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Revised models for the proportion of suspended sediments in hillslope soil loss – an empirical understanding

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Abstract: This paper investigates the proportion of suspended sediment in hillslope erosion using measured data and presents preliminary models. The P2R Dynamic-SedNet (PD-SedNet) model calculates the proportion of suspended sediment in runoff from hillslope erosion as directly proportional to the proportion of dispersed silt and clay in the surface soil. However, many soils are composed of and erode as a large proportion of aggregates of primary particles. Exceptions occur where the surface soil is dispersive, non-cohesive (e.g., loose sand), or where the sediment is eroded from a hard-set surface. Laboratory data for bare, rainfall wet surface soils indicate that the proportion of fine particles (<0.125 mm) increases until surface soil silt and clay is 50 % and then flatten at about 25% suspended sediment. Suspended sediment is lower than the PD-SedNet equation for soil silt and clay greater than 15%. An equation (modified Loch/Lu) was fitted to these laboratory data. Suspended sediment data for eight plots and catchments in Queensland and six in SE Asia with bare soil were also plotted against soil silt and clay, and the PD-SedNet and modified Loch/Lu equations. Two relationships emerged: 1) data for dispersive, mulga, non-cohesive and hardsetting soils fit around the PD-SedNet line, and 2) data for "aggregated soils" fit around the modified Loch/Lu line. For aggregated soils, when soil silt and clay is 60%, PD-SedNet proportion of suspended sediment is 60% while the data/Loch/Lu equation indicates it is ~25%. That is, the PD-SedNet equation gives a large overestimate for bare, aggregated soils.

However, much of Queensland's cropping and grazing land is not bare. Data from two studies in grazing and three in cropping show that the proportion of suspended sediment increases with increasing cover. The proportion of suspended sediment is strongly related to ground cover for grazing and cultivated catchments, but the relationship differed for different soils. As cover increases, the proportion of suspended sediment approaches the PD-SedNet line. However, at high enough cover the proportion of suspended sediment exceeds that calculated with the PD-SedNet equation. For example, for the Wallumbilla Grey Vertosol, the soil silt plus clay is 48%, giving a PD-SedNet estimate of suspended sediment of 48% whereas the Wallumbilla suspended sediment can vary from 17 to 80% depending on cover. A more general method is needed to estimate the proportion of suspended sediment. This method needs to account for the effects of soil and cover as shown here, and other factor known to affect the proportion of suspended sediment, such as prior land use and slope. The results presented here are at small plot and catchment scale; an unresolved issue remains that coarser sediment will continue to be deposited with increasing scale. At what scale should suspended sediment be defined? Future work should concentrate on deriving more relationships with cover and finding a method for predicting these relationships based on commonly available data and resolving the scale issue.

Keywords: *Cover, Great Barrier Reef (GBR), soil erosion, sediment delivery, sediment size*

1. INTRODUCTION

Suspended sediment is a major contributor to poor marine water quality in the Great Barrier Reef (GBR) (McCloskey et al., 2021). Gullies are the major source of sediment, with comparable contributions from hillslopes and streambanks (McCloskey et al., 2021). Approximately half of generated sediment is delivered to the GBR lagoon; the remainder is deposited on floodplains, trapped in reservoirs etc. Grazing lands contribute 53% of the fine sediment, while conservation lands contribute a further 13% (a function of their relatively large areas); the remainder is sourced from a range of other land uses. However, sediment from other land uses can be locally significant. Soils in the GBR catchment include a wide range; the dominant soil are Sodosols, Vertosols, Kandosols, Rudosols and Chromosols.

The Paddock to Reef Dynamic-SedNet model (Waters 2014) calculates the proportion of suspended sediment in hillslope erosion as directly proportional to the proportion of dispersed silt and clay in the surface soil:

TSS load to stream (kg/day) = RUSLE sediment load (kg/day) * (silt + clay) * HSDR   Eqn 1

where RUSLE is the Revised Universal Soil Loss Equation (Renard et al., 1997), silt and clay are proportions and HSDR is a Hill Slope Deliver Ratio. This differs from the SedNet model of Wilkinson et al., (2014) by including the silt + clay term. The SedNet fine sediment budget is for silt and clay sized sediment (<20 μm), rather than for 'suspended sediment'. Sediment delivery ratios of 0.03 to 0.3 are applied in PD-SedNet (McCloskey et al., 2021).

Soils are often composed of, and eroded as, aggregates of primary particles (Figure 1) which are water stable (Meyer *et al.* 1980; Meyer 1985). The PD-SedNet relationship does not attribute any variation in the proportion of suspended sediment to the degree of aggregation of soils. Aggregates are coarser than the dispersed soil particles, being composed of amalgamations of primary particles, but have lower density. Meyer (1985) found sediment from interrill plots (on 17 soils in US croplands) contained only 55% of the silt and clay sized particles found in the dispersed soil, the remainder being bound into aggregates. Exceptions occur where the surface soil is dispersive, non-cohesive (e.g., loose sand), or where the sediment is eroded from a hard-set surface and has a sediment particle size distribution like or mostly like the dispersed surface soil (Silburn et al. 2011), i.e. the sediment contains a small proportion of aggregated particles. The relationship used in PD-SedNet would be corrected for these cases. In this paper, relationships are derived to estimate the proportion of suspended sediment in hillslope soil loss, using measured data.

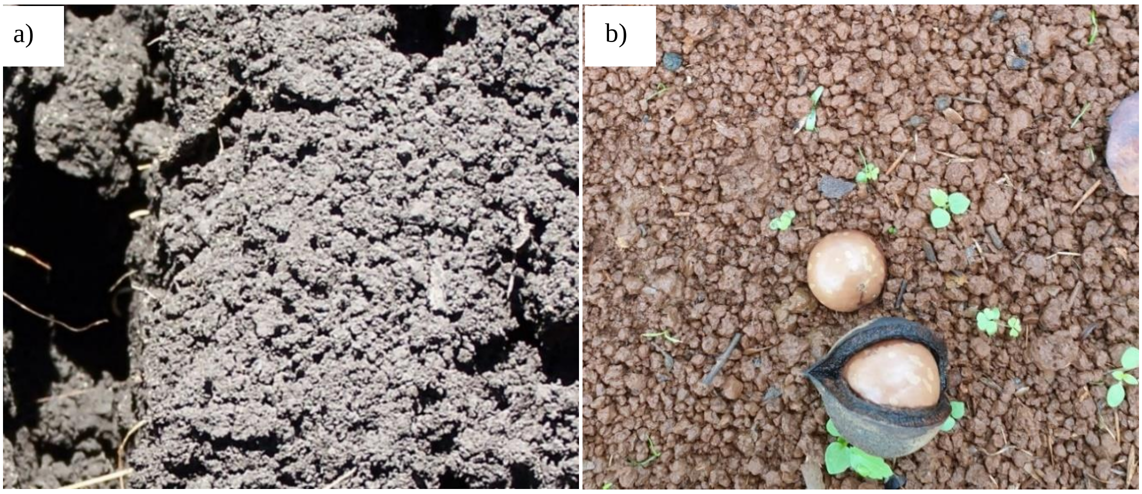

Figure 1. Surface of a) a Vertosol and b) a Ferrosol, with aggregated particles (& macadamias). Upon wetting these aggregates break down to smaller aggregates with some primary particles.

1.1 What sediment sizes occur in hillslope erosion and in streams?

Data on sediment sizes in runoff for small catchments in Queensland are rare. Freebairn and Wockner (1986a) found from wet sieving suspended sediments (after settling of coarser particles) that all sediments were <0.125 mm (the finest sieve) on cultivated Vertosols. In contrast, sediment eroded in rills had only ~12% <0.125 mm particles for the Black Vertosol and ~40% for the Grey Vertosol (Freebairn and Wockner, 1986b). Thus, all particles >0.125 mm eroded in the rills were deposited in the contour bank channel. In semi-arid grazing lands with hard set surface soils, Silburn *et al.* (2011) found 90-98% of suspended sediment was fine-sized (<0.053 mm). Clay-sized sediment (7–14%) was depleted in suspended sediment, compared with 18–24% in soil, indicating that some clay was transported in aggregates of silt size or larger. That is, sediment from hard set soils was mostly, but not fully disaggregated. Thornton and Elledge (2019) found for bare fallow and heavily grazed small catchments, 93% of sediment in runoff was <0.016 mm size.

The predominance of <0.016 mm sediments from small catchments is the same at larger catchment scales. Packett *et al.* (2009) in the Fitzroy River and Bainbridge *et al.* (2014) and Bainbridge *et al.* (2016) in the Burdekin and Wet tropics found that most of the sediment was <0.020 mm. However, smaller, wetter coastal catchments have coarser sediments with more (65-75%) 0.016-0.63 mm sediment than larger, drier catchments. Overall, sediment in runoff from small catchments and streams was of fine sizes.

2. RESULTS AND DISUSSION

2.1 Estimating the proportion of suspended sediment in runoff

Two types of data were used to develop equations for estimating suspended sediment in runoff. Firstly, Loch *et al.* (1998) measured the sizes of particles in rainfall wet surface soils. The finest size measured was <0.125 mm (P_{125}). This was used as a surrogate for suspended sediment. Lu *et al.* (2003) fitted an equation between these P_{125} data, as a proportion of P_{125*} of the dispersed soil (sum of clay, silt and fine sand (<0.125mm)), and the dispersed clay in the surface soil (their Fig. 2; $P_{125}/P_{125*} = 100*\mathrm{Exp}(-0.019\ \mathrm{Clay}\%)$). This provided a model for the proportion of fine particles in a wide range of Queensland cropping soils. Secondly, these data were compared with data for suspended load from bare hillslope plots and catchments (Table 1).

2.2 Suspended sediment data for bare conditions

Data for suspended sediment as a proportion of total soil loss for bare plots were taken from eight small catchment or plots in Queensland and six plots in SE Asia (Table 1). The Queensland catchments had surface clay contents ranging from 9-62 %. Four of the plots were uncultivated bare scalds (3 at Springvale and 1 at Mt. Mort). The SE Asia (ACIAR) sites had surface clay contents of 2-56%. Two of the sites had dispersive soil (Kenmaman and Springvale eroded), and one was sandy and non-cohesive (Goomborian). Two of the SE Asian sites had high organic matter (~5%) (Los Banos and ViSCA). Thus, while the number of sites is limited, they do have a wide range of soil texture. Plots were only 10's of m^2 in area while catchments were 0.7 to ~6 ha. The Asian data represent widely different soils to the Queensland one. This diversity is a good test of the robustness of the model.

Table 1. Small catchments and plots with data for suspended and total sediment loads, for bare soils.

Catchment (Area Ha or m^2)	Soil [A]	Land-use	Surface dispersed silt plus clay	Soil condition	Source
Queensland					
Greenmount (0,8-1.4 ha)	Black Vertosol	Cultivated winter crops	83	Cohesive	Freebairn & Wockner (1986b; a)
Greenwood (0.7-1 ha)	Grey Vertosol	As above	66	Cohesive	As above
Wallumbilla (2.4-5.9 ha)	Grey Vertosol	As above	48	Cohesive	Freebairn *et al.* (2009)
Springvale (14-640 m^2, mainly 40-70 m^2)					Silburn *et al.* (2011)
Mudstone	Leptic Rudosol	Uncultivated grazing	25	Hard setting	As above
Sandstone	Orthic Tenosol	Uncultivated grazing	40	Hard setting	As above
Eroded mudstone	Leptic Rudosol	Uncultivated grazing	53	Dispersive	As above
Mt. Mort (30 m^2)	Grey Sodosol	Uncultivated grazing	16	Hard setting	Silburn (1994)
Croxdale hard mulga (1-1.2 ha)	Red Kandosol	Uncultivated grazing	44	Hard setting	Miles and Johnston (1990)[B]
ACIAR SE Asia					Coughlan and Rose (1997)
Kenmanan, Malaysia (20 m^2)	Orthoxic Tropudult	Horticulture	35	Dispersive	Ciesiolka *et al.* (1995)
Khon Kaen, Thailand (150 m^2)	Oxic Paleustult	Rozelle	21	Cohesive	As above
Los Banos, Philippines (72 m^2)	Typic Tropudalf	Maize	91	5% OM[C] high silt	As above
ViSCA, Philippines (72 m^2)	Oxic Dystropept	Maize, peanuts	91	5% OM	As above
Goomborian, Australia 18-3500 m^2)	Lithis Eutropept	Pineapples	14	Non-cohesive	As above
Imbil, Australia (~20-80 m^2)	Lithic Eutropept, gravelly	Pineapples	21	Initially non-cohesive[D]	Ciesiolka *et al.* (1995)

A - ACS - Australian Soil Classification (Isbell, 2002) or Soil Taxonomy (Soil Survey Staff, 1999) as given in the source papers. B – The soil data were reported in Silburn *et al.* (2011). C - OM organic matter content. D – The soil consolidated over time and a stone armoured surface was created as fines were removed by erosion (Ciesiolka *et al.* 1995).

The Loch data for P_{125} and the proportion of suspended sediment from the catchments are ploted against their soil silt and clay content in Figure 2. Given these P_{125} data in Figure 2 are plotted against % silt plus clay rather than % clay as used by Lu *et al.* (2003), a new equation was fitted giving $Y = -0.0068X^2 + 0.8893X$ ($R^2 = 0.73$), where X = % dispersed silt plus clay and $Y = P_{125}$. This was used as a first approximation of the catchment data in Figure 2. Data for interrill erosion on 17 US cultivated soils (Meyer 1985) also fits this relationship except for two points that are underestimated by 12-15 % suspended sediment (data not shown).

Two relationships emerged: 1) dispersive, mulga, non-cohesive and some hardsetting soils fit around the PD-SedNet line (Figure 2), and 2) aggregated soils fit around the modified Loch/Lu line. The aggregated soils do not fit the PD-SedNet line. For the Lu/Loch line, the proportion of suspended sediment initially increases and then flattens out (or declines) as silt and clay increases. For higher silt and clay soils, there is a large and increasing discrepancy in the proportion of suspended sediment between the PD-SedNet and Loch/Lu lines. Data for Greenmount is below the fitted line, which may indicate less suspended sediment at high silt and clay contents, but this cannot be confirmed with the data available here. Two sites from SE Asia also had low suspended sediment. These soils had high organic matter content and one had high silt. Relationships are shown (Figure 2), for the two classes of soils. Thus, the proportion of suspended sediment can be estimated from commonly available soil properties, for bare soils.

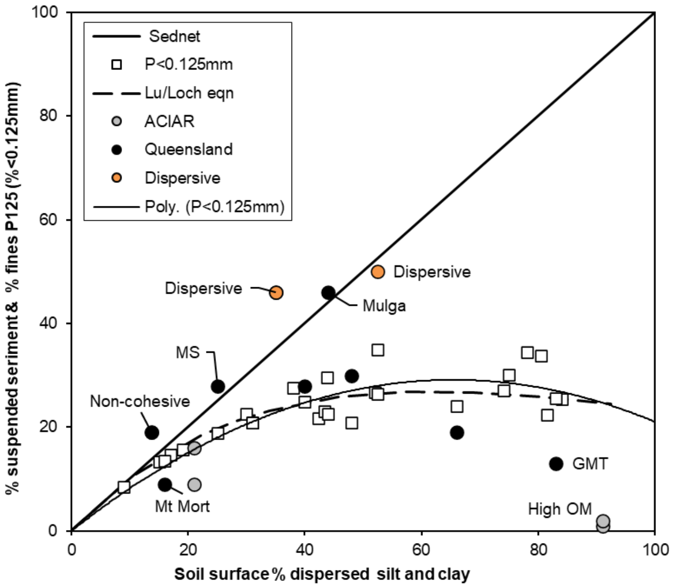

Figure 2. Proportion of suspended sediment for Queensland and SE Asian plots and catchments with bare soil. Greenmount (GMT). Springvale mudstone derived soil (MS), Mulga and Mt Mort have hardsetting surfaces.

2.3 Effect of cover on the proportion of suspended sediment

Young (1980) found for six of seven US cropping studies, the proportion of sediment particles >0.05 mm decreased substantially with increasing cover, i.e., fines increased. However, the proportion of clay-sized sediment (<0.002 mm) increased with increasing cover. Scanlan *et al.* (1996) and Silburn *et al.* (2011) also showed the proportion of suspended load increases with increasing cover (pasture biomass and litter) in grazing lands. Silburn (2011a) fitted simple models for his suspended load and bed load against cover. When these were recombined to estimate the proportion of suspended load, curvilinear relationships resulted (Figure 3). Soil derived from mudstone and from sandstone had similar relationships while those on somewhat sodic eroded mudstone were different with greater suspended sediment.

Here further data are presented for three cultivated cropping catchment studies with a range of tillage and crop treatments. Cover entailed crop residue (stubble) and some time standing crop canopy cover. The proportion of suspended sediment increases with increasing cover for all three studies (Figure) with generally good relationships for most wheat and wheat stubble (tillage) treatments. However, some treatments such as zero-till and wheat, and sunflowers, for the Acland Grey Vertosol have higher and lower suspended sediment than the other tillage treatments, respectively (Figure a). The suspended proportions for two Grey Vertosols (Acland and Wallumbilla) have similar relationships to cover, with slopes of 0.01, whereas the Black Vertosol has a lower slope (Figure a). The Grey Vertosols have rainfall wet P<0.125 mm of 26% and 44%, respectivily, while the Black Vertosol has only 18% (Foley and Silburn 2002), that is, has less fine particles.

While a curvialiear relationship (Figure 3) is logical if both suspended and bed load have a declining exponential relationship with cover, the data for the three cropping sites appear to fit a linear relationship. This may be because the soil loss-cover relationship is less steep for the cropping sites than for grazing sites. While the relationship expected is now clearer, there are large differences between sites. Thus, a general model is not available for inclusion in a catchment model. A future step is to relate the slopes of the suspended load vs cover linear regressions soil and sediment properties.

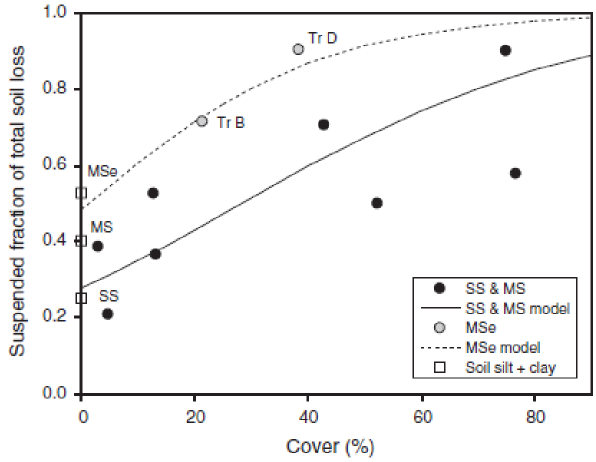

Figure 3. Effect of cover on the proportion of suspended sediment for sandstone (SS), mudstone (MS), and eroded mudstone (MSe) derived soils. (Source: Silburn *et al.* (2011)).

As cover increases the proportion of suspended sediment approaches the PD-SedNet line. However, at high enough cover, the proportion of suspended sediment exceeds that calculated with the PD-SedNet equation. For example, for the Wallumbilla Grey Vertosol the soil silt and clay is 48%, giving a PD-SedNet estimate of suspended sediment of 48% whereas the Wallumbilla suspended sediment can vary from 17-80% depending on cover. A more general method is needed to estimate the proportion of suspended sediment. This method needs to account for the effects of soil and cover as seen in Figure 2 and Figure 3, repectively, and other factor mensioned below. Other factors will also affect sediment sizes in runoff, a major one being prior land use; soil aggregates are larger when soil has never been cultivated, under pasture or forest. The tillage trial catchment data also indicates that taller crop canopies such as sunflower and sorghum have lower suspended load proportions than shorter crops (Figure 4a). The proportion of suspended sediment also decreases with increasing slope up to 10% slope then was constant (Young, 1980) as runoff has more capacity to transport larger particles on steeper slopes.

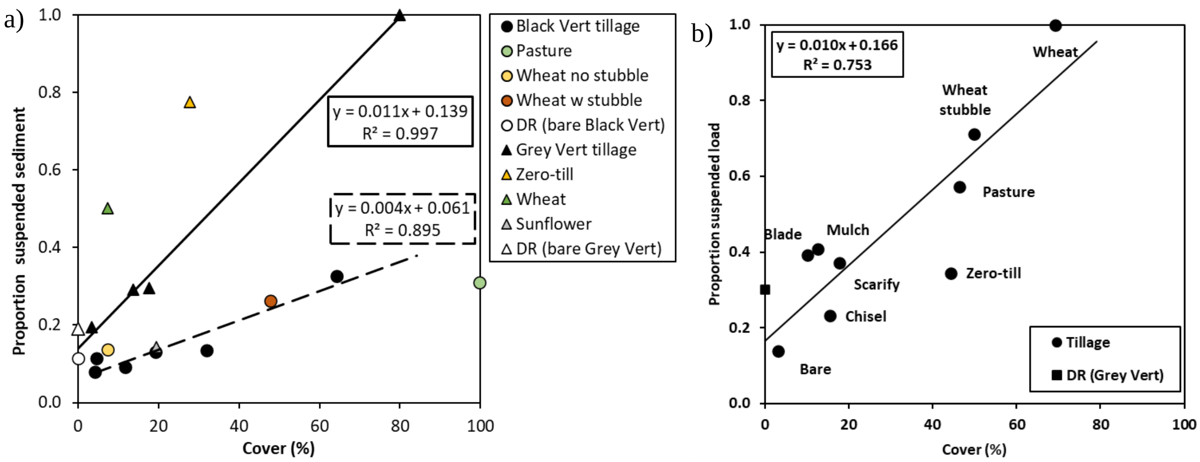

Figure 4. Effects of cover on the proportion of suspended sediment at a) Greenmount (Black Vertosol) and Acland (Grey Vertosol), summer fallow tillage treatments (stubble burnt, incorporated, mulched & zero-tillage) & other crops, and b) Wallumbilla (Grey Vertosol) tillage trial. Delivery ratios (DR) for bare soil are also shown.

3. Cover C-Factor relationships

There is considerable evidence that the default Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) cover C-factor relationship typically overpredicts soil loss in Queensland (Freebairn and Wockner 1986b; Loch 2000; Rosewell 1990; Silburn *et al.* 2011). The measured relationships are steeper than the RUSLE default. The RUSLE cover C-factor relationship was derived for cropping soil in the US, which are generally siltier than Queensland cropping soils; Queensland soils are generally higher in clay and lower in silt. Any future evaluation of sediment modelling in Queensland should investigate effects of changing this relationship.

4. CONCLUSIONS AND RECOMMENDATIONS

Data for plots and catchments were analysed to determine the relationship between the proportion of hillslope soil loss as suspended load on bare plots and compared to the equation used in PD-SedNet. Two relationships emerged: 1) dispersive, mulga, non-cohesive and some hard-setting soils fit around the PD-SedNet line; and 2) aggregated soils fit around the modified Loch/Lu line. For aggregated soils, the PD-SedNet equation greatly overestimates the proportion of soil loss that is suspended sediment. The proportion of suspended sediment was then related to ground cover for data from grazing and cropping experiments. The proportion of suspended sediment increased with increasing cover and was well related to cover for grazing and cultivated catchments (R^2 0.75-0.99), but the relationship differed for different soils. The results presented here are at small plot and catchment scale; an unresolved issue remains that coarser sediment will continue to be deposited with increasing scale. Future work should concentrate on deriving more relationships with cover and on finding a method for predicting these relationships based on commonly available data and resolving the scale issue.

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