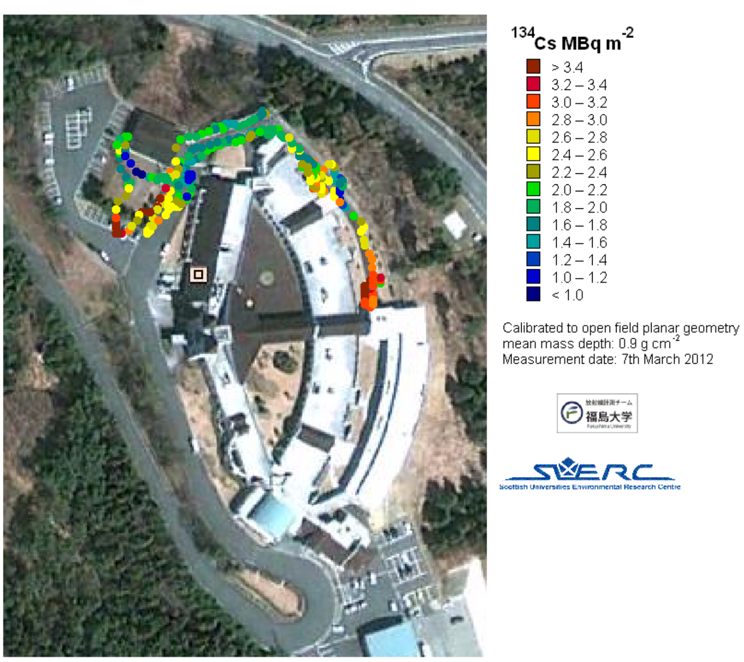


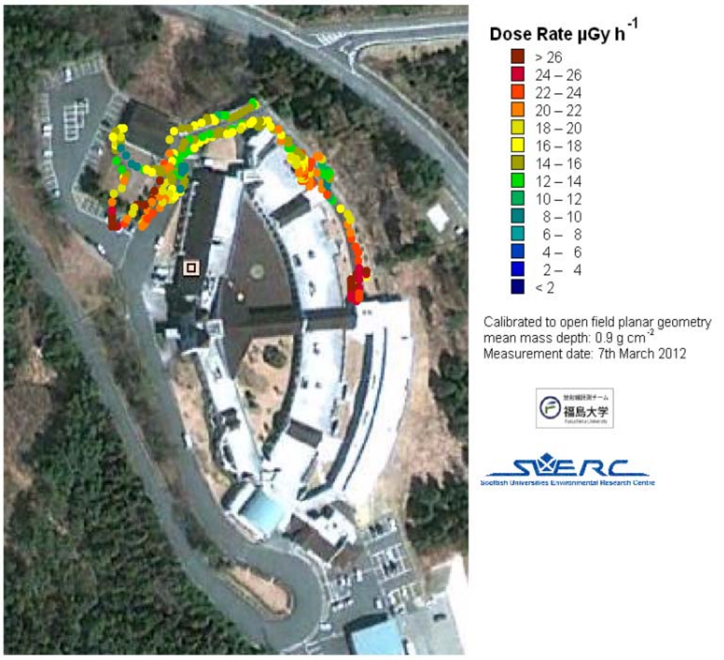

of Glasgow

SUERC
Scottish Universities Environmental Research Centre

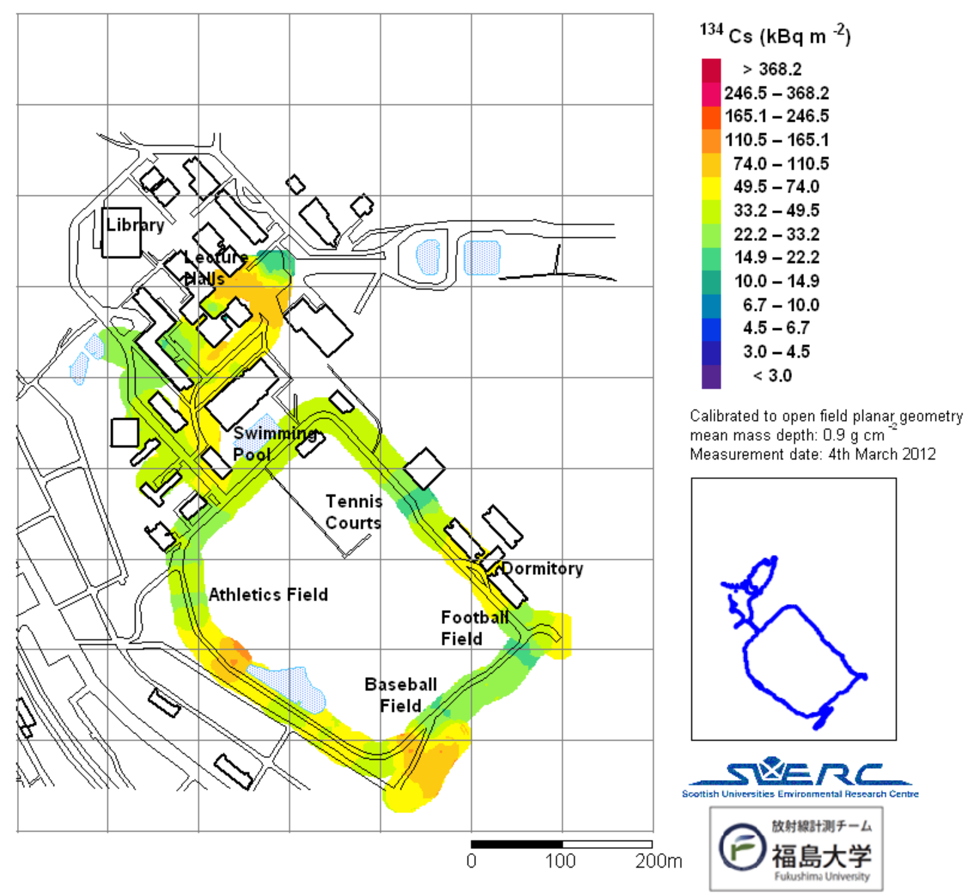



# Okuma Daycare Centre 7th March 2012

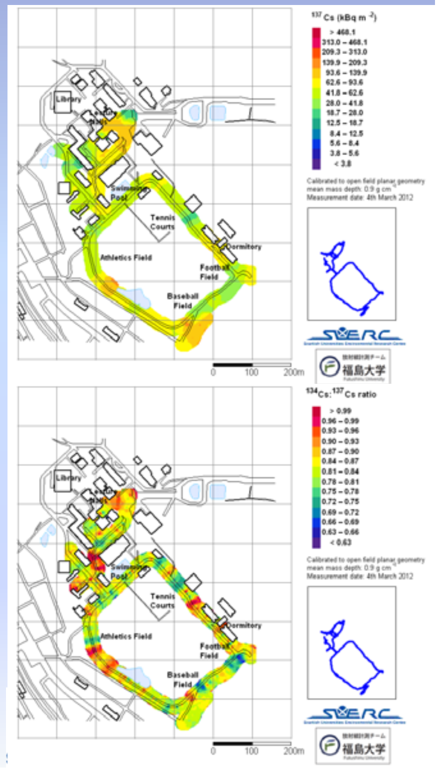


# Fukushima University Kanayagawa Campus
# 6th March 2012



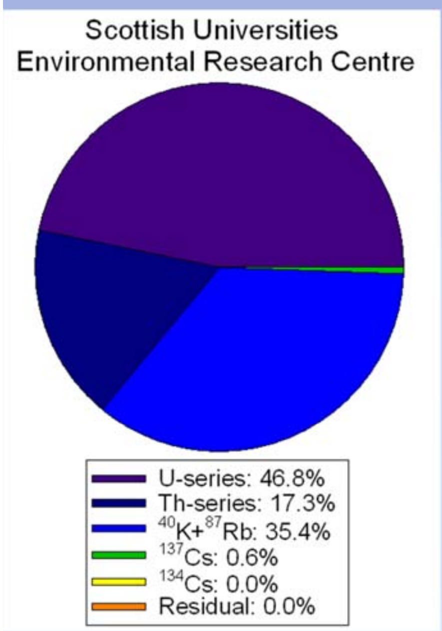

Can we use this to direct remediation?

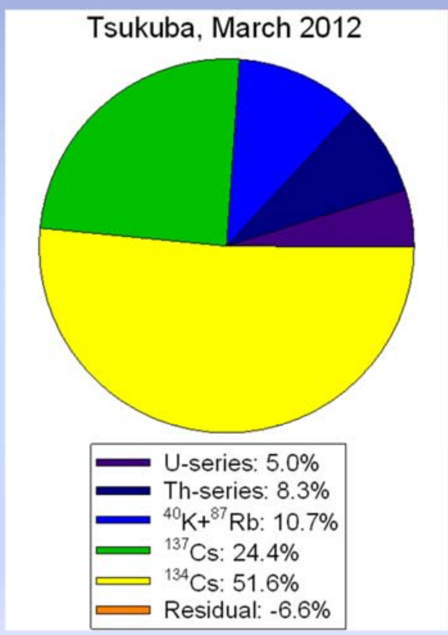


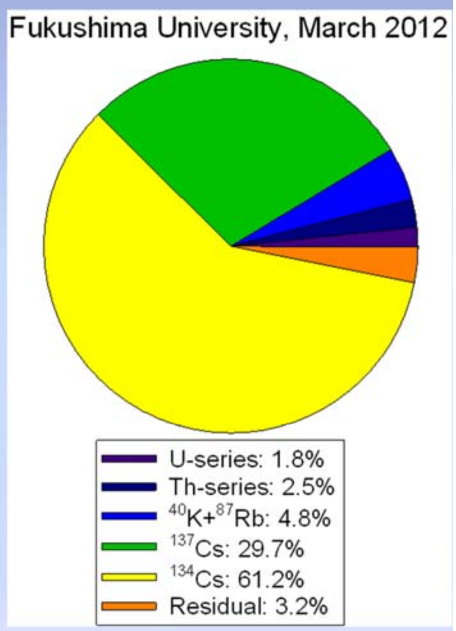
# Apportionment of dose rate

The charts show the relative proportions of dose rates due to individual nuclides

- Can we use this type of information to set and evaluate targets for remediation ?



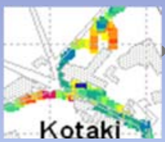




University of Glasgow

SUERC Scottish Universities Environmental Research Centre

# Gamma dose rate map Iizaka 20th May 2012
# Conducted during the SRRCE meeting

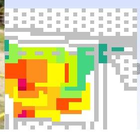
## Conference Hotel

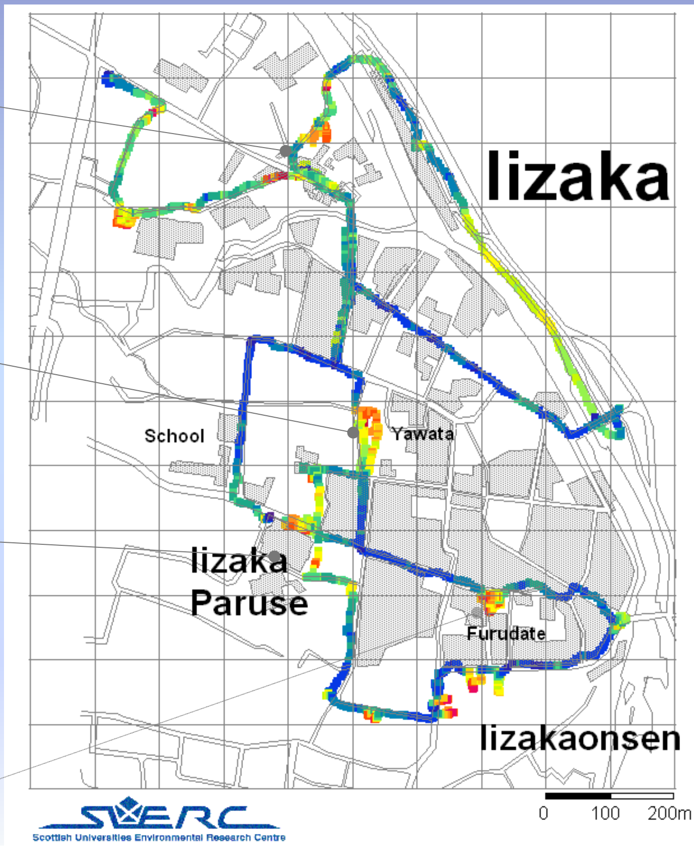




## Shrine


## Conference Venue

## Play Park



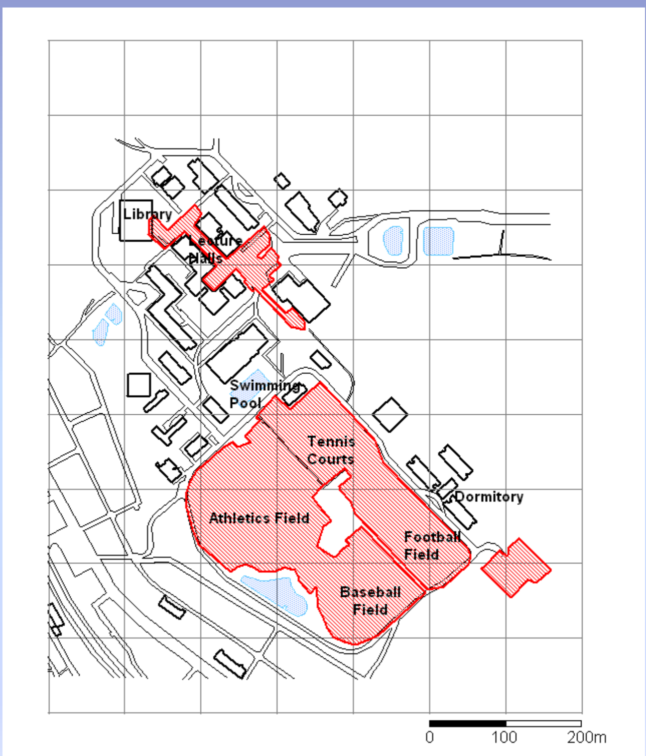



**Gamma Dose Rate ($\mu Gy\ h^{-1}$)**

- > 0.91
- 0.84 – 0.91
- 0.77 – 0.84
- 0.70 – 0.77
- 0.63 – 0.70
- 0.56 – 0.63
- 0.49 – 0.56
- 0.42 – 0.49
- 0.35 – 0.42
- 0.28 – 0.35
- 0.21 – 0.28
- 0.14 – 0.21
- 0.07 – 0.14
- < 0.07

Calibrated to open field planar geometry
mean mass depth: 0.9 g $cm^{-2}$
Measurement date: 20th May 2012

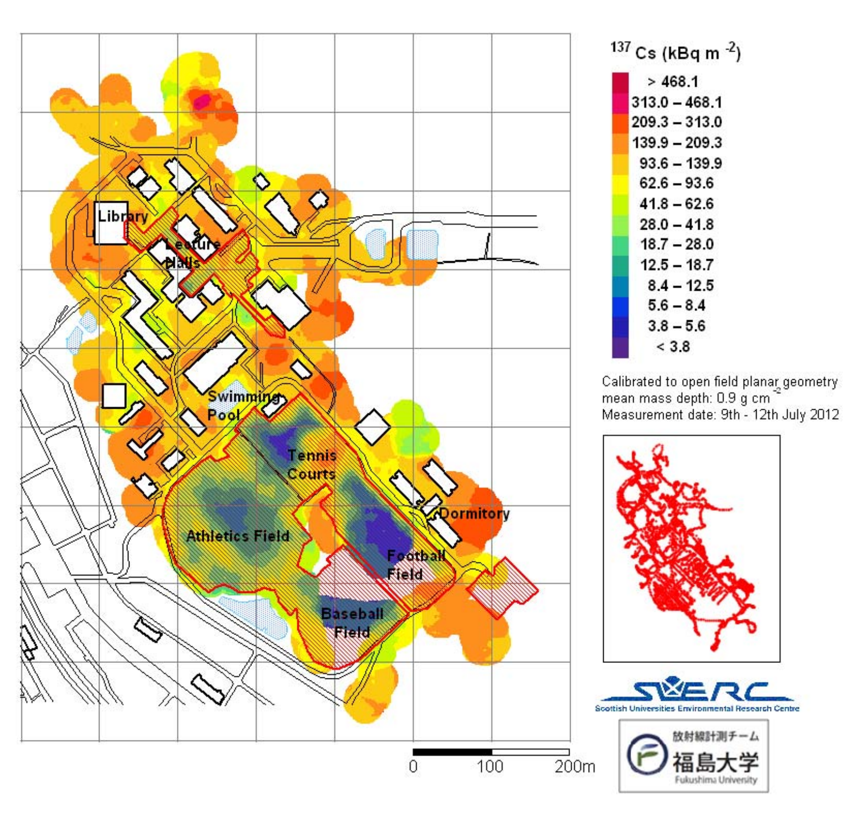
# University of Fukushima : areas subject to remediation July 2012

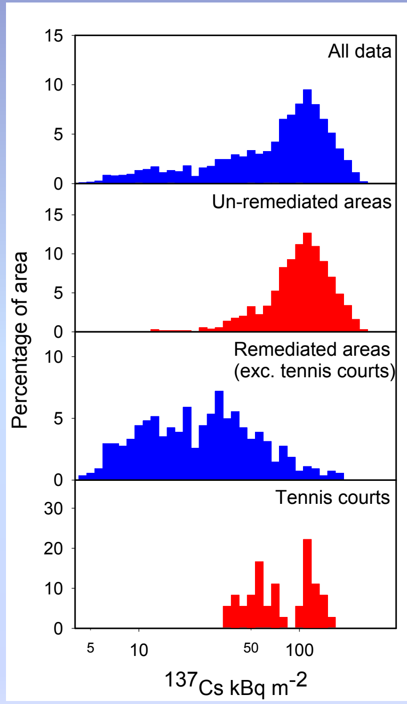



University of Glasgow

Scottish Universities Environmental Research Centre

# University of Fukushima : 137Cs map showing remediated areas

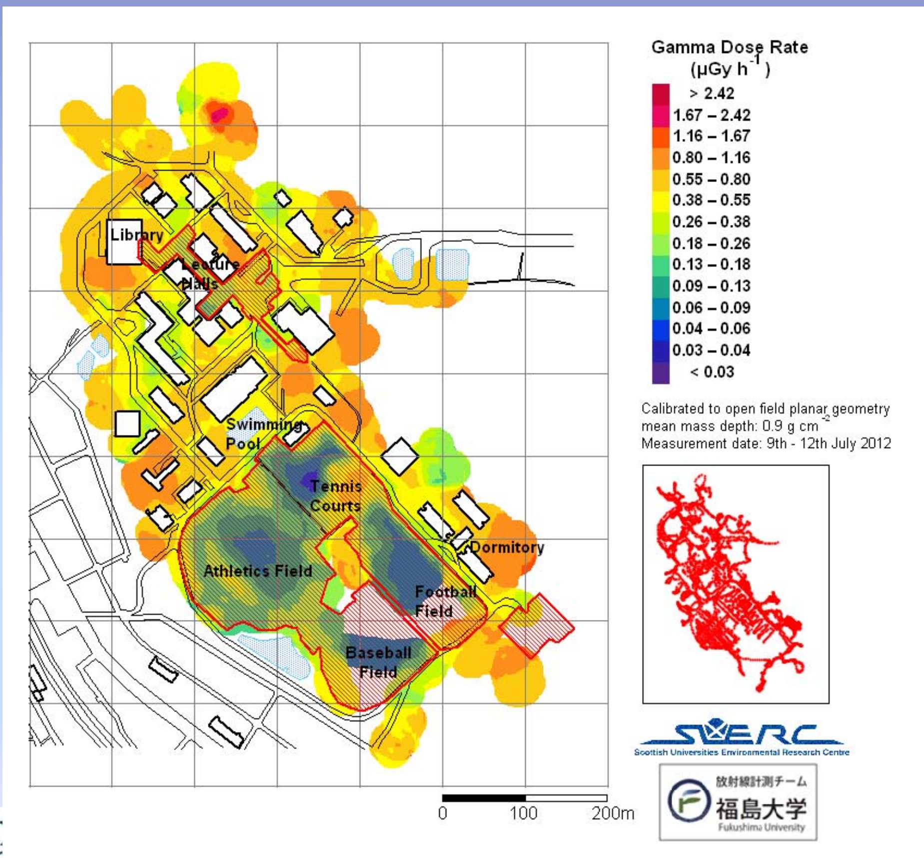


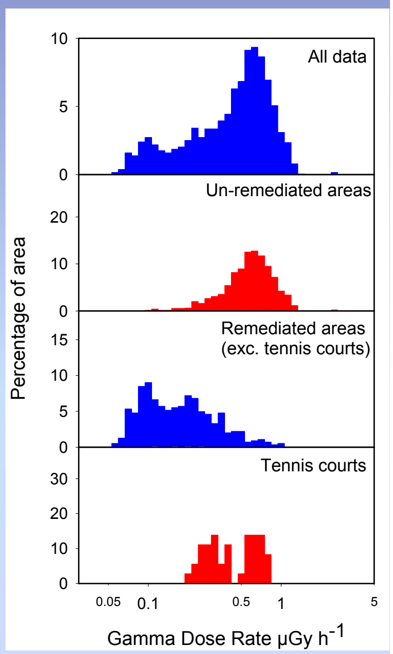




University of Glasgow

Scottish Universities Environmental Research Centre

# University of Fukushima : Gamma dose rate showing remediated areas



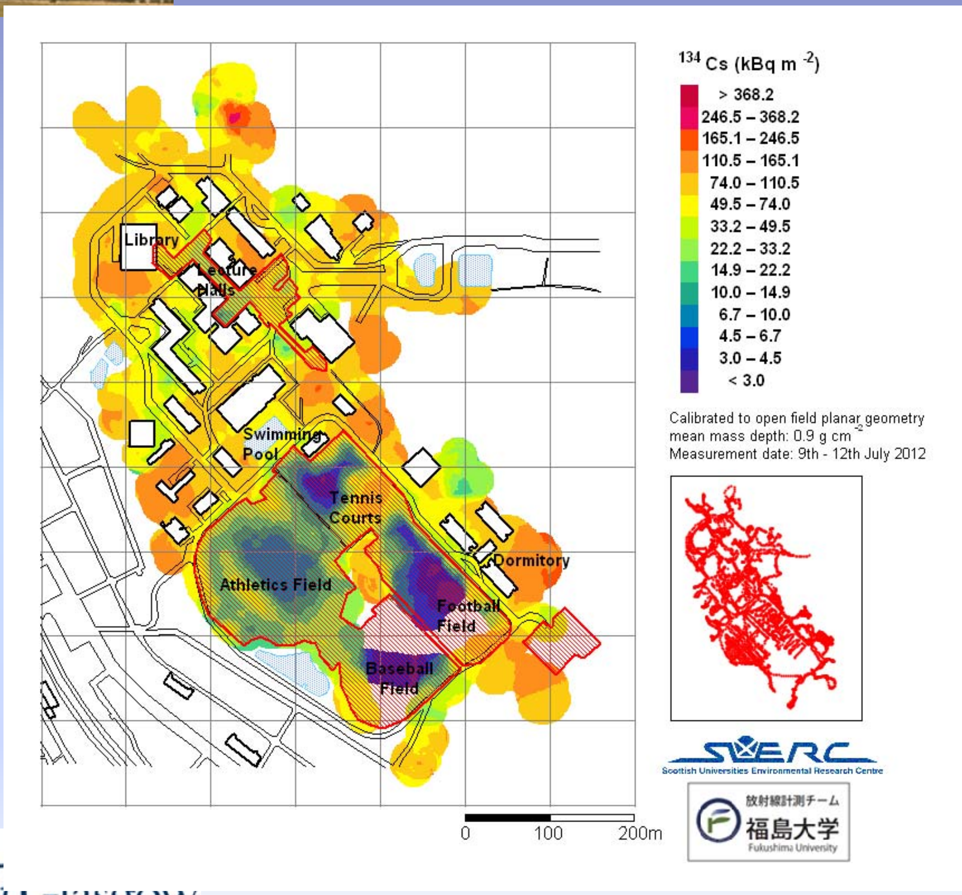



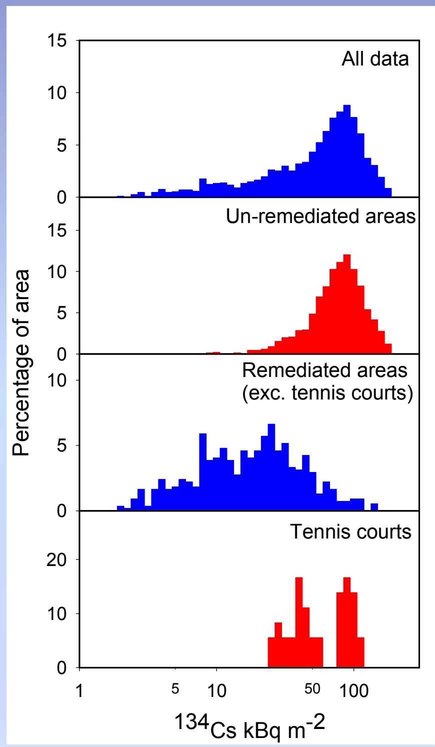

Remediated areas are on average 4 times lower than untreated areas

University of Glasgow

Scottish Universities Environmental Research Centre

# University of Fukushima : $^{134}$Cs map showing remediated areas



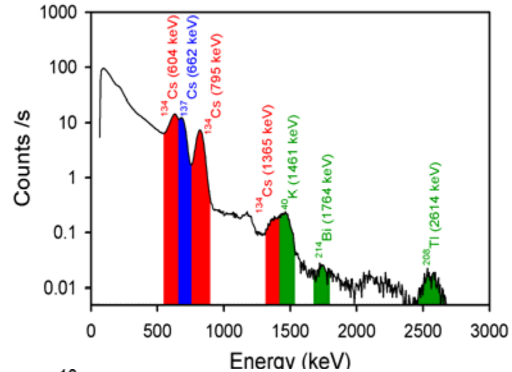



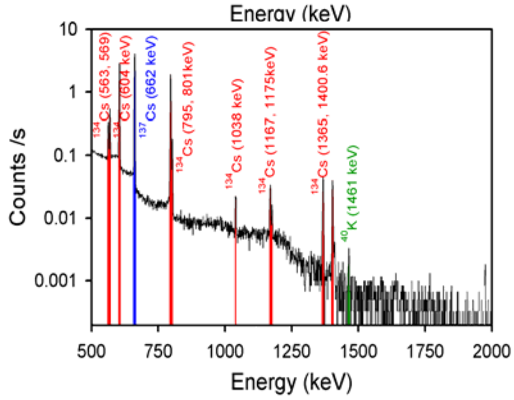


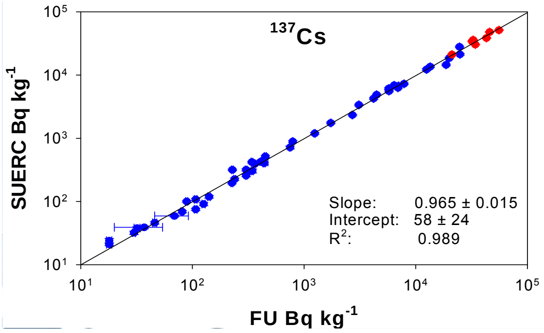

# Analysis of the effectiveness of remediation

| | $^{134}$Cs (kBq m$^{-2}$) | | $^{137}$Cs (kBq m$^{-2}$) | | Dose Rate (μGy h$^{-1}$) | |
|---|---|---|---|---|---|---|
| | Remediated | Unremediated | Remediated | Unremediated | Remediated | Unremediated |
| Mean | 23.8 | 80.0 | 36.9 | 121.4 | 0.20 | 0.58 |
| Std dev | 21.8 | 34.6 | 32.9 | 51.9 | 0.15 | 0.24 |
| Percentiles | | | | | | |
| 10$^{th}$ | 4.9 | 37.8 | 9.2 | 56.7 | 0.08 | 0.30 |
| 50$^{th}$ | 17.2 | 76.8 | 27.7 | 117.2 | 0.15 | 0.56 |
| 90$^{th}$ | 48.6 | 124.3 | 76.2 | 189.9 | 0.36 | 0.87 |

Remediated areas are on average 4 times lower than untreated areas



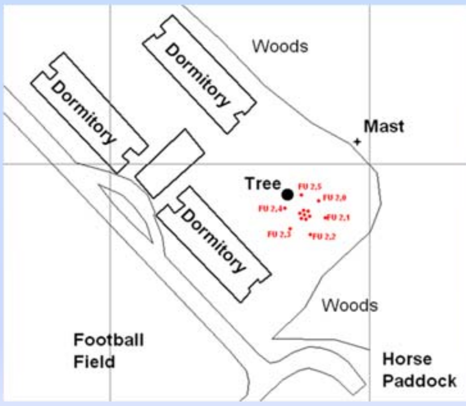



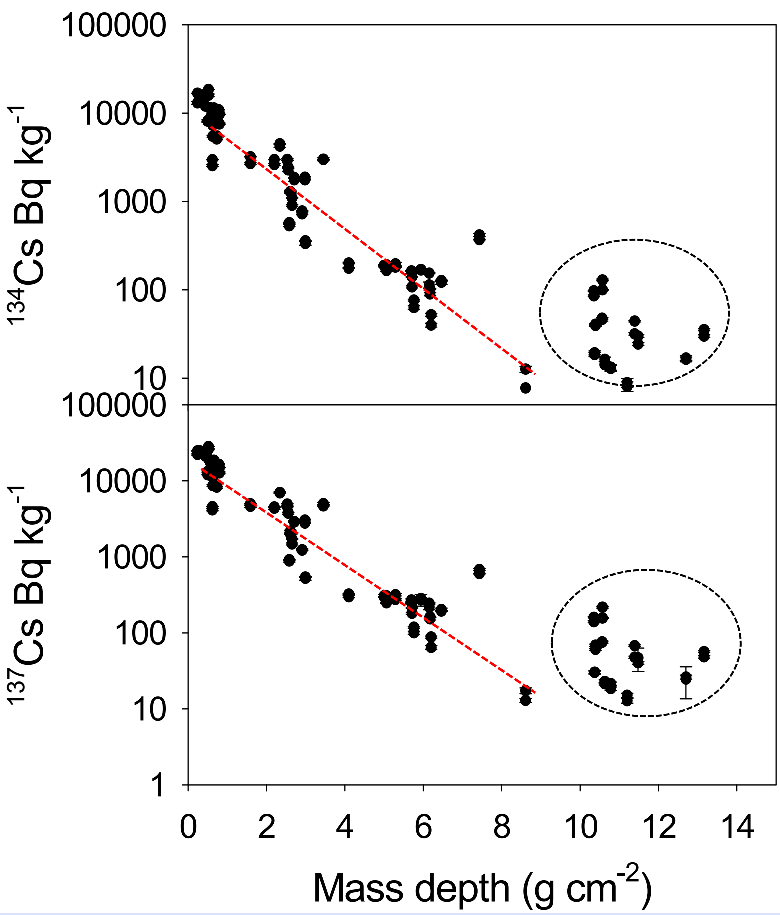

## Calibration site at Fukushima University

- Sampled in July 2012
- Tyler et al 1996,*J. Environ. Radioactivity, 33(3), 213-235*.
- Soil cores analysed at Fukushima and SUERC
- Relative to international standards
- Results in good agreement for $^{137}$Cs
- Reference values can be used to check dose rate and in-situ instruments and by local groups

Mean mass depth : 0.9 ± 0.1 g cm$^{-2}$
$^{137}$Cs 265 ± 20 kBq m$^{-2}$
$^{134}$Cs 165 ± 20 kBq m$^{-2}$
Dose rate 1.24 ± 0.13 μGy h$^{-1}$




Scottish Universities Environmental Research Centre



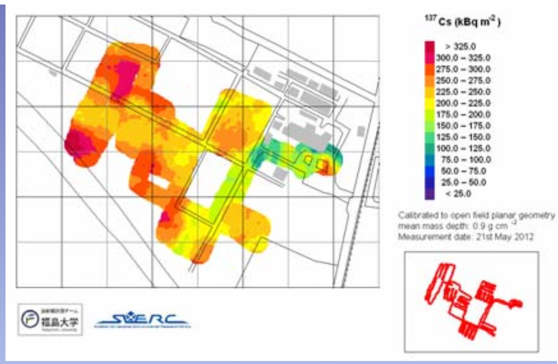

## Calibration site at Fukushima University

- Depth Profiles from 13 cores
- Above 10 g cm$^{-2}$ the profiles are approximately exponential with mean mass of 0.9 g cm$^{-2}$
- But do the data below 10 g cm$^{-2}$ belong to the same distribution?
  - Why not?
  - Sample handling?
  - Multiple components?

University of Glasgow

Scottish Universities Environmental Research Centre

# Fukushima Prefecture Fruit Tree Research Institute

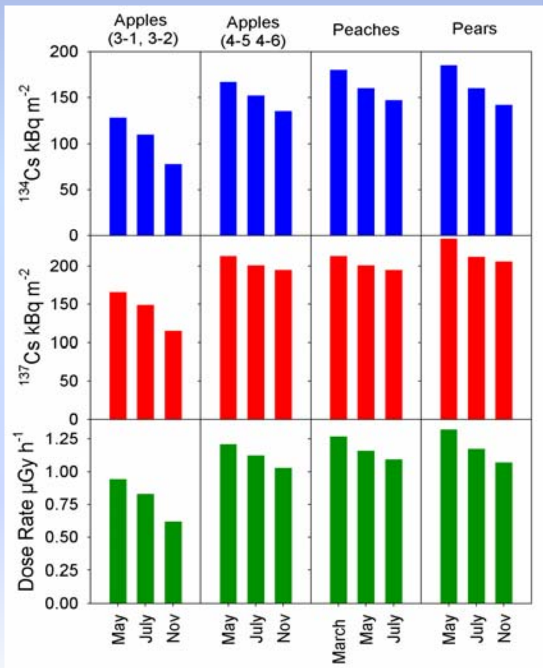



Do radiometric data from experimental orchards help to understand the pathways and impacts of fruit cultivation in the presence radiocaesium?

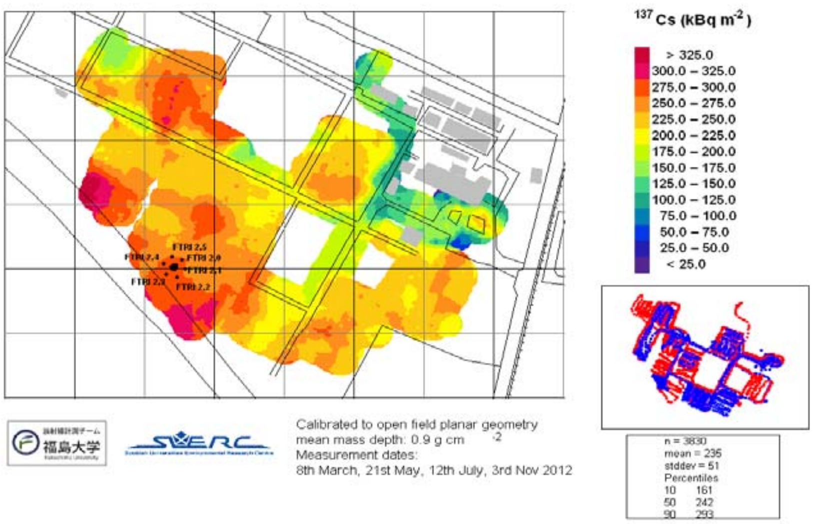
Can we use this to evaluate solutions?

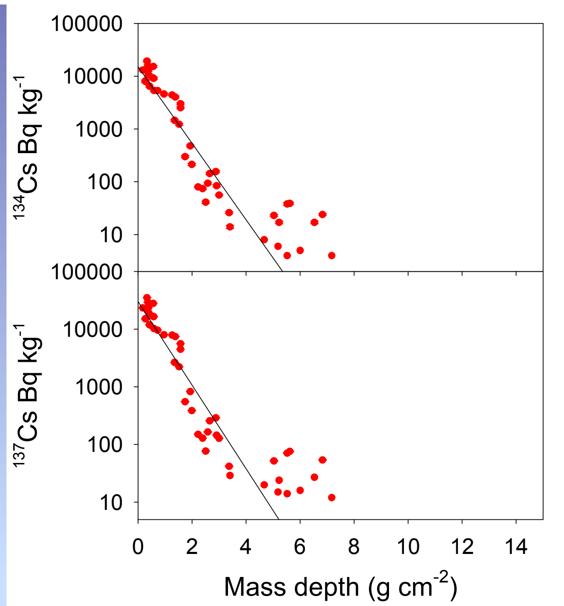
Mapping in March, May, July and Nov 2012 with training

Calibration site sampled




University of Glasgow



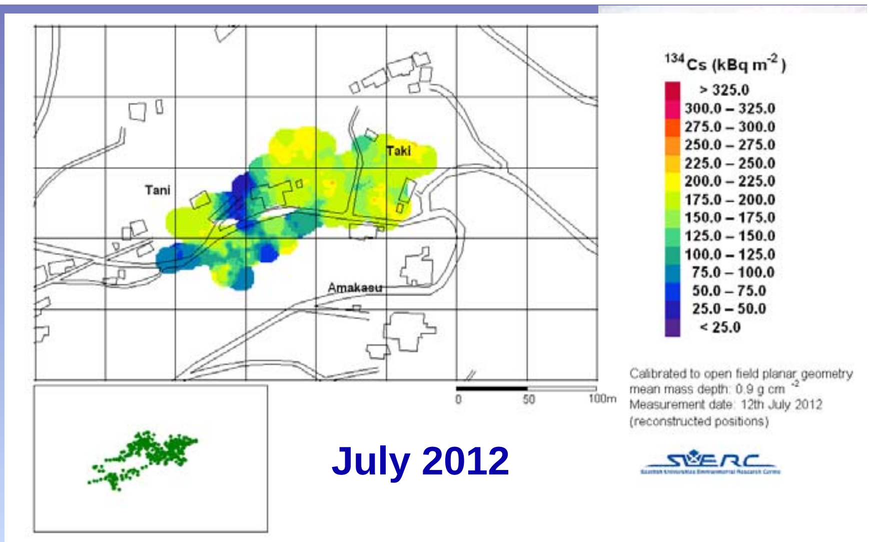

| | Reference Value | Backpack measurement |
|---|---|---|
| $^{134}$Cs kBq m$^{-2}$ | 135 ± 20 | 171 ± 3 |
| $^{137}$Cs kBq m$^{-2}$ | 245 ± 30 | 263 ± 6 |

Reference value for 3rd November 2012. Mean mass depth 0.70 ± 0.05 g cm$^{-2}$. Calculated from gamma spectrometry at SUERC, no comparison with FU yet.
Backpack measurements calibrated to FU calibration site, mean mass depth 0.9 g cm$^{-2}$.

University of Glasgow

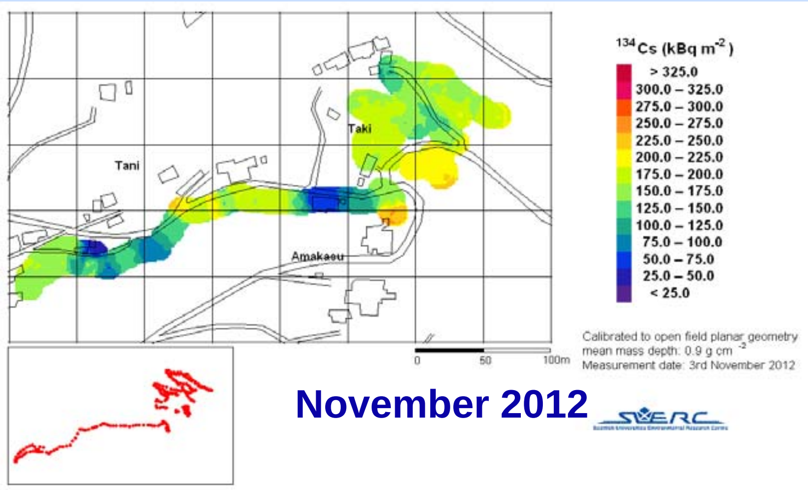
SUERC Scottish Universities Environmental Research Centre

## Citrus cultivation near Mount Shinobu




"Yuzu" fruit from 2012 shows higher levels of radioactivity (by an order of magnitude) than apples, pears, peaches and grapes cultivated in Fukushima

Why?




**IAEA Technical report 472**

Interception?

Translocation?

Root uptake?

Soil immobilisation?

Contamination levels?

We think that the clue lies in evergreen nature of the tree, coupled to local topography

---

## Biomass energy harvesting and phytoremediation ? Can they be used synergistically?

FCO prosperity funded investigation with Mitsubishi Morgan Stanley, Suncare, University of Tsukuba, NNL, and input from SUERC

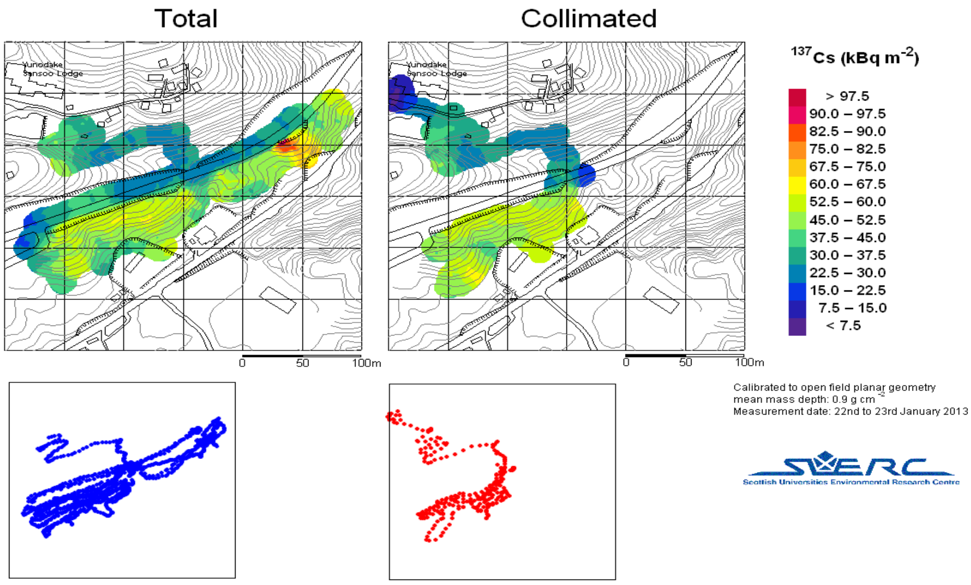
January 2013 fieldwork near Iwaki using a collimator to establish the proportions of total Cs radiation originating in forest canopy

Remapping following forest litter removal to determine remediation factor

Control area to account for environmental change

University of Glasgow

SUERC Scottish Universities Environmental Research Centre




| | Cedar | | | Deciduous | | |
|---|---|---|---|---|---|---|
| | Uncollimated | Collimated | Reduction | Uncollimated | Collimated | Reduction |
| Number | 459 | 174 | | 35 | 18 | |
| $^{134}Cs$ kBq m$^{-2}$ | 25.8 ± 0.2 | 24.7 ± 0.2 | 1.1 ± 0.3 | 14.4 ± 0.3 | 13.5 ± 0.4 | 0.9 ± 0.5 |
| $^{137}Cs$ kBq m$^{-2}$ | 53.0 ± 0.4 | 53.0 ± 0.4 | 0.0 ± 0.6 | 28.7 ± 0.7 | 27.8 ± 0.7 | 0.9 ± 1.0 |
| Dose Rate μGy h$^{-1}$ | 0.258 ± 0.001 | 0.253 ± 0.002 | 0.005 ± 0.002 | 0.157 ± 0.002 | 0.150 ± 0.003 | 0.007 ± 0.004 |

University of Glasgow

SUERC Scottish Universities Environmental Research Centre

# Discussion points and conclusions

- Both low and high resolution spectrometry can be used for quantitative AGS, CGS and ground based mapping of radiocaesium and gamma dose rate
- Post Chernobyl experience, and experience of measuring the footprint of nuclear sites, and the impact of discharges to the Irish sea have provided a framework for validation of methods
- AGS is well suited to detailed regional scale investigations providing low ground clearance and close line spacings are used
- Protocols and data exchange formats have been defined in EU research, and quantitative international validation studies performed
- For more detailed work ground based approaches yield greater spatial resolution, appropriate to site specific evaluations
- Last year's visits have confirmed the utility of radiometrics as a means of targetting and evaluating remediation, and helping to understand the distribution and dynamic behaviour of radiocaesium in important urban and rural systems
- Calibration sites were sampled and analysed in two locations providing an initial basis for cross-validation of Japanese and international teams
- It is hoped that this work can be extended in the future with the aim of helping to improve confidence in the long term recovery of Fukushima