Time to establish a ^{137}Cs-derived net soil redistribution baseline for Australia?

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Abstract
Reliable quantitative data on the extent and rates of soil erosion are needed to underpin the selection of effective soil conservation measures, to inform carbon balances for greenhouse gas abatement and carbon storage and in understanding soil function across landscapes for sustainable agricultural systems. The caesium-137 (^{137}Cs) technique has been used successfully in many parts of the world to estimate net (ca. 30-50 years) soil redistribution by wind and water erosion and tillage activities. It is a point-based technique that lends itself to mapping over large areas but which has hitherto been confined largely to individual fields and hillslopes. The application of the ^{137}Cs technique to map soil redistribution every ≈5 km across Australia is achieved using geostatistics and nationally coordinated measurements from ≈200 locations. Between the mid-1950s to early 1990s the median net soil redistribution for the Australian continent was -0.19 t ha^{-1} yr^{-1}. Soil erosion exceeding 0.5 t ha^{-1} yr^{-1} was estimated to occur over 16% of Australia, mainly in the cultivated regions where the median net soil redistribution was -1.26 t ha^{-1} yr^{-1}, more than eight times larger than the rate on uncultivated land (-0.16 t ha^{-1} yr^{-1}). The approach demonstrates a viable methodology for establishing a national baseline which could be readily applied in other countries. The baseline map of net soil redistribution and its uncertainty provide the opportunity to optimise a future ^{137}Cs survey before ^{137}Cs detection is not viable. We propose that this baseline map of net soil redistribution is updated using measurements from samples collected as part of other national campaigns.

Key Words
Caesium-137 (^{137}Cs), soil erosion, geostatistics, sequential indicator co-simulation, rainfall, land-use

Introduction
Soil erosion may be a highly selective process causing fine, nutrient-rich material to be removed, progressively coarsening the soil and reducing the moisture capacity. Accumulation of dust, however, can significantly improve soil fertility. Degradation of soil particularly by erosion decreases agricultural productivity and has considerable on-site and off-site impacts and costs, evident in the September, 2009 Australian dust storms. Changes in land use are widely recognised as capable of greatly accelerating soil erosion and erosion in excess of soil production may result in decreased agricultural potential. The loss of vegetation cover increases the susceptibility of the soil to erosion (erodibility) by wind, water and tillage. Whilst erodibility maps raise the awareness of the risk of soil erosion they may be misleading as management tools because soil redistribution processes may not be adequately taken into account.

Most soil erosion measurement and monitoring approaches have limited representativeness and insufficient duration, to provide reliable estimates of soil erosion. It is particularly problematic in semi-arid environments where soil erosion is highly variable in space and time and often insidious requiring the removal of considerable quantities before loss is noticeable. Extrapolation of results from small experimental plots across large areas is notoriously unreliable. These difficulties in measuring and monitoring soil erosion in space and time are likely responsible for its common neglect in carbon balances for greenhouse gas abatement and carbon storage and in understanding soil function across landscapes and agricultural systems. The aim here is to provide the first map of ^{137}Cs-derived net (mid 1950s to early 1990s) soil redistribution across Australia. The intention is for this map to serve as a baseline against which subsequent national assessments may be made and to raise awareness of the methodology for sampling and mapping over the continent using few samples.

The artificial radioactive tracer caesium-137 (^{137}Cs) has been used successfully to measure net (ca. 40 year) soil redistribution rates in many environments including Australia (Ritchie and McHenry, 1990). Its widespread use is probably because the ^{137}Cs technique overcomes many of the problems of monitoring soil erosion and deposition over the medium-term (5 to 50 years) and at the hillslope scale (Walling and Quine, 1991). In this respect, the ^{137}Cs technique offers the greatest potential for measuring net soil flux in semi-arid environments where soil flux monitoring difficulties are compounded by considerable spatial and temporal variability of the controlling factors. The ^{137}Cs technique has commonly been applied to small areas (fields or hillslopes) often because the use of traditional approaches to sampling using regular grids and large area mapping is prohibitively expensive and therefore representative baselines using the ^{137}Cs technique over very large areas have not previously been attempted. However, the combination of nested sampling and geostatistics has considerably extended the size of the area that may be investigated and mapped (de Roo, 1991; Chappell, 1998; Chappell and Warren, 2003). A national reconnaissance survey of ^{137}Cs-derived soil erosion in Australia was instigated during the early 1990s for selected agro-economic sites (206 sites) and the national perspective was presented by Loughran *et al*. (2004). These samples are used here with geostatistics to produce a preliminary map of net soil redistribution across the continent. A related map of the spatial uncertainty is used to discuss improvements in the maps and for establishing a baseline before the ^{137}Cs technique becomes no longer viable.

Methods

Field and laboratory methods

This study used the measurements from the national reconnaissance survey. The survey collected soil along single transects, down complete slopes, at paired sites in the same locality as typical land management practices within selected agricultural-economic regions. Field sampling commenced in 1991 and over 5000 samples were collected and analysed for 206 sites throughout Australia (Figure 1a). The way in which the samples were obtained from the soil, their preparation for, and the method of, gamma-ray spectrometry to measure ^{137}Cs activity is described in Loughran *et al*. (2004).

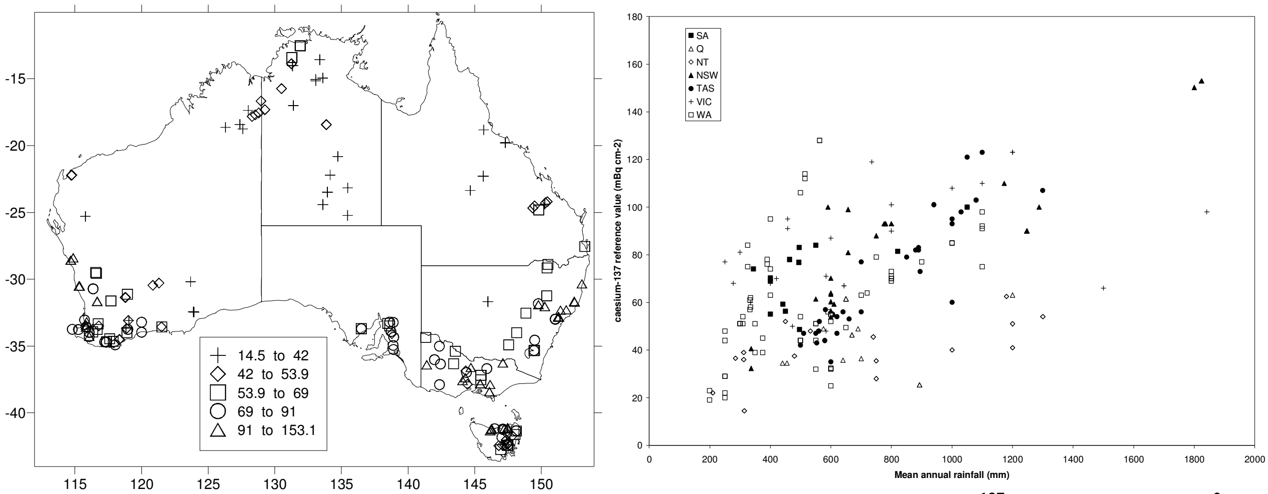

Figure 1. Locations of sites in Australia where soil was sampled for use as a reference ^{137}Cs value (mBq cm^2) (a) and the relationship between long-term (1954-1990) mean annual rainfall and ^{137}Cs reference values separated for each state and territory (b).

^{137}Cs technique for estimating net soil redistribution

Thermonuclear weapons tests performed above ground in the 1950s released the artificial radionuclide caesium-137 (^{137}Cs) into the atmosphere where it circulated within each of the Earth's hemispheres. The ^{137}Cs arrived at the Earth's surface with rainfall and is strongly associated with its spatial distribution (Figure 1b). It is assumed that once the ^{137}Cs reached the soil surface it was fixed rapidly and firmly to soils and becomes an effective tracer of soil redistribution (Ritchie and McHenry, 1990). At locations in the landscape where there is little or no soil erosion or deposition (undisturbed) the amount of ^{137}Cs in the soil is reduced by radioactive decay (^{137}Cs half-life 30.2 years). At other locations the amount of soil ^{137}Cs is a function of the erosion and / or deposition intensity and duration. A calibration relationship is required to convert the percentage of ^{137}Cs lost or gained (X) relative to the ^{137}Cs inventory at the undisturbed reference location. This study follows that of Loughran *et al*. (2004) and uses two models; one for calculating net soil loss (Y; kg ha^{-1} yr^{-1}) for sites which had never been cultivated (N=31; Equation 1) and the other for sites which had been used for cultivation (N=61; Equation 2):

$$Y=17.49\ (1.0821)^X \quad (1)$$

$$Y=296.1\ (1.0539)^X \quad (2)$$

Net soil accumulation was calculated using these equations in reverse mode for sites which had gained ^{137}Cs. In this case, Y is net soil gain and X is the percentage ^{137}Cs gain relative to the reference value. Both relationships were derived from long-term soil-loss measurements using runoff-erosion plots, or similar experiments in New South Wales, Queensland and Western Australia (Loughran and Elliott, 1996).

Mapping net soil redistribution

The few studies that have accurately mapped net soil flux over large areas have used innovative sampling designs and/or geostatistical procedures. However, the map of local estimates from (co-)kriging often smoothes out local details. Such conditional bias is a serious shortcoming when trying to detect patterns of extremes such as zones of large and small ^{137}Cs and soil erosion. Sequential indicator co-simulation for uncertainty modelling is used here to generate an ensemble of equally probable realisations of the property spatial distribution and enable differences amongst the realisations to be used as a measure of uncertainty. A map of reference ^{137}Cs and its uncertainty is produced using sequential indicator co-simulation with long-term (1954-1990) mean annual rainfall data for Australia (Jeffrey *et al*., 2001). A map of ^{137}Cs activity and its uncertainty is produced using the same technique but combined with the Australian Soil Classification. The percentage difference between these maps relative to the reference value is used to calculate net soil redistribution using the equations (1 and 2) above. Land use data (1992/93) mapped at the national scale provided by the Bureau of Rural Sciences determined whether a point was ever cultivated or not and therefore which equation to use in the estimate.

Results

The median indicator variograms of ^{137}Cs reference inventory and ^{137}Cs inventory (not shown) were fitted best with linear-with-sill models and identified a range of spatial dependence of around 2150 km (21°). In both cases a large proportion (>50%) of the total variance was nugget. A considerable amount of variation in these properties had not been captured by the median values of the reconnaissance survey samples. The values of the optimised model parameters were used in the median approximation sequential indicator (co-) simulations. The linear-with-sill model could not be used in this process and was replaced by the spherical model as an adequate approximation of the former model.

The map of per-point median ^{137}Cs reference inventory is shown in Figure 2a. There is good correspondence between the measured reference values (Figure 1a) and the map. Notably, the ^{137}Cs reference pattern resembles that of rainfall but does not over-estimate the reference values in northern Australia where rainfall is large. This pattern is consistent with the expected fallout pattern. The per-point interquartile range is small considering the relatively few samples across the continent because of the relationship with the rainfall data. Where the variance is large there are very few, if any, samples and it is in these areas that future samples should be obtained to improve the map and establish the reference inventory.

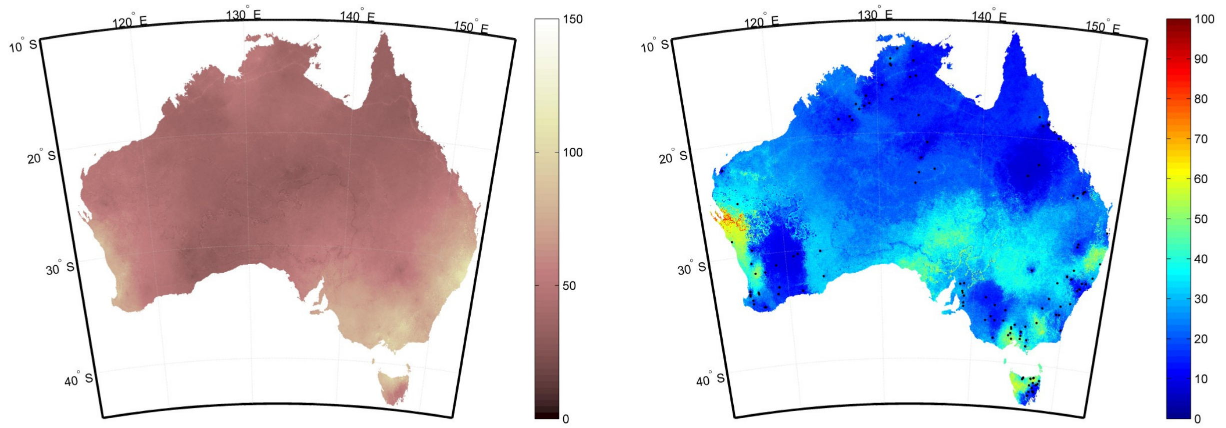

Figure 2. The per-point median ^{137}Cs reference inventory (mBq cm^{-2}) (a) and interquartile range (mBq cm^{-2}) from the median approximation of sequential indicator co-simulation with long-term (1954-1990) mean annual rainfall.

The map of per-point median ^{137}Cs activity shows that across Australia there is less ^{137}Cs activity than the reference values (not shown). The percentage difference between the ^{137}Cs reference map and the activity map shows this pattern and also identifies those locations where there is net ^{137}Cs gain (not shown). The land-use classification was used to determine which of the empirical models to use in the conversion of the percentage ^{137}Cs difference to net soil redistribution. The per-point realisations median net soil redistribution shows areas that are stable, depositional or have very small erosion rates across the majority of Australia. Areas that have large net erosion rates include the main cultivated areas along the coastal regions of Western Australia, South Australia, Victoria, New South Wales and Queensland. The most eroded area is in the western most region of Western Australia (Pilbara region). Assuming a symmetrical distribution in the realisations this region has an erosion rate with uncertainty of >6±3 t ha^{-1} yr^{-1}. The areas of greatest uncertainty include mid South Australia, mid New South Wales and south-west Queensland. The areas of greatest uncertainty are those associated with net soil gain. The main cultivation regions of Australia are similarly uncertain (±2 t ha^{-1} yr^{-1}) and there is more than a 60% probability that these regions are eroding.

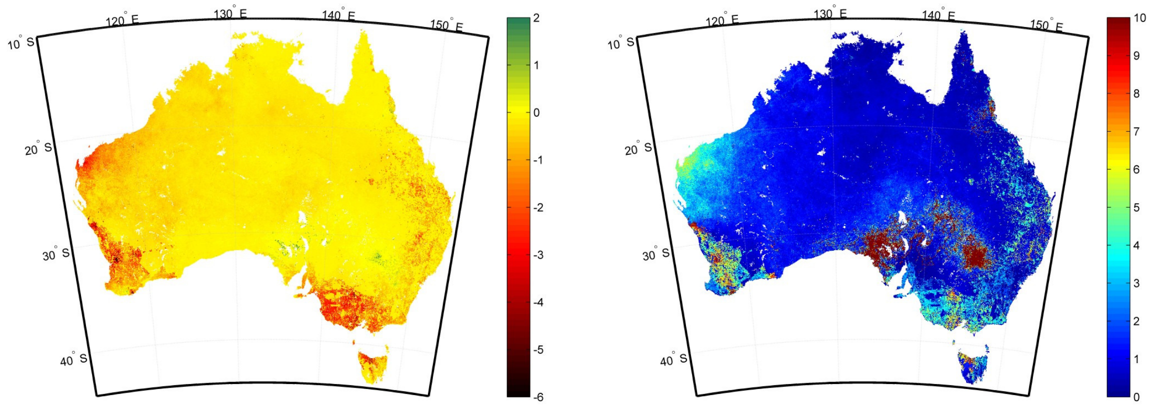

Figure 3. The per-point median ^{137}Cs-derived net (1950s-1990) soil redistribution rate (t ha^{-1} yr^{-1}) of Australia (a) and its interquartile range (t ha^{-1} yr^{-1}) (b).

Conclusion

We presented a workflow for the estimation of a baseline ^{137}Cs-derived net soil redistribution across Australia which represents its status in the early 1990s. The workflow is based on the soil ^{137}Cs samples collected at that time and the sequential indicator simulations with ancillary (rainfall and soil type) data. The results demonstrated that the geostatistical techniques applied here provide a powerful method to estimate ^{137}Cs and net soil redistribution across Australia using few samples. Many soil profiles have been collected across Australia and stored in the national soil archive and others are being collected as part of new national programmes. These samples may be suitable for ^{137}Cs measurement to improve the current map and to produce a new map which enables consideration of previous management practices and soil conservation policies. Any future national ^{137}Cs samples for comparison with the baseline should be undertaken soon before detection is not viable.

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