Geographical Systems Approach to the Assessment of Soil Erosion Using RUSLE Model

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Keywords

Erosion, Universal Soil Loss equation, Cover management, Supporting practice, Environmental Accounts, #OpenData, Queensland Murray-Darling Basin.

Abstract

Knowledge of long term soil loss by water erosion is fundamental to assess soil health for natural resource management and the development of regional environmental accounts. We developed a spatially explicit model based on the Revised Universal Soil Loss Equation (RUSLE) to quantify soil erosion between 1870 and 2012 in Queensland's Murray-Darling Basin region. To examine human impacts on erosion, we compared two long-term scenarios: historical conditions, based on historical land use change; and reference conditions, based on pre-European vegetation cover. Spatially variable factors for the RUSLE model were derived from state-wide datasets as best available information. We produced statistics and maps of soil depths across 186 map units under historical and reference conditions and calculated indicator condition scores for soil erosion, contributing towards a soil condition measure for environmental accounting.

Introduction

In *Accounting metrics for building regionally based environmental accounts* (2008), the Wentworth Group outlined a simple way to account for natural assets on a broad scale. Regional environmental accounts should enable communities to understand and track the status and direction of changes to environmental assets. Regionally based benchmarks of health relative to a reference condition were central to the design and allow for calculation of net losses and gains. Results could then be compared across regions for any asset and scale. The focus was to identify indicators that measured condition of environmental assets, consolidate expert opinion (to identify methods, data, analysis and reference conditions) and use existing datasets.

Soil assets are ecologically valuable and an important component of environmental accounts. A measure of soil asset condition for environmental accounting required an appropriate water erosion measure for the Queensland Murray-Darling Basin (QMDB; **Figure 28**). This paper outlines the methods undertaken to calculate the water erosion indicator for soil condition in the Land Account for the Queensland Murray-Darling Basin. In developing this paper, we considered four questions central to the development of a soil condition account:

1. How much soil has been lost across the QMDB through water erosion?
2. How have rates of erosion changed over time?
3. Can we demonstrate the impacts of management actions to reduce/reverse erosion? (a key question facing those reviewing the Natural Resource Management plan for the Border Rivers / Maranoa-Balonne).
4. Can the RUSLE be used as an indicator for monitoring change in soil water erosion (condition indicator) over time?

1. Queensland Murray-Darling Committe Inc.
2. Wentworth Group of Concerned Scientists
3. CSIRO
4. Department of Natural Resources and Mines

This paper builds on the work of Brough *et al* (2004a; 2004b) and describes the activities used to improve the input data for a Universal Soil Loss Equation (RUSLE) estimate for the QMDB, to support resource planning and decision making at a regional scale. It aims to demonstrate the value of undertaking the systems approach to deriving science information products; the potential for collaboration and information sharing.

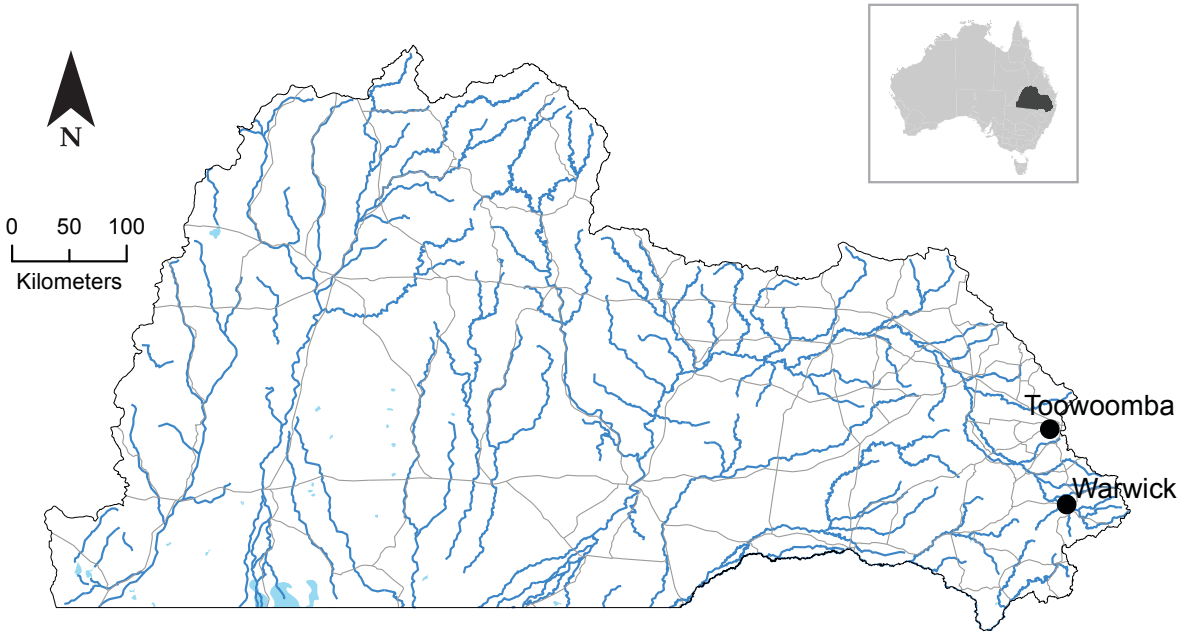

Figure 28: Location of the Queensland Murray-Darling Basin in Australia

Materials and Methods

The USLE was developed for croplands in the 1960s (Wischmeier and Smith 1965) and revised in 1997 as the RUSLE (Renard *et al.*) as a land-use independent empirical model estimating average annual sheet or rill hillslope erosion. It calculated mean annual soil loss (t ha-1 y-1) as a product of six factors: soil loss (E) due to rainfall (R), soil erodibility (K), topography (L), steepness (S), land cover management (C) and land management practice (P):

$$E=RKLSCP$$

Although the RUSLE doesn't account for soil loss from gully, wind or tillage erosion, it was selected as the most appropriate method based on the modest amount of parameters, ability to adapt to Australian conditions (Lu *et al.* 2001), availability of digital data (Rosewell 1997) and the ability to predict erosion potential on a cell by cell basis in a raster based Geographical Information System (GIS) (Lu *et al.* 2001). Importantly, it estimates the soil loss from the largest proportion of the land area supporting the production base.

Data Acquisition

Data was compiled from different sources, scales and projections (**Table 17**). The following criteria were used to select the best available datasets:

- Consistently captured and complete for the entire study area.
- Processing steps kept to a minimum to limit resampling errors.
- Can be used to detect change (over a suitable time scale).

Table 17. Properties of spatially distributed maps used as factors to implement RUSLE.

Table 17: Properties of spatially distributed maps used as factors to implement RUSLE.

A =	R *	K *	L *	S *	C *	P
AVERAGE ANNUAL SOIL LOSS DUE TO WATER (T/HA/YR)	Rainfall Erosivity runoff factor	Soil Erodibility factor	Slope length factor	Slope-gradient (steepness) factor	Cover management	Supporting erosion control practice
LOGIC	Derived from daily rainfall data as described in Lu *et al.* (2001) and improved by Brough *et al.* (2004).	Derived on soil physical characteristics of particle size, permeability and structure. More detailed descriptions in Brough (2003) and Brough *et al.* (2004)	The Hickey (2000) method was modified by capping maximum slope at 500m and masking flat areas (1%).	Accounts for an increase in erosion with increasing slope steepness.	Measured as the ratio of soil loss from land cropped for specific conditions to the corresponding loss from tilled land under continuous fallow conditions	Ratio of soil loss due to practices that modify the flow pattern, gradient, or direction of surface runoff.
ANALYSIS	Rainfall Erosivity Models.	Look-up attribute table.	GIS Terrain analysis.		Historical conditions: Look-up attribute table applied to mapped decadal land use. Reference conditions: C = 0.01.	Insufficient data so P assumed to be 1.
DATA SOURCE (SUMMARY)	Annual grid, derived from daily rainfall grids (SILO) for the years 1901-2012 and long term 100 year average.	Queensland Combined Soils Coverage (Brough *et al.* 2006a)	3 second (~90m) DEM-S SRTM (Gallant 2010)		Decadal (2009, 1999 etc) land use mapping and historical mapping projects. (also available was an annual / seasonal remotely sensed data for years 1988-2013)	Decadal (2009, 1999 etc) simplified
RESOLUTION	500m grid	92m grid, resampled to 30m	92m grid, resampled to 30m	92m grid, resampled to 30m	30m	
SI* UNIT	MJ.mm/ (ha.h.year)	t/ha/h per ha/MJ/ mm	Radians	Unit less	Range 0-1	Range 0-1
METADATA REFERENCE	(DSITIA and DNRM 2014b)	(DSITIA 2014a)	(DSITIA and DNRM 2014a)	(DSITIA 2014c)	(QLUMP 2004; ABARES 2011) Cfactor unpublished	

*Standard International Unit.

Rainfall Erosivity (R)

Rainfall erosivity was derived from daily rainfall data (averaged annually for 1900 – 2012; long-term average used pre-1900) as described in Lu *et al.* (2001) and improved by Brough *et al.* (2004a; 2004b) (**Figure 29**a). Data were supplied as 5km grids. Geoprocessing included filling null values with the mean of 5 x 5 neighbouring pixels, reprojecting and resampling to the specifications of the LS raster datasets.

Soil steepness (S), Length of slope (L), and Soil Erodibility (K)

Data for soil steepness (range 0.3 – 12.8), length of slope (1 – 9.8) and soil erodibility (0.0108 to 0.1047) were derived from a Queensland-wide analysis for the region (**Figure 29**b-d). K-factor values for the resistance of the soil to sheet and rill erosion were derived from the attributes assigned to polygons in the Queensland Combined Soil Coverage (Brough *et al.* 2006). Roswell's (1997) erodibility class classification was used to display extent of K-factor.

Cover Management (C)

C-factor was "the ratio of soil loss from land maintained under specified conditions to the corresponding loss from continuous tilled bare fallow" (Wischmeier and Smith 1965). It measured the combined effect of a range of interrelated vegetative cover and crop management variables (canopy cover x canopy height x surface cover).

We proposed two methods that differed in spatial and temporal resolution. Method 1 used remote sensing data to provide a high-resolution (30m) annual land cover surface (1988 – 2013) while Method 2 was a compilation of decadal historical datasets over the long term (1870 -2012). We used method 2 in the environmental account because of the ability to compare among years and examine long term trends (**Figure 29**e).

Method 1: Remote Sensing C-factor

Spatially and temporally variable C-factor estimates for 1988-2013 were created using the remotely sensed (end of dry season, Landsat archive from 1986) Bare Ground Index (Byrne *et al.* 2004; Searle and Ellis 2009) and more recently the fractional cover index (fCI) (Trevithick and Scarth 2013). Remotely sensed data was available at a 30m resolution raster for the years 1988-2013. It was derived from seasonal Landsat fractional cover data and provided as is by the Queensland Remote Sensing Centre, Science Division, Queensland Department of Science, Information Technology and the Arts.

Method 2: Historical Compilation C-factor

To build a historical land use layer dataset from 1870 to 2012, we developed a process to identify

a) useful attributes to record land use and/or management;

b) for including expert opinion in determining land use/management;

c) a summary of major changes in land use;

d) availability and type of data; and

e) decision rules for assigning estimates of cover factor.

The following data was obtained to assist in the spatial mapping of land use:

1. Attributes to be used to record land use and/or management
2. Expert opinion was obtained for both potential sources of data and local knowledge. A 50 kilometre grid index (APDS 2013) was used to describe occurrence (present, absent or unknown); and distribution (widespread, localised) of cropping and clearing. Some local knowledge provided was quite specific / property based.
3. A summary of historical land use changes in the QMDB was compiled as a table. Key periods include: Pre-settlement 1770, Pastoral settlement 1840-1880; Closer settlement 1880-1940, World War I, Tractor-based farming starts (1939), World War II, First salinity and erosion appears (1955), Broad-scale clearing 1960-1980, End Burn Bash Bury (physical agriculture) 1979, Start minimum till (chemical agriculture) 1989.
4. Many of the attributes were estimated based on historical land and soil surveys (DNRM 1953; 1959a; b; 1963; 1988a; b; c; d; 2006; 2012; Isbell 1956; MDBC 1976).
5. Decision rules for assigning estimates of cover factor.

Historical land use changes would be mapped at the year ending each decade due to data availability. A classification was assigned to each of the polygons (**Table 18**).

Table 18: Simplified land use classes developed for QMDC soil account.

Simplified land Use	Simplified land use sub-group	Notes
Cleared	CLEARED	
Uncleared	CONSERVATION	Remnant vegetation (current extent) (DNRM 2013)
Cultivated	OLD CROPPING	All areas identified as cultivated and not classed as New Cropping.
	NEW CROPPING	Based on figures published by GRDC (Llewellyn and D'Emden 2009) the estimated area of adoption for Zero till was ~1% 1969, 2-20% in 1979, 20-52% in 1989 and 52-85% in 1999. It was assumed that higher 'quality' cropping country would have been a priority for zero till adoption; it was assumed that similar criteria to those used to identify Strategic Cropping land would be a sufficient proxy. Earlier adoption of zero till was assumed to originate from near Dalby and Toowoomba in the early 1960s.
	HORTICULTURE	Not mapped as part of this version
	IRRIGATION	Not mapped as part of this version
Water	WATER	

Potential C-factor values (**Table 19**) were estimated by reclassifying Queensland Broad Vegetation Groups according to land cover types and assigning to the simplified set of land use classes listed in **Table 18** (assuming groundcover of 70% for grasslands). Cropping values were based on Freebairn *et al.* (1986; 1989) for east of Chinchilla, and Freebairn *et al.* (2009) for west of Chinchilla. All pasture values were derived from Silburn *et al.* (2011) and Silburn (Silburn 2011).

Table 19: Estimated C-factor for land cover types.

Land cover type^	C-factor	Note/Source
Rainforests	0.0001	DBVG5M=1
Closed forests	0.0010	Default, used where c-factor is unknown, usually where foliage projection in canopy is >20%
Nature Conservation^	0.0050	DBVG5M= 4, 5, 9 and 10(Silburn 2013)
Undisturbed, bare land	0.4500	
Pasture cover		
100%	0.0020	Function of pasture cover (Silburn 2014)
80%	0.0130	Function of pasture cover (Silburn 2014)
50%	0.0670	DBVG5M=6, 13, 14
40%	0.0990	Function of pasture cover (Silburn 2014)
30%	0.1410	
20%	0.2000	
10%	0.2910	
New cropping^	0.1500	Winter crop – summer fallow; Zero tillage. Applied to eastern Condamine to Chinchilla, including Brigalow (Silburn 2014)
New cropping^	0.2100	Summer crop, winter fallow – minimum tillage. Applied west of Condamine (Silburn 2014).
Old cropping^	0.4700	Summer crop, winter fallow – Wallumbilla chisel. Applied west of Condamine (Silburn 2014). All years.
Old cropping^	0.7500	Winter crop – summer fallow, stubble burnt. Applied to eastern region. Condamine to Chinchilla, including Brigalow (Silburn 2014).
Summer crop, winter fallow; Disc/chisel tillage	0.6200	(Silburn 2014)
Highly disturbed, bare land	1.0000	

^Simplified Land Use category) (Blackley 2014)

Supporting Practice (P)

Very few studies include the support practice factor as it's often difficult to identify disturbed lands, including cultivation, that have been managed for erosion by systems of diversion/contour banks, terracing and strip cropping. Furthermore, the C-factors in **Table 19** for crop lands were measured between contour banks (terraces) so already account for their effects; some error (underestimation) may occur where/when contour banks were not in use *e.g.* old cropping. Where known, supporting practices could be integrated into the RUSLE as per **Table 19**, however supporting practices are currently unknown so the P factor was set to 1.

Table 20: Land cover types and P-factor (after Kuok et al. 2013)

Support practice	P-factor	Note
UNFARMED LANDS	0.001	
CONTOUR STRIP-CROPPING	0.350	Strip-cropping is used in the Condamine but only on/near flat land
CONTOURING	0.600	
TERRACING	0.150	
NONE	1.000	No erosion support practices

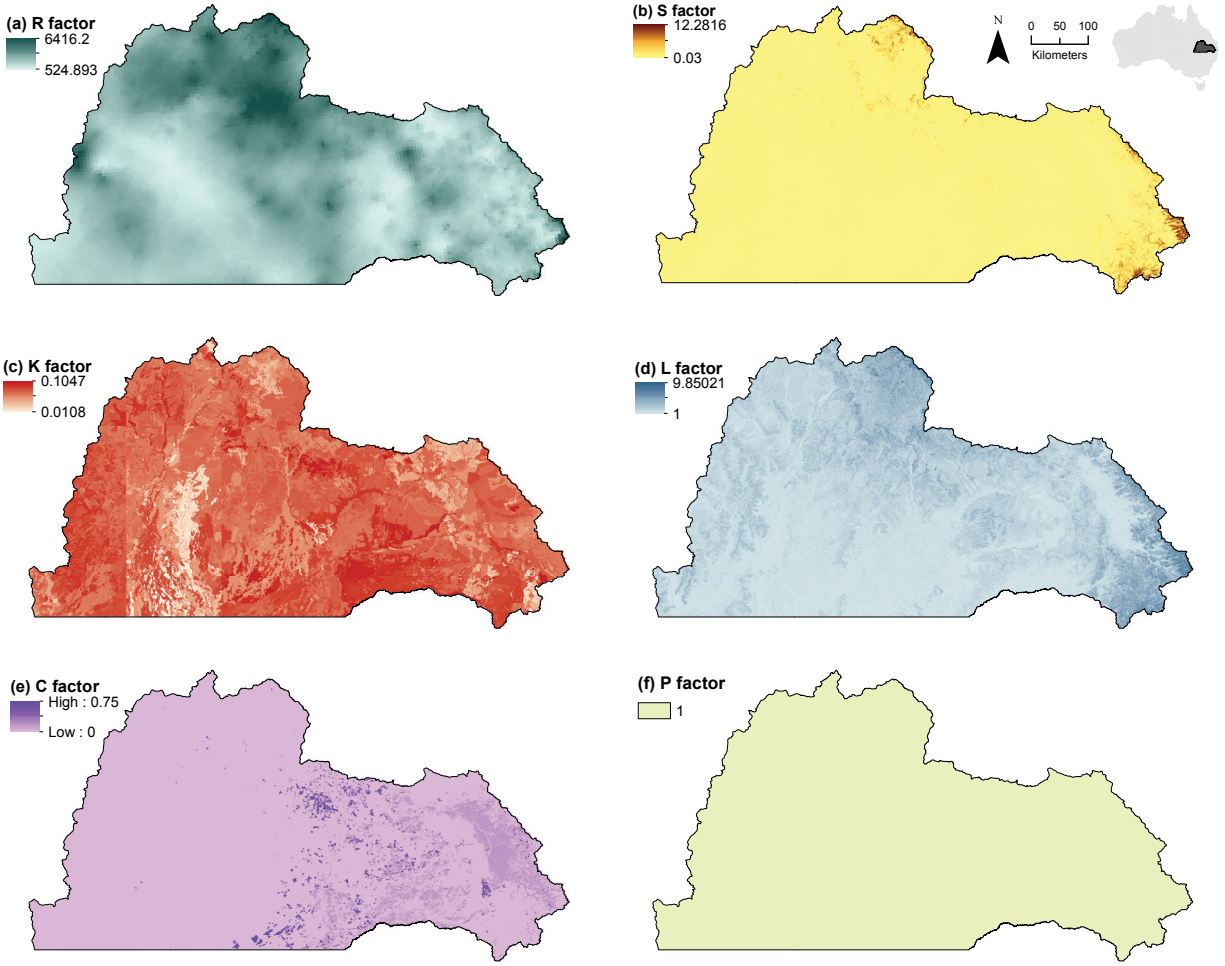

Figure 29: Spatial distribution of erosion factors: (a) rainfall erosivity (2012), R; (b) slope steepness, S; (c) soil erodibility, K; (d) length of slope, L; (e) cover management (2012), C; and (f) supporting practice, P.

Analysis

Our analysis had three components:
(1) data processing and management;
(2) modelling soil erosion under historical and reference conditions between 1870 and 2012;
(3) converting to soil depth on a cumulative basis for clearer interpretation; and
(4) calculating the indicator condition score.

Data Processing and Management

Datasets were transformed into the following spatial framework:

- GDA94 Australian Albers projection
- 30m x 30m grid, to minimise rounding and resampling errors
- Extent limited to Queensland Murray-Darling Basin
- Single band, double precision, 64bit pixel depth.
- Vector data converted to raster (as per DSITIA and DNRM 2014a).

Following best practice principles (Black *et al.* 2011), at least three versions of data were maintained: raw, working and final. Lineage was maintained as 'decision rules' and working versions were assigned a corresponding version number. Spatial coverages were stored on the secure server at Queensland Murray-Darling Committee Inc. and publicly available on the CRIS server (Blackley 2014).

Modelling Historical and Reference Conditions

Land use and management practices potentially have a major impact on predicted rate of soil loss (Lu *et al.* 2003) and may cause significant local problems. Broadacre industries, including grazed woodlands, contribute a significant proportion to the total loss due to the vast extent of land they occupy.

To quantify the impact of land use and management practices on predicted erosion, historical erosion was compared to erosion under natural pre-European vegetation cover (reference conditions). Annual soil erosion was modelled using the RUSLE model under historical and reference conditions (1870 to 2012). The historical model used the R, K, L, S, C and P factors (**Table 17**), with the C factor reflecting historical vegetation cover and land use change. The reference model used the same R, K, L, S and P factors but used a fixed C factor to reflect natural vegetation cover (C = 0.01). The resulting model yielded soil erosion in tonnes per hectare per year (t ha^{-1} y^{-1}).

Converting to Soil Depth

To determine the significance of soil loss, it was decided that an interpretation of soil loss in the context of soil depth to bedrock would be a useful approach as the loss of soil is more significant on shallow hillslope soils than on deep alluvial soils.

We calculated soil depth under historical and reference conditions. Soil erosion (E; t $ha^{-1}y^{-1}$) was converted to depth (mm yr^{-1}) for each pixel using soil bulk density (BD) from ASRIS (0-30cm bulk density values) (ACLEP and NCST 2011) according to the following equation:

$$E_{mm} = \frac{E_{t\,ha^{-1}y^{-1}}}{BD_{g/cm^3}}$$

We calculated the depth to bedrock (D) for each year (n) using the equation below. We first summed annual values to calculate cumulative depth of soil eroded for each year in the period (1870 – 2012). We then estimated soil depth for each year by subtracting cumulative erosion from an original depth to regolith (DR) surface based on the National Soil Attribute Maps (CSIRO and TERN 2014; Wilford *et al.* 2014). Finally, we summarised soil depth for each map unit based on mean depth of pixels.

$$D_n = D_R - \sum_{n=1870}^{2012} E_{mm,n}$$

Calculating Indicator Condition Score

Indicator condition scores for each year (ICSn) were based on differences in mean soil depth between historical (H) and reference (R) conditions for each map unit:

$$ICS_n = \frac{D_{H,n,mean}}{D_{R,n,mean}}$$

Results were published at a decadal time-step, as consistent with the land use data period.

Results

Soil erosion indicator condition for the Queensland Murray-Darling Basin region was 95 in 2012. Spatial differences existed among classification units used (**Figure 30**), with lower condition scores in the northeast and higher condition scores in the southwest (**Figure 31**). Condition of soil erosion declined across the region from 100 in 1879 to 95 in 2012 (**Table 21**), relative to the pre-European reference condition (100). Within the region, these trends varied depending on the landscape **Figure 32**). For example, soils in basaltic uplands experienced an initial steeper decline in condition (higher initial impact of soil erosion) whereas soils in the Brigalow plains and uplands experienced a more gradual decline.

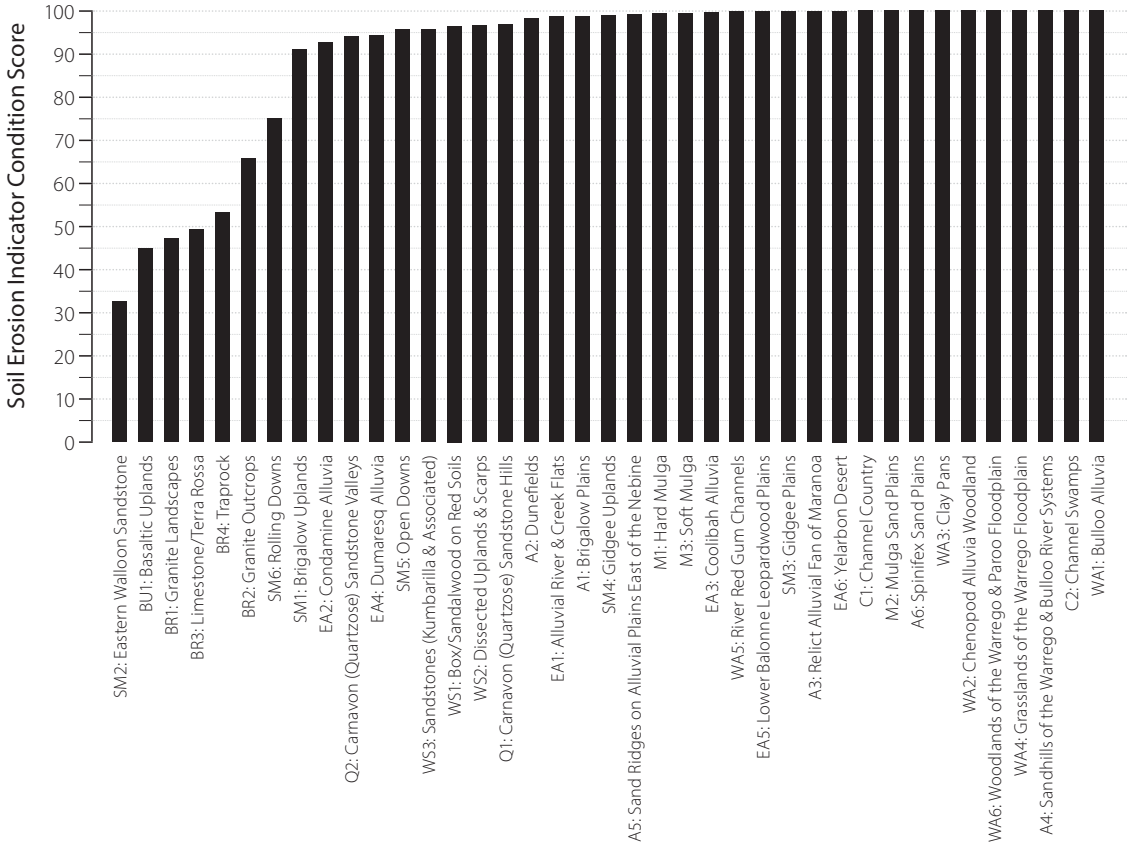

Figure 30: Indicator condition scores for landscape units within the Queensland Murray-Darling Basin.

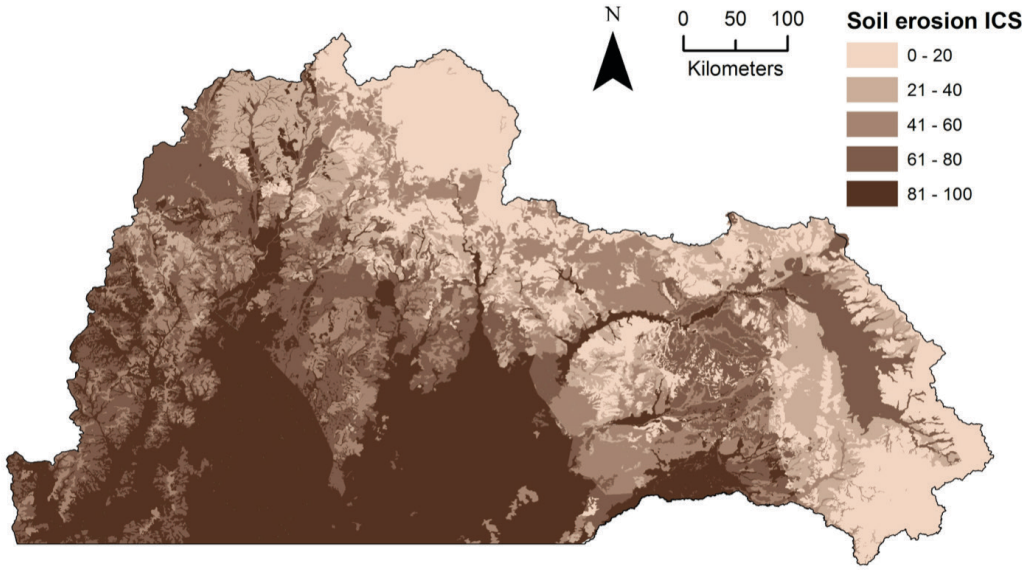

Figure 31: Indicator condition scores for soil erosion for map units across the Queensland Murray-Darling Basin in 2012.

Table 21: Trend in soil erosion based on the indicator condition score (ICS) across the Queensland Murray-Darling Basin. Reference was assumed to be under pre-European conditions.

Indicator	1879	1889	1899	1909	1919	1929	1939	1949	1959	1969	1979	1989	1999	2009	2012
Erosion	100	100	100	100	100	99	98	98	97	97	96	96	95	95	95

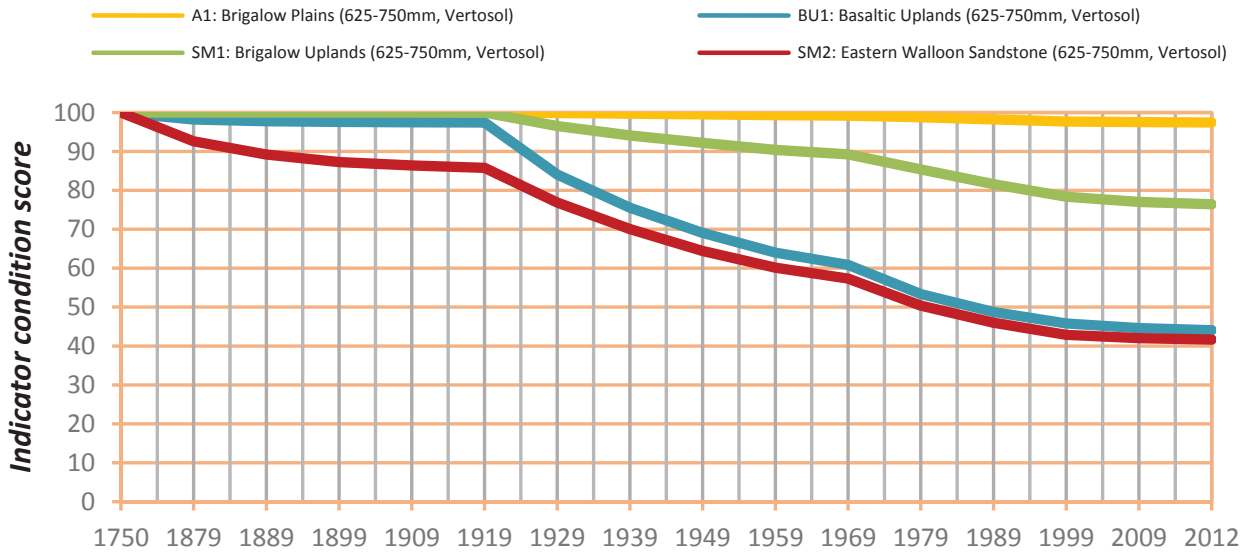

Figure 32: Trends in erosion indicator condition (1879 - 2012) for four soil map units within the region.

Discussion

Uncertainty and Risk: Quality Assessment

A range of risks and uncertainties were identified (after Black et al. 2011). In the absence of empirical data for some factors, data underlying the model relied on expert opinion. The method required acceptance of the RUSLE model, which has many simplifications and limitations. There were problems with model input data, including parameters and driving data sets, because grid cell representation of landscape assumed uniformity with respect to rainfall, soil, crop, aspect and slope gradient over 92m square pixels.

Relationship of Erosion to Soil Management

The analysis of soil loss will assist management by demonstrating major drivers contributing to soil loss in the region, where in the region soil erosion is occurring (related to land uses), where management practices are being used to reduce erosion, and what is the overall effectiveness of management and investment in the region.

Implications and Recommendations for Improvements

Current work should be regarded as environmental accounts (preliminary). A preliminary draft of the RUSLE could be implemented with limited processing capabilities. Although it was completed on proprietary software, similar results could be achieved on open source software. All outputs were made suitable for use in Multi Criteria Analysis Software - Shell Tool. Other products were made available including inherent hazards to hillslope soil erosion based on physical features of landscapes, land management and climate (Brough *et al.* 2004c).

To further this work, the following recommendations should be implemented:

1. Validation of environmental account estimates using ground truthing, experimental sites and local knowledge.
2. Updates and improvements to RUSLE factors:
    a. R-factor: Annual R-factors could be improved using monthly estimates to reflect inter-annual variability in rainfall. These datasets may be available from the Queensland Government.
    b. K-factor: K factors were calculated using a method developed for crop lands; this method has only been validated for grazing lands in one study in Queensland (Silburn 2011). Future K-factors need to be derived specifically for soils in grazing lands.
    c. L and S factors: Accuracy of terrain-based factors may improve using finer scale Digital Elevation Models and LiDAR data. Advances in this field could be conducted by organisations such as Geoscience Australia.
    d. C-factor: NRM regions could relatively easily update historical land use information through the following activities:
        - Remotely-sensed C-factors from 1988 onwards could be used to ground-truth values we assumed and provide measures of uncertainty around estimates. Historical cover and C-factor for non-cropping lands could be reconstructed using models such as GRASP and Aussi-GRASP (ref).
        - Public consultation during sub-catchment planning process to identify key development dates, such as: when was area first cleared or cropped, when was paddock removed from cropping rotation and when did tillage practices change?
        - Decadal land use layer: Incorporation of archived aerial photography.
        - Further analysis of available remote sensing data.
        - Seasonal remote sensing of ground cover (Brough *et al.* 2004c; Trevithick and Scarth 2013) could be incorporated into C-factor estimates to better describe where the cover is in the landscape. This provides data towards the percent pasture cover estimates in Table 19.
4. GIS processing could be improved by transferring the model to a more efficient, scripted, time series model.

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