Success of soil conservation works in reducing soil erosion rates and sediment yields in central eastern Australia

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Abstract A review of soil loss rates for erosion plots and sediment yields for small and large drainage basins, which have been treated to varying degrees by soil conservation and land management practices in the same climatic zone of central eastern Australia, shows remarkably similar but highly variable values (3-233.5 t km^{-2} $year^{-1}$) for land areas which range through 9 orders of magnitude (from 0.01 ha to 27 720 km^2). Soil erosion and sediment transport are storm-dominated due to the large variability of rainfall and runoff throughout most of Australia. In such an environment, it is essential to carefully design the research programme to ensure that there is an adequate number of replicate treatments for the same basin area to unequivocally identify the effects of the treatment. As this has not been done to any significant degree for land areas greater than 0.88 km^2 in size, it can be concluded that soil conservation works are only successful in reducing on-site soil erosion rates and off-site sediment yields in small drainage basins.

INTRODUCTION

Land degradation by water erosion has been a significant environmental problem in various parts of Australia since the early 1800s (Erskine & Bell, 1982; Erskine, 1994). The first national assessment of land degradation in Australia was conducted between 1975 and 1977, and found that the major degradation processes were water erosion, wind erosion and vegetation degradation (Anon., 1978). About 66% of Australia's cropland and 40% of grazing land required treatment for erosion control. Water erosion affected over 70% of cropland in New South Wales and Queensland, nearly 50% in West Australia, 15% or less in Victoria and South Australia, and very little in the Northern Territory and Tasmania (Anon., 1978). In 1988, the Soil Conservation Service of New South Wales carried out a systematic survey of land degradation in that state (Anon., 1988). It was found that 2.8% of the state was affected by moderate to extreme sheet and rill erosion, 11.9% by moderate to extreme gully erosion, 2.9% by various types of mass movements, 10.3% by scalding and 25.0% by moderate to extreme wind erosion (Anon., 1988). Soil erosion has a significant effect on soil productivity with the removal of 150 mm of topsoil reducing wheat yields by between 19 and 52% (Barr, 1957; Hamilton, 1970). In the Murray-Darling basin of eastern Australia, crop income foregone due to water erosion is estimated at (A) \$5 million per year for New South Wales alone (Aveyard, 1988).

Erskine & Saynor (1995) reviewed the published work on the effects of soil conservation works on reducing soil erosion rates and sediment yields in Australia. They concluded that soil conservation works undertaken on small drainage basins greatly reduced sediment yields by decreasing upland soil erosion rates. However, large decreases in upland soil erosion rates often led to reworking of downstream temporary sediment storages which often maintained high sediment loads on the main streams (Marker, 1976; Erskine, 1994). Similar results have been reported in other countries (Trimble, 1983).

Soil conservation works are often justified on the grounds of their effectiveness in reducing both on-site erosion rates and off-site sediment yields (Erskine, 1994; Erskine & Saynor, 1995). Most major urban water supply and irrigation dams in New South Wales have had major soil conservation programmes completed within their drainage basins to reduce sediment yields and hence dam sedimentation rates. The purpose of this paper is to determine, from a review of the available information, whether soil conservation works reduce both on-site erosion rates and off-site sediment yields in central eastern Australia. Three spatial scales are analysed:
(a) soil erosion rates on plots;
(b) sediment yields from small drainage basins (up to 100 ha in area); and
(c) sediment yields from large drainage basins.
The area to be examined includes the headwaters of the southern tributaries of the Murray-Darling River in New South Wales. Table 1 lists the rainfall erosivity (R) and storm erosivity (EI) values from the Universal Soil Loss Equation for the main study sites. There is only a small range in erosivity between sites, reducing the effect of this factor on soil erosion rates. It must be stressed that the soil erosion rates and sediment yields reported below were obtained by different researchers using different methods over various time periods for study areas of greatly different sizes. As a result, all of the reported values may **not** be directly comparable. Nevertheless, this is an inevitable shortcoming of any review of published work.

Table 1 Rainfall erosivity and storm erosivity values for the study sites in central eastern Australia (from Rosewell, 1993; Zolotarev & Rosewell, 1993).

Location	Rainfall erosivity (R) (MJ mm ha^{-1} h^{-1} $year^{-1}$)	Storm erosivity[a] (EI) (MJ mm ha^{-1} h^{-1})
Canberra	1180	810
Wagga Wagga	1090	730
Cowra	1190	790
Bathurst	1166	750
Wellington	1350	910

[a]For a 1:10 year storm of 30 minutes duration.

EROSION PLOTS

The Soil Conservation Service of New South Wales was formed in 1938, just 3 years after the US Soil Conservation Service. It immediately established a series of six research centres, three of which are located within the study area. A number of trials were initiated at each research centre to determine the runoff and soil loss rates from experimental soil erosion plots subjected to various crop rotations and treatments over a long time period (Wiltshire, 1947, 1948). The "cultural treatments trial", which is discussed below, consisted of experiments on cropping rotations of various durations as well as on various pasture treatments (Edwards, 1987). It has provided in excess of 3000 plot years of data. Closed plots as described by Wiltshire (1947) were used for these trials. Each plot is 41 m long and 2.44 m wide (100 m^2 or 0.01 ha) and is fully enclosed by sturdy side walls. Runoff and soil loss measurements were carried out according to the methods of Wiltshire (1948), although some modifications were made during the course of the trials (Edwards, 1987).

The results of the cultural treatments trial at the Cowra, Wagga Wagga and Wellington research stations are summarized in Table 2. Kinnell's (1983) results for 3

Table 2 Results of erosion plot experiments at Cowra, Wagga Wagga, Wellington and Canberra. The results for the first three sites were calculated from Edwards' (1987) data and those for the last site, from Kinnell's (1983) data.

Land use treatment	No. of plots	Mean annual runoff (mm)	Mean annual soil loss (t ha^{-1} $year^{-1}$)	Time period
COWRA				
Wheat – 2 year rotation	6	22.7	1.7	1943-1975
Wheat – 3 year rotation	9	13.6	0.6	1943-1975
Wheat – 4 year rotation	12	12.2	1.2	1955-1975
Volunteer pasture	3	5.7	0.2	1943-1975
Lucerne	3	21.6	0.8	1943-1954
Sown pasture	3	21.3	0.7	1943-1954
Wheat – 2 year rotation – stubble mulch	6	15.8	0.7	1949-1954
WAGGA WAGGA				
Wheat – 2 year rotation	6	33.4	1.6	1947-1976
Wheat – 3 year rotation	9	21.1	0.9	1947-1976
Lucerne	3	10.9	0.1	1947-1976
Mixed pasture	3	8.1	0.04	1947-1976
Retired land	3	6.4	0.03	1947-1976
WELLINGTON				
Wheat – 2 year rotation	6	21.2	1.1	1949-1958
Wheat – 3 year rotation	9	22.6	0.9	1949-1958
Permanent pasture	3	6.8	0.1	1949-1958
Retired land	3	9.8	0.03	1949-1958
CANBERRA				
Bare fallow	3	N/A	44.0	1979-1981

N/A – not available although the data were collected.

bare fallow plots (identical to the Soil Conservation Service's plots) at the CSIRO Ginninderra Experiment Station at Canberra are also included in Table 2. In most cases, three replicates of each treatment were used. Details on climate, soils, slope, etc at each site are contained in Edwards (1987) and Kinnell (1983).

The interaction of land use and land management has a major impact on soil loss rates (Edwards, 1993). As expected, by far the highest soil loss rate was recorded on bare fallow land. Wheat produced the next highest soil loss rates ($\bar{x} = 1.09 \pm 0.13$ t ha^{-1} $year^{-1}$) which significantly exceeded those from both pasture ($\bar{x} = 0.26 \pm 0.13$ t ha^{-1} $year^{-1}$) and retired land ($\bar{x} = 0.03$ t ha^{-1} $year^{-1}$). The reasons for the substantial differences in soil loss rates between the various land uses are differences in runoff and ground cover. Mean annual runoff explains 70.7% of the variance in mean annual soil loss rates for the data in Table 2. Runoff and soil loss are both inversely related to ground cover although the exact form of the relationship is most likely curvilinear (Lang, 1979; Costin, 1980; Lang & McCaffrey, 1984). Therefore, land uses and land management practices which maintain a high ground cover will reduce both runoff and soil losses. In particular, runoff and soil loss increase rapidly at threshold ground cover values of less than about 70-75% or 0.7-1.0 kg m^{-2} (Costin, 1980; Lang, 1979; Lang & McCaffrey, 1984). Soil conservation must aim to maintain ground covers of greater than 70-75%.

Soil loss rates during individual intense storms can greatly exceed mean annual values (Edwards, 1987, 1993; Erskine & Saynor, 1995). The annual soil loss rates on the plots in Table 2 for years with large storms exceed mean and median annual values by between one and two orders of magnitude (Edwards, 1987). The reason for the high geomorphic effectiveness of large storms is the high variability of Australian hydrology (McMahon *et al.*, 1992).

SMALL DRAINAGE BASINS

Many authors have suggested that the results from erosion plots cannot be scaled up for use in entire drainage basins. Soil transported off an erosion plot is measured as a loss although it may have been deposited immediately downslope in a larger drainage basin. Sediment yields usually decline with increasing basin area because of the increasing importance of sediment storage. Sediment delivery ratios of much less than 50% have been widely reported, indicating that most of the soil eroded on slopes is not transported out of the basin but is deposited either immediately downslope or downstream. Nevertheless, the available evidence for central eastern Australia demonstrates that soil conservation works are successful in greatly reducing sediment yields from small drainage basins.

Table 3 lists the results of Adamson's (1974; 1976) research on the Soil Conservation Service's Wagga Wagga Research Station as well as Costin's (1980) and Haeusler's (1987) work on the CSIRO Ginninderra Experiment Station. Adamson (1974; 1976) investigated the long term effects of structural soil conservation works and improved land management on runoff and sediment yields on small paired drainage basins (Table 3). The treated basin consistently had higher ground cover, dry matter production and stock carrying capacity. For the first 22 years of the experiment, Adamson (1974) found that treatment caused a 74% reduction in runoff, a 99%

Table 3 Comparison of mean annual runoff and sediment yields from small basins which have been either treated or untreated with soil conservation works.

	Treated basin:				Untreated basin:			
Time period	Basin area (km^2)	Mean annual rainfall (mm)	Mean annual runoff (mm)	Mean annual sediment yield (t km^{-2} $year^{-1}$)	Mean annual runoff (mm)	Mean annual sediment yield (t km^{-2} $year^{-1}$)	Basin area (km^2)	Source
WAGGA WAGGA				1.8	28.4	165.1	0.073	Adamson
1952-1973	0.075	563	7.6					(1974)
1952-1974	0.075	576	12.2	3.2	37.8	202.0	0.073	Adamson (1976)
CANBERRA								
Ginninderra			Improved pasture					Costin
1966-1971	0.88	620	29	17.9				(1980)
Ginninderra			Grazing/urbanization/roading					Haeusler
1959-1987	1.16	635	N/A	233.5				(1987)

N/A – Not available.

reduction in sediment yield, a 79% reduction in the number of runoff events and a significant decrease in peak discharge (Table 3). Adamson (1976) extended the results for one further year to include an extreme event in 1974 (Table 3). This event resulted in the highest mean annual runoff and sediment yield on both treated and untreated basins and slightly changed the trends reported above (see Table 3). During 1974, 39.9% of the total runoff and 47.6% of the total sediment yield from the treated basin and 28.1% of the total runoff and 21.8% of the total sediment yield from the untreated basin occurred. This again highlights the significance of large, infrequent floods in dominating the hydrology of Australian basins.

Costin (1980) measured the effects of improved pasture on runoff and sediment yields from an 88 ha basin at Canberra (Table 3). He found that the mean annual runoff was equivalent to 4.7% of the incident rainfall and that the sediment yield was comprised almost entirely of suspended sediment with virtually no bed load and coarse floating debris. Again a major flood in 1970 produced almost one-fifth of the total runoff from 1967 to 1971 and 22% of the overall sediment yield for the 5 years. Haeusler (1987) demonstrated for a neighbouring basin on the Experiment Station that urbanization, roading and gullying produce substantial increases in sediment yields (by an order of magnitude).

While there are many published volumetric sediment yields for various land uses and land management practices for the Canberra area, these are not discussed here because of the methodological problems outlined by Erskine & Saynor (1995). However, A. Mahmoudzedah (1995, personal communication) found that small basins (<30 ha) near Bathurst produced 0.80 t km^{-2} $year^{-1}$ from forest, 2.48 t km^{-2} $year^{-1}$ from pasture and 2.54 t km^{-2} $year^{-1}$ from cropped areas. While this work does not explicitly address soil conservation, it does highlight the importance of maintaining undisturbed, well vegetated ground conditions in reducing sediment yields from small basins.

LARGE DRAINAGE BASINS

For the purposes of this discussion, large basins are defined as those with areas greater than 482 km^2. Table 4 lists the published sediment yields for such basins within the study area. While soil conservation works have been completed in parts of the drainage basins of six sites, most of the basins were **not** treated. As expected, there is a strong negative correlation ($r = -0.61$) between sediment yield and basin area (Canberra was deleted from the analysis because there is a sediment trap, which is periodically cleaned out, on the upper reaches of the lake). Interestingly, the reported yields ($\bar{x} = 83.1 \pm 18.3$ t km^{-2} $year^{-1}$) are much higher than those predicted for either region 1 (Southern Uplands) or 4 (Lowlands of the Murray-Darling basin) of Wasson (1994). The reasons for this discrepancy are unknown.

Surprisingly, the sediment yields for the small treated basins in Table 3 are much lower than those for the much larger (up to seven orders of magnitude larger) basins in Table 4. This highlights the magnitude of the impact of soil conservation works on reducing the sediment yields from small basins and suggests that channel and gully erosion are likely to be significant sediment sources in large basins (Erskine & Saynor, 1995).

It is doubtful whether any effect of soil conservation works on the sediment yields of large rivers could ever be detected in central eastern Australia. Recent sediment tracing in the area has demonstrated the importance of in-channel and gully sources of sediment (Erskine & Saynor, 1995). Furthermore, the significance of different sediment

Table 4 Sediment yields for large basins in the headwaters of the southern tributaries of the Murray River in New South Wales.

Site	Basin area (km^2)	Sediment yield (t km^{-2} $year^{-1}$)	Source
Murrumbidgee River			
Burrinjuck	13 000	37.8	Schumm (1968)
Burrinjuck	13 000	57.3*	Abrahams (1972
Wagga Wagga	27 720	21.7	Olive *et al.* (1994)
Canberra	1 865	20.0*	Abrahams (1972)
Lobs Hole	885	213	Yu and Neil (1994)
Cumberland	1 098	110	Yu and Neil (1994)
Cotter	482	45.6*	Abrahams (1972)
Yass	818	92.7*	Abrahams (1972)
Lachlan River			
Wyangla	8 300	111.3*	Abrahams (1972)
Murray River			
Hume	15 300	58.7*	Abrahams (1972)

*Volumetric sediment yields converted to mass assuming a mean bulk density of 1.4 g m^{-3} which was found by Wasson *et al.* (1987) for the Burrinjuck Dam sediments.

sources varies over decadal time periods in response to, among other things, step-functional rainfall changes which have been widely documented in south eastern Australia (Erskine & Bell, 1982; Wasson *et al.*, 1987).

DISCUSSION AND CONCLUSIONS

Lang (1992) recently evaluated the accuracy of the Wiltshire (1948) methods of sampling the soil-water mixture collected from soil-loss plots. He concluded that these methods should **not** be used and that the erosion data obtained by these methods should be treated with caution. In particular, the erosion rates obtained by these methods will have been **underestimated.** Unfortunately, this criticism applies to Kinnell's (1983) and Edwards' (1987) data in Table 2 and indicates that the reported soil loss rates are **minimum** values only.

The limited data on soil erosion rates and sediment yields presented in Tables 2, 3 and 4 for the same climatic zone show remarkably similar but highly variable values from land areas which range through **9** orders of magnitude. It is only possible to quantify the impacts of soil conservation works when a proper research design is adopted which incorporates an adequate number of replicate treatments for the same land/basin area. As this is rarely attempted for basin sizes greater than about 1 km^2, the effect of soil conservation works on reducing sediment yields in medium to large basins is unknown.

Soil conservation works are certainly capable of greatly reducing runoff, soil-loss rates and sediment yields from small basins which are highly impacted by agriculture and/or erosion. However, the high variability of Australian rainfall and runoff means that large, infrequent storms dominate soil erosion and sediment transport. As a result, soil erosion rates and sediment yields are temporally variable, making it difficult to isolate the effect of any one factor. Furthermore, the high variability of mean annual soil loss and sediment yields (L. J. Olive, 1995, personal communication) means that such values are only meaningful for long time periods which include multiple large events.

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