IDENTIFICATION OF THE PRINCIPAL MECHANISMS DRIVING SOIL ORGANIC CARBON EROSION ACROSS DIFFERENT SPATIAL SCALES.

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Submitted in fulfilment of the academic requirements for the degree of

Master of Science in Environmental Science

School of Agricultural, Earth and Environmental Sciences

University of KwaZulu-Natal

Pietermaritzburg

November 2013

DECLARATION

I Daniel Müller-Nedebock, hereby declare that:

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GENERAL ABSTRACT

Soil water erosion is recognized as the principal mechanisms behind soil organic carbon (SOC) losses from soils, a soil constituent essential for ecosystem functions. SOC erosion can thus be far-reaching, affecting the future human welfare and the sustainability of ecosystems. Little research has yet been done to investigate the main mechanisms involved in the lateral translocation of SOC on the landscape. Understanding the effects of the different water erosion mechanisms, which control SOC losses (SOC_L) at the hillslope level, creates scope for further scientific studies.

Empirical data from 357 plots, with a range in slope length from 1 (n=117) to 22.1m (n=240) were analysed to estimate the global variations of particulate organic carbon content (POC_C), POC losses (POC_L) and sediment POC enrichment ratio (ER). The global average POC_L rate was calculated to be 12.1 g C m^{-2} y^{-1}. Tropical clayey soil environments revealed the highest POC_L (POC_L=18.0 g C m^{-2} y^{-1}), followed by semi-arid sandy (POC_L=16.2 g C m^{-2} y^{-1}) and temperate clayey soil environments (POC_L=2.9 g C m^{-2} y^{-1}). The global net amount of SOC displaced from its original bulk soil on an annual basis was calculated to be 0.59±0.09 Gt C, making up an approximated 6.5% of the net annual fossil fuel induced C emissions (9 Gt C). POC_L data for different spatial scales revealed that up to 83% of the eroded POC re-deposits near its origin in hillslopes, and is not exported out of the catchment. The low organic carbon sediment ER obtained from the data of clayey soils (ER of 1.1) suggests that most of the eroded POC remains protected within soil aggregates. Consequently, erosion-induced carbon dioxide (CO_2) emissions in tropical areas with clayey soils are likely to be limited (less than 10%), as the process of POC re-burial in hillslopes is likely to decrease the rate of organic matter (OM) decomposition and thus serve as a potential carbon sink. Water erosion in sandy and silty soils revealed organic carbon sediment ER as high as 3.0 and 5.0, suggesting that in

these soils the eroded POC is not re-buried, but is made vulnerable to micro-decomposers, thus adding to the atmospheric CO_2 influx. The results obtained in the review study only reaffirm that large variations of POC_L are evident across the different pedo-climatic regions of the world, making it a scientific imperative to conduct further studies investigating the link between SOC erosion by water and the global carbon cycle.

A field study was designed to quantify the POC exported in the eroded sediments from $1x1m^2$ and $2x5m^2$ erosion plots, installed at different hillslope aspects, and to further identify the main erosion mechanisms involved in SOC erosion and the pertaining factors of control. The erosion plots were installed on five topographic positions under different soil types, varying vegetation cover, and geology in the foothills of the Drakensberg mountain range of South Africa. Soil loss (SL), sediment concentration (SC), runoff water (R) and POC_L data were obtained for every rainfall event from November 2010 up to February 2013. Scale ratios were calculated to determine which erosion mechanism, rain-impacted flow versus raindrop erosion, dominates R, SL and POC_L. Averaged out across the 32 rainfall events, there were no significant differences in R and POC_L between the two plot sizes but SL were markedly higher on the 5m compared to the 1m erosion plots (174.5 *vs* 27g m^{-1}). This demonstrates that the sheet erosion mechanism has a greater efficiency on longer as opposed to shorter slopes. Rain-impacted flow was least effective where soils displayed high vegetation coverage ($P < 0.05$) and most efficient on steep slopes with a high prevalence of soil surface crusting. By investigating the role of scale in erosion, it was possible to single out the controlling *in situ* (soil surface related conditions) and *ex situ* (rainfall characteristics) involved in the export of SOC from soils. This information will in future contribute toward generating SOC specific models and thus further inform erosion mitigation.

ACKNOWLEDGEMENTS

In very first place I would like to thank the Lord my God for his excellent guidance in my young life this far.

'*Dear Lord,*

You deserve all praise and my deepest gratitude, for without your strong guidance and constant reassurance of knowing the purpose for me, I would be wretched. You were always there for me, have held my hand in difficult times, have carried me through the storms of my life, and even though I do not deserve it, have been my salvation from the very start of my life through your son Jesus. Amen.'

I acknowledge and am deeply grateful for the perfect guidance from Dr Vincent Chaplot, my primary supervisor, throughout this dissertation. It was an honour to have been a student under him.

I acknowledge and would like to express my sincere thanks to Dr Pauline Chivenge, my co-supervisor, for always having an open door and being readily accessible for her students.

I acknowledge and would like to sincerely thank Professor Trevor Hill for contacting me and firstly referring me to such an interesting project under such excellent supervision.

I acknowledge and am deeply grateful for the generous funding from the Water Research Commission (WRC) and the African Conservation Trust (ACT) throughout the duration of this MSc degree.

I would also like to heartily thank my family for their support, love and persistent phone calls, which kept me motivated and focused throughout the degree.

PREFACE

The following MSc manuscript is composed of two academic papers. The first, ***Soil water erosion and the global carbon cycle: a global assessment*** (submitted to Global Change Biology on 27 August 2013 and awaiting publication) is a review paper that was constructed using the results from all accessible existing studies in the field of SOC erosion. In this study a global assessment was conducted, where the objectives were:

- To integrate and compare the outcomes of all available *in-situ* studies focussing on SOC erosion through water.
- To identify possibly existing global SOC erosion patterns.

The first paper, informing on global SOC trends, creates a fine literature basis for a supplementary study specific to the South African environment. It will thus be possible to decisively compare how the local South African trends, in terms of SOC erosion, differ from the global tendencies, and further investigate observable differences in regards to SOC dynamics. Hence the second paper: ***Mechanisms and controlling factors of soil organic carbon losses by sheet erosion,*** presents the results of a personal research experiment conducted in Potshini, positioned in the greater Thukela River basin of KwaZulu-Natal, South Africa. In this experiment the primary objectives were:

- To quantify and compare the particulate organic carbon (POC) exported in the eroded sediments from 1x1m^2 and 2x5m^2 erosion plots, installed at pre-selected hillslope positions.
- To identify the main erosion mechanisms involved in SOC erosion (i.e. splash or sheet erosion) and the pertaining factors of control.

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CHAPTER 1
INTRODUCTION

Soil organic carbon (SOC) is a key component necessary for the healthy functioning of terrestrial ecosystems. SOC is the main component of soil organic matter which serves the soil with many beneficial properties: it improves the physical soil structure by promoting aggregate formation and improves the overall aggregate stability of the soil and thus significantly enhances the soils porosity and water holding capacity and protects soil against compaction. It forms an integral building block for organic acids and acts as a natural pH buffer in the soil and improves the cation exchange capacity of the soil. Soil organic matter improves nutrient supply to the soil and the nutrient holding capacity and thus preventing nutrient leaching. Soil erosion is a major mechanism of land degradation removing SOC from its initial place and transferring it to either the hydrosphere or the atmosphere, thus affecting key ecosystem functions and services. Although extensive scientific research has been aimed at creating a better understanding of soil erosion processes, sediment transport and nutrient loss from soils through water erosion (Pimentel *et al.*, 1995; Biggelaar *et al.*, 2001; Lal., 2003), limited knowledge is yet available with regards to SOC erosion. It is only since the advent of global climate change propaganda, that more research is being directed towards further investigating SOC erosion as an important mechanism influencing the global carbon cycle.

The fact that the soil constitutes the third largest carbon sink globally, exceeded in magnitude only by the oceanic and the geologic carbon pools, demonstrates the impact that SOC can play in the global carbon cycle. The global soils are estimated to contain three times the amount of carbon present in all plants and animals (biotic carbon pool). Through photosynthesis, atmospheric carbon is reintroduced into the soil by plant biomass additions, where it can remain sequestered indefinitely. Terrestrial soils thus present the potential to reduce the influx of atmospheric carbon through terrestrial soil carbon sequestration.

Soils are however known to also be effective carbon sources, with ever increasing agricultural pressure and poor land management practices leading to soil degradation and associated SOC losses. The global cumulative historic SOC loss, calculated from 1850 to 1998, varies from report to report, but has been approximated at 241 Pg (Lal, 2004). In comparison, anthropogenic fossil fuel emissions produced approximately 270 Pg of C during the same time period, showing that SOC losses are momentous and may contribute significantly towards the global atmospheric C budget.

Pedo-climatic characteristics vary greatly across the latitudes, especially across the northern and southern hemisphere, hence it is to be expected that differing global soils, located under differing climatic conditions will produce varying results pertaining to SOC losses. It is only in the last two decades that the topic of SOC erosion has sparked interest for the scientific community and as a result, scientific studies relating to this topic are still sparse. The existing internationally acknowledged research on the topic was conducted by different scientist under differing climatic, topographic and bio-geographic conditions. The results of these scientific studies, although useful on a local scale, remain isolated and site specific. As relatively little is yet known about the global patterns of SOC water erosion and its primary controlling factors, the full potential of these isolated global studies can be achieved by merging them into one review study and using the conclusive results to inform global SOC dynamics.

Based on the data obtained from a global review presented in this manuscript, the total amount of SOC displaced each year by water erosion was calculated to be 0.55±0.08 Gt C. The highest particulate organic carbon loss (POC_L) rates were recorded in the tropical regions of the world. The semi-arid regions of the world, which are characteristic of significantly lower SOC stocks than the humid tropics, were marked by similar levels of POC losses to the tropics. The temperate regions, displayed SOC erosion rates 20% lower than those of the tropical and semi-arid areas. This review also recognised the impact that land use and land management can have on SOC erosion by water.

Sheet wash associated with splash appeared far more efficient than splash alone for detaching and transporting SOC as suggested by the significant increase in POC_L from microplot to plot scale. Plots revealed lower POC_L compared to microplots, meaning that sheet erosion quantified at plot scale, is a less efficient SOC erosion mechanism than splash. This paper revealed research potential for further studies to generate a guide delineating a range of "acceptable POC erosion", needed for a sustainable functioning of soils of all concerned pedo-climatic regions.

The cumulative soil losses monitored for the three seasons were six fold greater for 5m long erosion plots than on the 1m long plots. This is indicative that rain impacted flow (RIF) erosion, which operates more effectively on longer slopes, is the primary mechanism of soil erosion, in comparison to splash. Significantly lower POC_L per meter width on the longer plots inform on the overall limitation of transport and the predominance of splash in contrast to RIF in SOC water erosion. These findings were consistent with the results of studies conducted in semi-arid and tropical environments, which are displayed in Chapter 2. The efficiency of sheet erosion, with the contribution of RIF, was determined largely by slope gradient, vegetation cover, soil surface crusting and soil clay content. RIF erosion operated more effectively on longer slopes and proved to be the dominating mechanism of soil erosion, in comparison to splash. The efficiency of splash for SOC erosion was largely controlled by rainfall characteristic, such as intensity and duration.

CHAPTER 2
SOIL WATER ERSION AND THE GLOBAL CARBON CYCLE: A GLOBAL ASSESSMENT

2.1 Abstract

Soil organic carbon (SOC) being one of the primary components necessary for the ideal functionality of soils, and soil water erosion being a principal mechanism of SOC depletion, relatively little is yet known regarding the global trends of SOC water erosion and the associated factors controlling the erosion process. Empirical data from 357 plots with slope length range from 1m (n=117) to 22.1m (n=240) were analysed to estimate the global variations in particulate organic carbon content (POC_C), POC losses (POC_L) and sediment POC enrichment ratio (ER). The average POC_L was 12.1 g C m^{-2} y^{-1}, with a standard error of ± 1.8 g C m^{-2} y^{-1}. The highest POC_L were observed for tropical clayey soil environments (POC_L=18.0 g C m^{-2} y^{-1}), followed by semi-arid sandy soils (POC_L=16.2 g C m^{-2} y^{-1}) and temperate clayey environments (POC_L=2.9 g C m^{-2} y^{-1}). The total amount of SOC displaced annually from its original bulk soil was 0.59±0.09 Gt C, i.e. 6.5% of the net annual fossil fuel induced C emissions (9 Gt C). POC_L data for different spatial scales revealed that 83% of the eroded POC re-deposits near its origin in hillslopes. The low organic carbon enrichment of sediments from clayey soils (ER of 1.1) suggests that most of the eroded POC remains sheltered within soil aggregates. Consequently, erosion-induced CO_2 emissions are likely to be limited (less than 10%), while POC burial in hillslopes is likely to decrease the rate of OM decomposition and/or constitute an important carbon sink. Water erosion in sandy and silty soils revealed organic carbon sediment enrichments as high as 300 and 500% (ER=3.0; 5.0), resulting in additional greenhouse gas emissions ranging from 200 to 400%. These results underpin the importance of SOC detachment and transport processes in the global C cycle. Large variations are evident across the different pedo-climatic regions of the world.

2.2 Introduction

Water erosion has long been recognized to be the principal mechanism behind the losses from soils of organic carbon, a primary soil constituent essential for ecosystem functions such as food production and biodiversity (Lal, 1990). Soil organic carbon (SOC) erosion can thus be far-reaching, among many things affecting human welfare and the sustainability of ecosystems.

The soil water erosion process involves soil material detachment and transport through the physical action of raindrop impact (splash); shallow or deep overland flow. Whilst the impact of splash and overland flow on soil detachment and transport has been widely investigated (Kinnell, 2001), their effect on SOC erosion is yet to be investigated. There is a particular need to investigate the impact that sheet erosion processes in association with raindrop energy pose on SOC displacement.

SOC consists of particulate organic carbon (POC) and dissolved organic carbon (DOC), with POC making up the largest pool. Soil aggregates undeniably serve as physical protection for POC, through a range of interactions from inclusion to sorption (Tisdall and Oades, 1982; Jastrow, 1996; Torn *et al*., 1997; Baldock and Skjemstad, 2000; Masiello *et al*., 2004; Six *et al*., 2004; Rasmussen *et al*., 2005; Mikutta *et al*., 2006). Sheet erosion, either through the detachment and transport of entire aggregates, or through aggregate disruption and preferential POC erosion, is likely to play a key role in the global carbon cycle (Berhe et al., 2007), mainly as a major atmospheric source of CO_2 (Wiesmeier, 2012). In contrast, the re-burial of the eroded POC could potentiate carbon sequestration or at least decrease the decomposition rate of OM.

Lal (2003) estimated POC erosion by water to amount 4.0-6.0 Gt C y^{-1} globally. This figure remains debatable as it was computed by only using data obtained from the mouths of rivers, and by further assuming, without substantial empirical evidence, that 10% of the eroded SOC reaches the open ocean. More recently and by using modelling, Doetterl et al. (2012) estimated the global flux of eroded SOC to be as low as 0.403 (±0.2) Gt C y^{-1}. Moreover, large discrepancies seem to exist on the rates, measured *in-situ*, of SOC erosion by water. Bilgo *et al*. (2004) in Burkina Faso, Boegling *et al*. (2005) in Cameroon, Boye and Albrecht (2006) in Kenya and Martinez-Mena *et al*. (2002; 2008) in Spain, revealed insignificant POC losses, with rates lower than 1 g C m^{-2} y^{-1}. This corresponded in all cases to depletion rates of the total SOC stock in the A horizon of less than 0.7%. In contrast, Barthès *et al.* (2006) in Benin and Polyakov and Lal (2008) in USA revealed SOC depletion rates exceeding 30%. Moreover, based on the ER, which is the ratio comparing organic carbon content of the eroded sediments to that of the bulk soil, Bertol *et al*. (2007) in Brazil, Brunet *et al*. (2004, 2006) and Martinez-Mena *et al*. (2002) showed that water erosion in clayey soil environments does not result in preferential erosion of POC as displayed by a ER close to 1, whilst the studies conducted in sandy soils, such as these by Boegling *et al*. (2005) in Cameroon and Mchunu *et al*. (2011) in South Africa, pointed to a significant POC enrichment of sediments (ER of 12.2 and 5.9, respectively).

The large variations in POC erosion by water, from site to site, need more appraisals. This is important to precisely quantify the magnitude to which water erosion impacts the global carbon cycle and to identify the main controlling factors, which have remained largely unexplored. Studies of such calibre will inform and enrich the international community's capacity to design and implement optimal land management strategies aimed at minimising SOC losses, especially in the context of global change. Several research questions can be formulated addressing the lack of knowledge regarding the impact of soil water erosion on the global carbon cycle:

1. On the magnitude of SOC erosion by water: What is the amount of SOC displaced annually through water erosion and how does this amount vary from place to place? Does the erosion of SOC through water have a significant impact SOC stocks?

2. On the fate of the eroded SOC: What is the fate of the eroded SOC? What percentage of SOC is re-deposited close to its origin, as opposed to the percentage being re-deposited further downslope or reaching the river network? How much SOC is actually exported out of catchments and eventually reaches the open ocean?

3. On the processes and factors of control of SOC erosion: What are the main factors of control and the governing mechanisms involved in the SOC detachment and transport process?

In this study a global assessment was conducted, where the objective was to integrate and compare the outcomes of all available *in-situ* studies focussing on SOC erosion through water.

2.3 Materials and Methods

2.3.1 The accumulation process of the research papers

This study involved a thorough exploration of certain available academic reserves, such as Science Direct, Springerlink and Web of Knowledge. To make the search process as efficient as possible, a list of topic-related keywords was implemented. A plethora of papers was found dealing with soil C stocks and soil C content, yet only papers that specifically dealt with SOC erosion by water were selected for the purpose of this paper. The runoff and soil erosion data had to come exclusively from field experiments performed under natural rainfall conditions over the duration of an entire hydrological year. In each of the selected studies, the eroded sediment, soil C content and soil C stock were data points always originating from the same original bulk soil (i.e. the same position), therefore these data are representative of the same soil type and landuse and can thus be used to calculate the ER. All field data from the chosen studies were analysed in laboratories to determine the C content.

The studies used in this analysis all originate from different global locations, which are characteristic of vastly differing climatic attributes (e.g. mean annual precipitation, mean annual temperatures, mean annual trans-evaporation etc.). For the purpose of this study, especially for the generation of a regression equation, which would ultimately be used to devise a global prediction map, mean annual temperature and mean annual precipitation were recorded. As the chief focus of this study lies, however, in investigating SOC erosion by water erosion processes, section “2.4.4 Climate” is specifically focused only on the measured precipitation. The study offers a rich spectrum of results originating from diverse pedo-climatic and topographic conditions. The empirical data points used were mainly retrieved from grassland and cropland studies, which cover about 40% of all terrestrial land. The data base was composed of data points retrieved from 357 runoff plots, with a slope length range from 1 m (microplot, n=117) to 22.1 m (plots, n=240). Information regarding POC losses (POC_L) was included, provided that the survey yielding the data considered at least an entire rainy season. The studies that incorporated longer erosion plots in their experiments were used in an attempt to address the potential fate of the eroded SOC and its chief factors of control.

Even though SOC erosion is a relatively new field of research, the search yielded 37 peer reviewed papers. Most of these papers were published during the last decade, showing that this field has only gained academic interest recently and thus has great potential to be explored further (Table 2.1, Figure 2.1).

In the following, the term “SOC” was used to refer to the organic carbon in the soil, including light fraction, mineral-bound and both occluded and non-occluded OC, and “POC” to the particulate organic carbon in sediments, and “DOC” to the dissolved organic carbon in overland flow.

Table 2.1. Mean particulate carbon losses (POC_L) from microplot (LOS-length of slope, below 1m) to mini-catchment (LOS<1000 m) (All sizes), from microplots or plots with (1<LOS<22.1 m) only; ER: mean enrichment (calculated by using only microplot to plot sediments) in POC compared to the bulk soil; mean annual precipitation (MAP); mean annual temperature (MAT); altitude above sea level (Z); latitude (LAT); bulk density of the soil upper horizon (ρ_b); clay, silt ,sand; soil organic carbon content (SOC_C) in the soil upper horizon; SOC stocks (SOC_S), SOC density (SOC_D) and yearly SOC depletion rate (DR) of SOC_S (computed for the upper soil 10 cm layer). Data computed from 117 microplots; 240 plots with 1<LOS<22.1m, 33 plots with 22.1<LOS<100m and 26 mini-catchments (100<LOS<1000m) and surveyed under natural rainfall conditions over a minimum of one hydrologic year. n displays the number of treatments.

n	Author	Country	n	POC_L			ER	MAP	MAT	Z	CLAY	SAND	SOC_C	SOC_D	SOC_{DR}
				$g\ C\ m^{-2}\ y^{-1}$				mm	ºC	m	%	%	$g\ C\ kg^{-1}$	$Kg\ C\ m^{-3}$	%
				All sizes	*Microplots*	*Plots*	Mean								
1	Barthès et al. (2006)	Benin	3	16.7		16.7	0.7	1200	27	53	14.7	71.0	5.4	5.37	3.11
2	Bellanger et al. (2004)	Venezuela	3	9.8		9.8	0.2	1600	21	1200	26.0	52.7	155.4	275.50	0.04
3	Bilgo et al. (2004)	Burkina Faso	4	0.4		0.4	0.0	900	29	360	4.9	34.5	3.7	5.33	0.08
4	Bilgo et al. (2006)	Burkina Faso	4	9.7		9.7	4.3	850	29	360	5.2	71.9	3.4	5.33	1.82
5	Boegling et al. (2005)	Cameroon	5	0.7			12.2	1700	25	700	50.0	39.0	15.0	19.50	0.04
6	Boix-Fayos et al. (2009)	Spain	7	8.9			0.6	583	13	1200	15.3	26.6	16.5	16.95	0.53
7	Boutkhil et al. (2006)	Algeria	8	2.8		2.8	1.9	470	17	585	33.3	24.9	10.7	14.15	0.20
8	Boye and Albrecht (2006)	Kenya	10	0.7		0.7	3.3	1200	21	1290	29.8	51.2	17.9	18.76	0.04
9	Brunet et al. (2004)	Brazil	3	22.7	22.7		1.1	1200	22	1000	53.4	28.9	24.2	21.78	1.04
10	Brunet et al. (2006)	Brazil	3	2.4	2.4		1.0	1200	22	950	53.4	28.9	24.2	21.78	0.11
11	Chaplot and Poesen (2012)	Laos	12	8.4	18.3	6.4	0.7	1403	25	580	44.0	18.9	25.1	25.14	0.33
12	Chaplot et al. (2005)	Laos	7	1.1	2.0		1.6	1403	25	720	47.8	16.2	22.2	30.04	0.04
13	Chaplot et al. (2006)	Laos	3	0.9	1.6		1.4	1403	25	550	53.5	11.4	22.6	21.02	0.04
14	Chaplot et al. (2007)	Laos	5	37.8	37.8		2.3	1403	25	580	48.1	14.7	22.2	29.64	1.28
15	Cogle et al. (2002)	India	9	4.0		4.0	1.3	784	27	516	30.0	60.0	8.3	8.59	0.47
16	Drissa et al. (2004)	Mali	6	14.1		14.1	10.0	1076	25	400	20.1	22.8	2.1	2.40	5.87
17	Gachene et al. (1997)	Kenya	1	240.0		240.0	3.1	1000	19	2000	15.0	65.0	26.7	26.67	9.00
18	Gachene et al. (1997)	Benin	1	30.0		30.0	1.3	1200	26	200	8.8	8.8	6.7	6.67	4.50
19	Girmay et al. (2009)	Ethiopia	4	9.9		9.9	1.6	542	27	1500	33.7	36.5	18.5	24.28	0.41
20	Jacinthe et al. (2004)	U.S.A.	5	4.4			1.9	950	10	400	20.0	20.0	23.8	31.37	0.14
21	Juarez et al. (2011)	South Africa	5	8.4	8.4		1.9	684	17	1385	18.0	45.0	30.6	30.62	0.27
22	Martinez-Mena et al. (2002)	Spain	2	0.3		0.3	1.0	300	17	800	35.0	22.0	35.5	56.19	0.01
23	Martinez-Mena et al. (2008)	South East Spain	3	2.6		2.6	2.2	300	17	800	25.5	32.7	8.8	5.27	0.49
24	Martinez-Mena et al. (2011)	Spain	2	0.7		0.7	1.7	300	17	800	25.5	32.6	18.2	18.20	0.04
25	Mchunu and Chaplot (2012)	South Africa	3	4.2	4.2		1.8	684	13	1385	16.0	70.3	0.4	0.50	8.36
26	Mchunu et al. (2011)	South Africa	2	12.0		12.0	5.9	684	13	1385	18.0	45.0	13.0	15.11	0.79
27	Mchunu et al. (2011)	South Africa	2	12.0		12.0	5.9	684	13	29	18.0	68.0	13.0	15.11	0.79
28	Moyo et al. (1998)	Zimbabwe	1	20.0		20.0	1.9	500	26	1479	9.7	9.7	5.0	5.00	4.00
29	Orchard et al. (2012)	South Africa	5	19.6	24.5	26.2	2.6	684	13	1385	16.0	70.3	13.0	16.71	1.17
30	Phan Ha et al. (2012)	Vietnam	5	1.8	2.9	0.7	1.6	960	22	102	45.0	30.0	29.1	26.78	0.07
31	Polyakov and Lal (2008)	U.S.A.	3	22.0		22.0	1.4	932	11	250	21.9	20.5	5.0	6.50	3.38
32	Quinton et al. (2006)	United Kingdom	10	0.6			3.6	621	9	85	10.0	75.0	11.0	11.02	0.05
33	Rodríguez et al. (2004)	Spain	2	0.9		0.9	0.8	730	16	1000	22.3	6.3	134.5	68.70	0.01
34	Roose et al. (1978)	Burkina Faso	1	180.0		180.0	6.3	800	29	400	27.4	27.4	4.3	11.33	15.88
35	Roose et al. (1980)a	Ivory Coast	1	20.0		20.0	1.8	2100	27	219	20.1	20.1	11.3	4.33	4.62
36	Roose et al. (1980)b	Ivory Coast	1	10.0		10.0	2.6	1350	27	219	18.2	18.2	7.0	7.00	1.43
37	Rumpel et al. (2006)	Laos	6	7.9	2.0		2.3	1403	25	718	48.3	15.8	20.8	20.78	0.38
		Min.		***0.3***	***1.6***	***0.3***	***0.02***	***300***	***9***	***29***	***4.9***	***6.3***	***0.4***	***0.5***	***0.01***
		Max.		***240.0***	***37.8***	***240.0***	***14.8***	***2100***	***29***	***2000***	***82.8***	***86.2***	***155.4***	***275.5***	***15.9***
		Mean		***21.0***	***11.5***	***26.1***	***2.4***	***995.8***	***21.3***	***727.02***	***29.8***	***36.7***	***21.7***	***25.1***	***1.9***

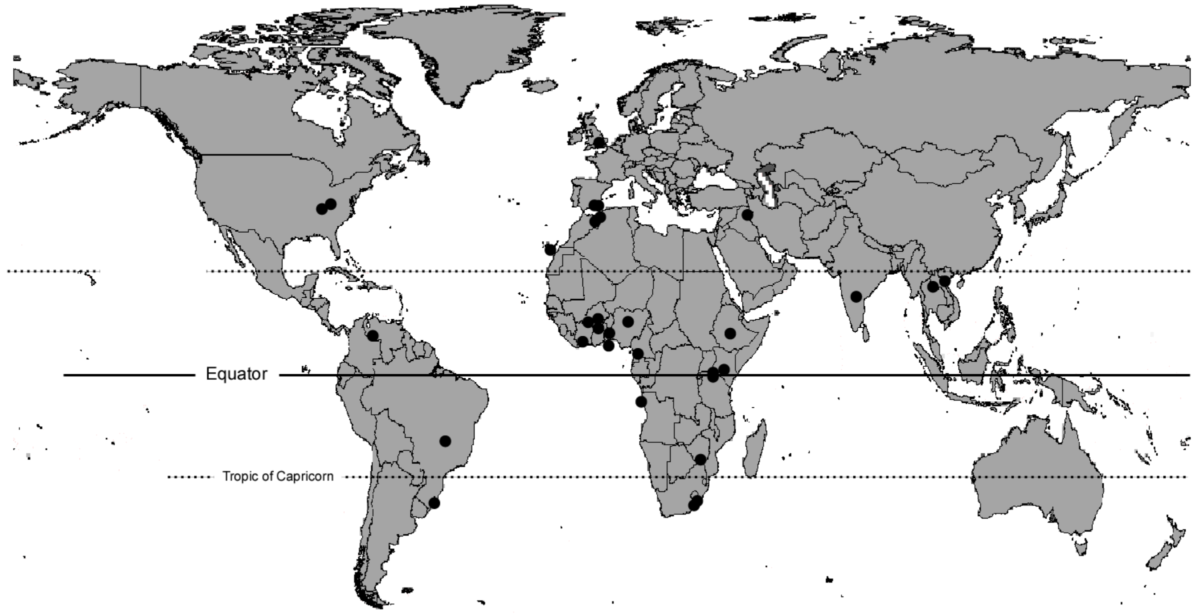

Figure 2.1. Location of the 37 research papers on soil carbon erosion and used for this study.

2.3.2 Data base generation

One Hundred and seventeen microplots (slope length, L below 1m), 240 plots (1<L<22.1 m), 33 long plots (22.1<L<100 m) and 26 mini-catchments (100<L<1000 m), totalling 416 data points, were entered into the database.

2.3.3 Soil carbon erosion data

For each data point, the considered variables were runoff (R), which corresponded to the overland flow generated from a given spatial scale per annum (L m^2 yr^{-1}); sediment concentration in R (SC in g l^{-1}) and soil losses (SL in g $m^2 yr^{-1}$, Equation 2.1).

$$SL = R \times SC \tag{2.1}$$

Mean particulate organic carbon content (POC_C) in the eroded sediments and mean dissolved organic carbon content (DOC_C) in R were also considered. These variables were used to compute the annual losses of POC (POC_L, g C m^{-2} y^{-1}) and DOC (DOC_L, g C m^{-2} y^{-1}) (Equations 2.2 and 2.3).

$$POC_L = POC_C \times R \times SC \tag{2.2}$$

$$DOC_L = R \times DOC_C \tag{2.3}$$

2.3.4 Environmental factors and soil properties

Several environmental and topographic variables were estimated for each of the 416 data points: mean 30-year annual precipitation (MAP), mean 30-year annual temperature (MAT), altitude above sea level (Z), mean slope gradient (S), slope length (L), along with latitude (LAT) and longitude (LONG). When the climatic information was not recorded in a given article, it was extracted from the WORLDCLIM database (Hijmans *et al.*, 2005) with a spatial resolution of 30" (approximately 1 km). Likewise, in those cases where Z was not stated in a paper, a 30" resolution global DEM from the U.S Geological Survey (1993) was utilised to estimate the altitude by means of the areas respective geographic coordinates. Information pertaining to land use was consistently available, as was the detailed information on the specific land management practices. The information was reported in diverse categories, varying from shrub land, orchard, maize, fallow, paddies to primary or secondary forests, and was gathered into five distinct land use and land management classes as follows: (1) forest and fallow, (2) grass and Shrub, (3) conservation tillage and no tillage, (4) tillage.

The soil sampling depth range of all sample data used in this study was limited exclusively to the upper soil A horizon (0-0.05 to 0-0.3 m). Soil samples were taken by the studies to determine ρ_b, clay, silt and sand content as well as the soil organic carbon stocks (SOC_S, Equation 2.4). Papers which did not report these data were not considered.

$$SOC_S = x_1 \times x_2 \times x_3 (1 - \frac{x_4}{100}) \qquad (2.4)$$

SOC_S is representative of the SOC stock (kg C m^{-2}); x_1 is SOC_C concentration in the ≤2 mm soil material (g C kg^{-1}); x_2 is the soil bulk density ρb (Mg m^{-3}); x_3 is the thickness of the soil layer (m); x_4 is the proportion of fragments of >2mm, given as a percentage.

Water erosion only affects the very top most layer of soil, therefore exclusively top-soil data was used in the computation of SOC_S. The thirty six studies used dry combustion to estimate SOC_C. Because the information regarding SOC was reported for a sampling depth range (0.05 to 0.3m), errors in the interpretations of SOC_S could occur (Balesdent *et al.*, 1990). Therefore, the data points were compared based rather on equivalent soil mass, as is indicated in Equation 2.5 (SOC_D).

$$SOC_D = SOC_S \times \frac{1}{x_3} \qquad (2.5)$$

In this equation SOC_D represents SOC density in kg C m^3.

Finally, the yearly depletion rate of SOC_D (SOC_{DR}, % y^{-1}) was estimated following Equation 2.6:

$$SOC_{DR} = (\frac{SOC_L}{\mathrm{SOC}_\mathrm{D}}) \times 100 \qquad (2.6)$$

2.3.5 Estimation of the sediment enrichment in organic carbon

For each data point, the information regarding POCc and SOCc was subsequently used to compute the ER (Equation 2.7), which is a ratio comparing the organic carbon content of the eroded sediments to SOC_C in the top soil, with sediments and top-soil, both originating from the same location.

$$ER = \frac{POC_C}{SOC_C} \qquad (2.7)$$

The ER determines the degree of preferential erosion of SOC. It can further be used to determine and explain which water erosion mechanism predominates in a particular soil and whether the eroded material is potentially rendered unprotected from decomposers.

2.3.6 Statistical, multivariate analysis

Basic statistics (minimum, maximum, median, mean, variance, standard deviation, 25^{th} and 75^{th} percentiles and the coefficient of variation) were first calculated (Table 2.2). The second phase of the statistical analysis was aimed at analysing the correlations between variables by creating a correlation matrix and then performing an ANOVA (Table 2.3). A principal components analysis (PCA), was then conducted in order to identify the various relationships between the variables of interest (i.e. SOC erosion variables such as: POC_C, POC_L, SOC_{DR} and ER) and certain environmental variables. A statistical PCA is applicable when a large number of variables are being investigated, yet only a limited number of variables (known as the principal variables) will account for most of the variance in the data field (Smith *et al*., 2001). Finally, a multiple stepwise regression analysis was conducted, resulting in the generation of a map portraying the global ER trends. This method was selected for practicality purposes, as it allows for certain variables to be predicted, using more readily accessible variables, such as climate, soil texture and certain terrain attributes. Moreover, this mapping technique allows a more accurate representation of spatial trends, especially when the sampling is inhomogeneous, as it is the case in the present study.

For the linear regressions analysis, only parameters with a statistical significance of 0.01 were considered to produce the predictive equations. The 5% outliers were removed from the data base before the start of the analysis.

The numeric estimates were transformed into a series of categories, ranging from “Very low” to “Very high”. The “Very low” category included the lowest 10% of the estimates; the “Low” category was representative of the 10-35% range; the “Moderate” category representative of the 35-65%; the “High” category represented a range of 65-90%; while the

“Very high” category corresponded to estimates of up to 90% and therefore depicts areas with the highest SOC enrichment ratio.

Table 2.2**.** Summary of statistics for particulate organic carbon (POC) content (POC_C), POC losses (POC_L), enrichment ratio of sediments in POC compared to the bulk soil (ER), soil organic carbon density (SOC_D) and the yearly depletion rate of SOC stocks in the 0-0.1m soil layer (SOC_{DR}). Three hundred and fifty seven plots with a slope length 22.1 m and below were considered.

	POC_C g C kg^{-1}	**POC_L** g C $m^{-2}y^{-1}$	**ER**	**SOC_D** Kg C m^{-3}	**SOC_{DR}** % y^{-1}
Minimum	0.1	0.001	0.0	0.3	0.0
Maximum	116.0	240.0	14.0	456.5	24.3
Mean	32.1	12.1	2.5	24.5	1.6
Median	28.3	3.7	1.7	17.9	0.2
Variance	596.2	826.9	6.6	2250.2	14.1
Standard deviation	24.4	28.8	2.6	47.4	3.8
Skewness	1.2	6.1	2.7	7.2	4.0
Quartile1	14.1	0.9	1.3	8.2	0.1
Quartile3	46.4	11.4	2.6	25.5	1.4
Kurtosis	1.7	42.6	7.8	61.0	18.0
CV	76.0	238.2	101.3	193.6	234.6
SE	1.5	1.8	0.2	3.0	0.2

Table 2.3. Statistical ANOVA comparing the SOC enrichment in sediment to the bulk soil (ER) and the particulate organic carbon losses (POC_L), on the one hand, and selected environmental variables (particulate organic carbon losses: POC_L; particulate organic carbon content POC_C in the sediments; mean annual precipitation: MAP; mean annual temperature: MAT; altitude above sea level: Z, latitude: LAT; bulk density of the soil upper horizon: ρ_b; clay, silt ,sand; soil organic carbon content (SOC_C) and SOC stocks (SOC_S) in the upper soil horizon), on the other hand. N= 357 plots with a length range from 1 to 22.1 m and surveyed under natural rainfall conditions.

	DF	MS	F	p
	POC_L			
POC_C	5	1590	2.9	0.001*
ER	5	2843	2.9	0.014*
MAP	5	5184	33.3	0.000***
MAT	5	5730	13.6	0.000***
Z	5	3781	10.9	0.000***
LAT	5	4062	7.7	0.000***
ρ_b	5	1220	1.1	0.301
CLAY	5	2017	3.2	0.000***
SILT	5	870	0.7	0.855
SAND	5	2442	6.1	0.000***
SOC_C	5	822	0.6	0.903
L	5	1138	1.0	0.434
	ER			
POC_C	5	1.9	1.8	0.040*
POC_L	5	2.9	3.8	0.000***
MAP	5	4.2	4.9	0.000***
MAT	5	7.4	11.7	0.000***
Z	5	4.5	6.8	0.000***
LAT	5	3.2	2.8	0.003*
ρ_b	5	3.7	2.5	0.12
CLAY	5	2.2	1.8	0.029*
SILT	5	2.8	2.6	0.002*
SAND	5	2.8	3.3	0.000***
SOC_C	5	2.9	3.7	0.000***
L	5	15.4	14.7	0.000***

* significant at $p<0.05$ levels
*** significant at $p<0.001$ levels

2.4 Results

2.4.1 Rate of SOC erosion by water at different spatial scales

The average POC_L computed from the data points of 117 microplots with the slope length (L) of 1 m was 11.5 g C m^{-2} y^{-1} with a standard error of ± 2.0 g C m^{-2} y^{-1}. The POC losses ranged from 4 g C m^{-2} y^{-1}, as shown in the studies of Rumpel *et al*. (2006) in Laos and Phan Ha *et al*. (2012) in Vietnam, to about 20 g C m^{-2} y^{-1}, shown by Brunet *et al*. (2004) in Brazil and Chaplot *et al*. (2007) (Table 2.1).

The average POC_L were significantly higher (up to 26.1±11.2 g C m^{-2} y^{-1}) for runoff plots (L between 1 and 22 m, n=240) data (Figure 2.2 A). POC_L from plots ranged between 0.3 and 0.4 g C m^{-2} y^{-1} in the drylands of Spain (Martinez-Mena et al., 2002) and Burkina Faso (Bilgo *et al*., 2004) to extreme losses of up to 240 g C m^{-2} y^{-1}, recorded in wet, sandy environments of Kenya (Gachene *et al*., 1997) (Table 2.1). Long plots (22<L<100 m; n=33) revealed substantially lower POC_L rates (4.4 ±0.5 g C m^{-2} y^{-1}, Figure 2.2 A) in comparison to shorter plots (28.0 ±11.5 g C m^{-2} y^{-1}) and mini-catchment level (13.5±7.0 g C m^{-2} y^{-1}).

Soil losses on a microplot scale went up to 6.1±2.3 kg m^{-2} y^{-1}, yet decreased rapidly to 1.5 kg m^{-2} y^{-1} on 1 to 22.1 m long plots, which corresponded to a 4.6 kg m^{-2} y^{-1} (i.e. 75%) (Figure 2.2 C).

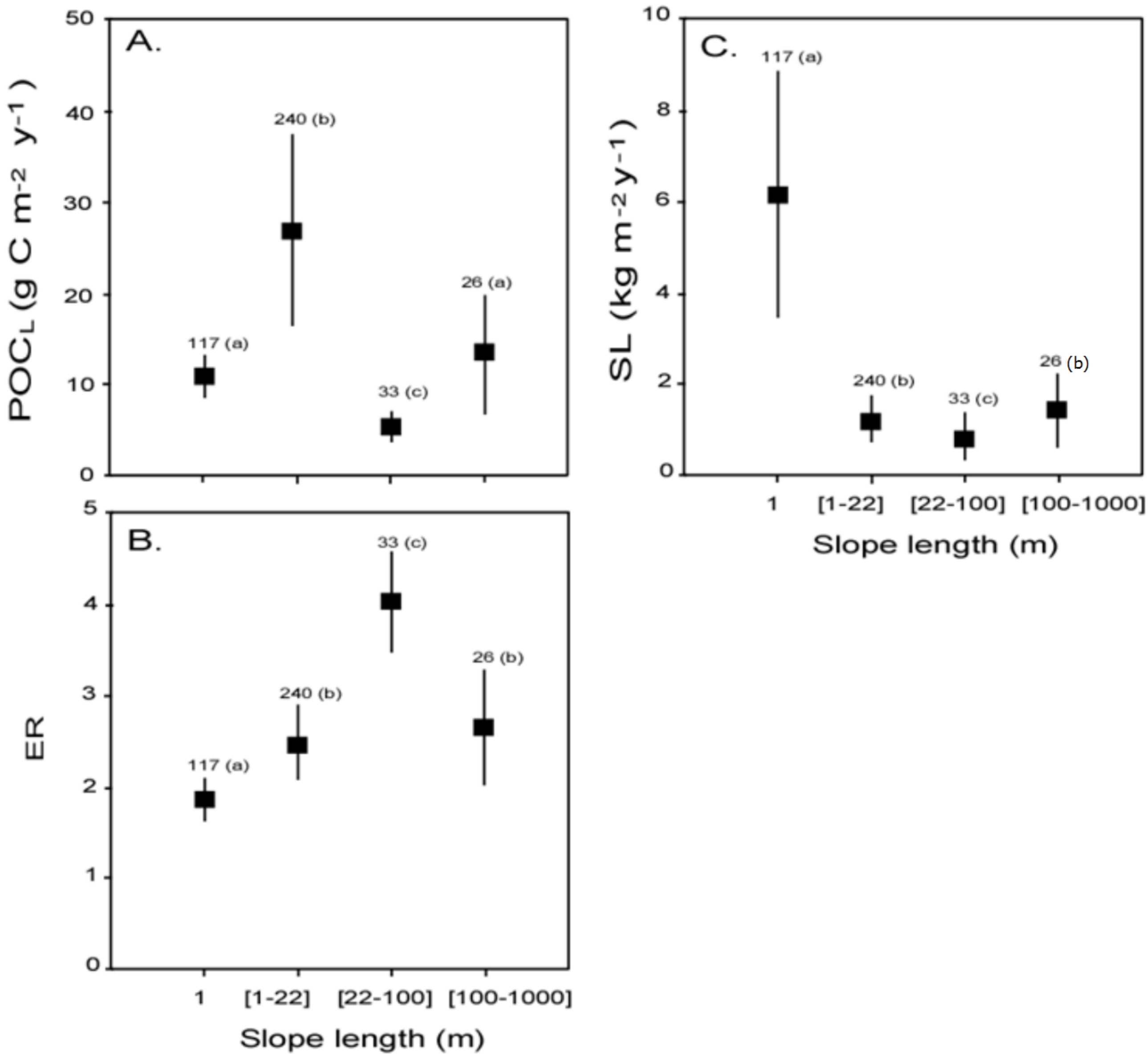

Figure 2.2. Impact of slope length on the mean and standard error of particulate organic carbon losses (POC$_L$, A); sediment enrichment ratio in organic carbon (ER, B) and.Slope length (SL, (C)).The figures above the box and whisker plots are the number of observations. The letters in brackets were included to indicate a significant statistical difference between the classes. Different letters symbolize a significant statistical difference (using $P<0.05$).

2.4.2 Organic carbon enrichment in sediments compared to the bulk soil

On the whole, the eroded sediments collected at all spatial scales tended to have a higher organic carbon content than the bulk soil, as shown by an ER higher than 1 (Table 2.1, Figure 2.2B). For microplots the average ER was 1.8 with a SE of 0.1. A significant difference at $P<0.05$ was noted for the plot scale where the average ER was 2.5±0.4. On the long plot scale the highest of the average ER (ER value of 4.0±0.5) between different plot scales was observed, while the average ER for the mini-catchment scale was 2.6±0.6. The lowest ER values (ER<1) were reported by Bilgo *et al*. (2004) in Burkina Faso, Bellanger *et al*. (2004) in Venezuela and Barthes *et al*. (2006) in Benin. In contrast, the highest ER values were observed in two studies conducted in Cameroon by Boegling *et al*. (2005) (ER=12.2) and Amegashie *et al*. (2011) (ER= 6.3). Drissa *et al*. (2004) also conducted a study in Mali, which revealed a high ER=10.0 (Table 2.1). Finally, ER values close to 1 were found in studies conducted in clayey soil environments as for instance those of Brunet *et al*. (2004 and 2006) in Brazil, Chaplot *et al*. (2005, 2007) in Laos and Phan Ha *et al*. (2012) in Vietnam.

2.4.3 Impact of controlling factors on the displacement of SOC from its original place, land use and land management

In Figure 2.3, POC_L from plots with a length of slope (LOS) below 22.1m (n=357) were explored and compared against different land uses and land management systems. The least POC_L were observed under the land use “Forest” (POC_L=2.4 gC m^{-2} y^{-1}) followed by “Fallow” (POC_L=5.5 gC m^{-2} y^{-1}) and “Grass” (POC_L=6.6 gC m^{-2} y^{-1}). These losses were significantly lower than those from croplands, which revealed an average POC_L of 18.0 gC m^{-2} y^{-1} from tilled soils (T) and 11.2 g C m^{-2} y^{-1} from no-till soils (NT). Based on these results, conservation tillage practices (NT) decreased POC_L by 6.8 gC m^{-2} y^{-1} or 37% annually compared to tilled soils.

The ER for the different land uses differed only slightly between the various land uses and management categories (Figure 2.4A) with differences not statistically significant at the $P<0.05$ level.

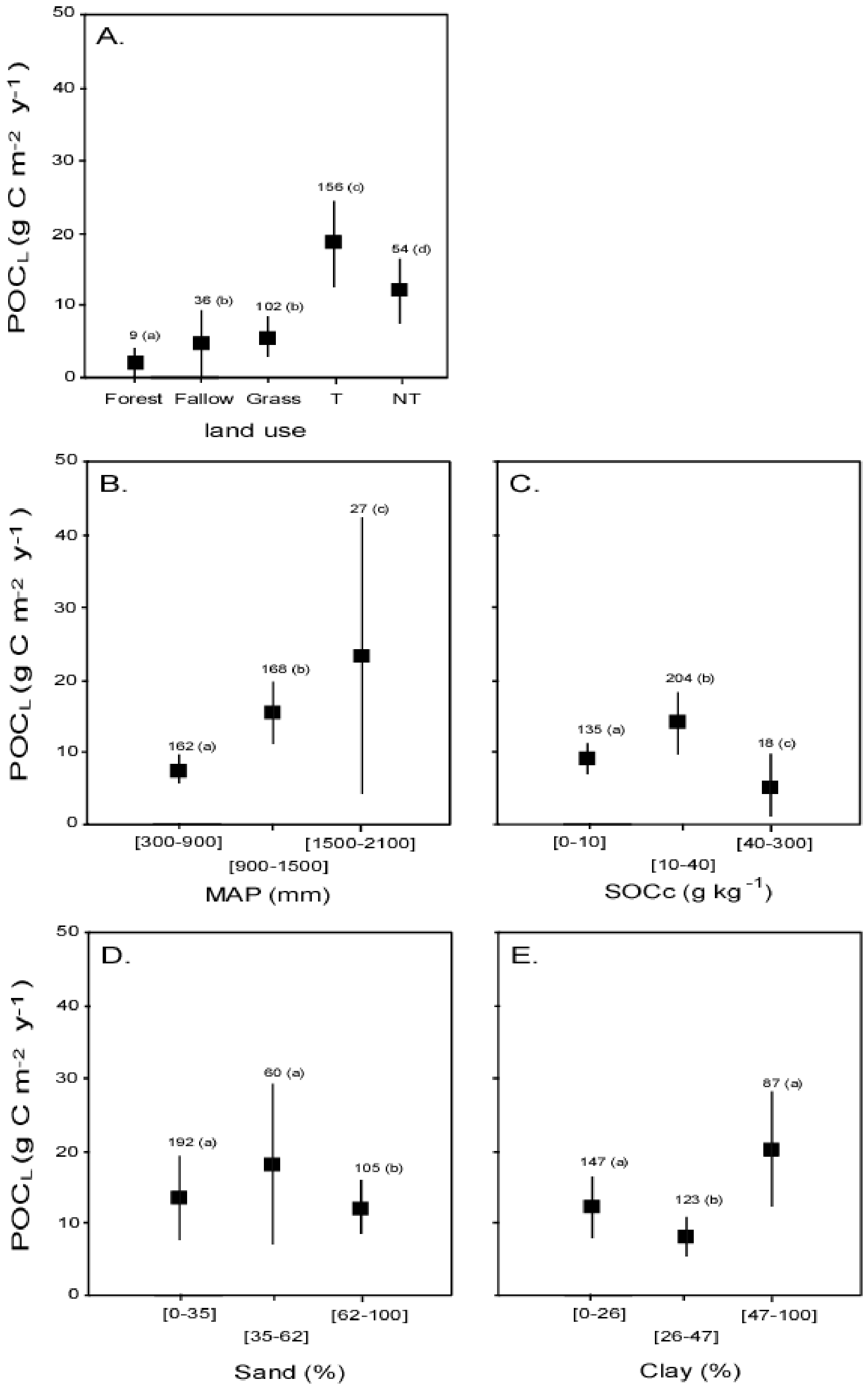

Figure 2.3. Mean and standard error of particulate organic carbon losses (POC_L) for different: (A) land uses, (B) slope length, (C) MAP, (D) SOC_C, (E, F) sand and clay content. The values above the box and whisker plots indicate the number of observations. The letters in brackets were included to indicate a significant statistical difference between the classes. Different letters symbolize a significant statistical difference (using $P<0.05$). n=357 plots with a slope length below 22.1m.

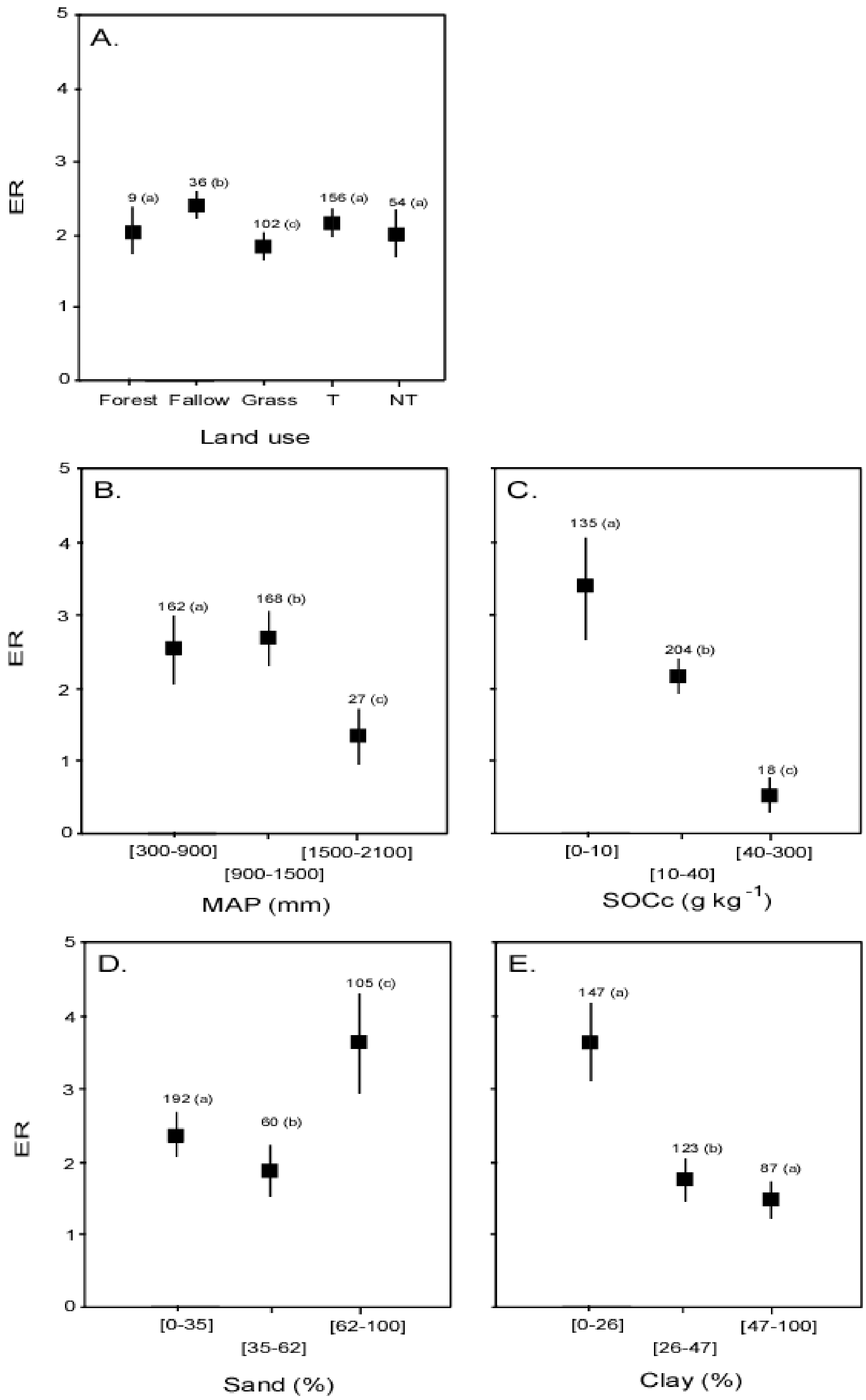

Figure 2.4. Mean and standard error of sediment enrichment in organic carbon compared to the bulk soil (ER) for: (A) different land use categories, (B) slope length, (C) MAP, (D) SOC_C, (E, F) sand and clay content. n=357 plots with a slope length below 22.1m.

2.4.4 Climate

Figure 2.3B, showing the correlative relationship between MAP and POC_L, reveals that soils are bound to produce the highest POC_L in areas receiving the highest mean annual precipitation. The POC_L increase from 7.1 ± 2.0 gC m^{-2} y^{-1}, with a corresponding MAP between 300 and 900mm y^{-1}, to 15.1 ± 8.1 gC m^{-2} y^{-1} for a higher rainfall category (900<MAP<1500mm y^{-1}) and to 22.3 ± 18.1 gC m^{-2} y^{-1} for the highest rainfall category (1500<MAP<2100mm y^{-1}), which corresponded to significant differences at $P<0.05$. The ER showed a contrasting trend to that of the POC_L (Figure 2.4B), with the highest mean enrichments (ER>=2.5) being found in areas with MAP<1500 mm y^{-1} and the lowest (ER=1.3) being found in areas where MAP>1500mm y^{-1}.

2.4.5 Soil organic carbon

Figure 2.3C reveals that as the SOC_C in the bulk soil increased from 0 to 40 g C kg^{-1}, POC_L increased correspondingly from an average loss rate of 9.1 gC $m^{-2}y^{-1}$ for 0<SOC_C<10 g C kg^{-1}, to an average of 14.2 gC $m^{-2}y^{-1}$ for 10<SOC_C<40 g C kg^{-1}. POC_L decreased thereafter to 4.1 gC $m^{-2}y^{-1}$ with a SOC_C higher than 40 g C kg^{-1}. There was a significant decrease in the ER with an increasing SOC content in the bulk soil (Figure 2.4C). An ER=3.3 was revealed for a SOC_C lower than 10 g C kg^{-1} to an ER=0.5 for a SOC_C exceeding 40 g C kg^{-1} (Figure 2.4C).

2.4.6 Soil texture

There was no significant relationship between POC_L and either silt, clay or sand content (Figure 2.3D, E). The highest POC_L, of up to of 20.0 g C m^{-2} y^{-1}, were resulted in clayey soil environments where soils were characteristic of clay contents exceeding 47%. POC_L did not exceed 15 g C m^{-2} y^{-1}, for clayey soils with a clay content of below 47% (Figure 2.3E). The ER increased significantly in two stages corresponding to increases in bulk soil sand content. The first major increase was noticed in the sand content range of 35-62%, and the second from 62-100% (Figure 2.4D). A decrease in the ER was noticed for an increase in soil clay content (Figure 2.4E). As the clay content in the bulk soil increased from 47-68%, the ER values diminished in accordance to become as low as 1.4.

2.4.7 Multiple relationships between SOC erosion and the selected factors of control

Deeper insights into the relationships between the variables are displayed by the PCA in Figure 2.5. In this figure microplot and plot scale data as well as POC erosion variables were included as variables of analysis, and the environmental variables were included as supplementary variables.

The first two axes of the PCA explained 51% of the total data variability. Axis 1 explained 32% of the data variability and correlated to the highest degree with soil texture. Sand content was correlated with positively to Axis 1 and clay content had a negative value. Latitude, slope and MAP also correlated negatively with the same axis. Axis 1 could thus be described as an indicator of the proximity to the equator, with closer proximities being associated with high clay content in soils and high MAP. POC_L and SL proved to have negative values on Axis 1, which also indicated that soil erosion and soil carbon erosion by water tends to increase with increasing proximity to the equator. The fact that ER and SOC_{DR} both exhibited positive values on axis 1, pointed out that the SOC sediment enrichment ratio increases and the soil SOC depletion rate accelerates as soil sand content increases and MAP decreases.

Based on averages calculated for the pedo-climatic regions of the world (Table 2.4), the highest average POC_L were yielded in tropical clayey soil environments (18.0 g C $m^{-2}yr^{-1}$), followed by semi-arid, sandy soil conditions with POC loss rates of 16.2 g C $m^{-2}yr^{-1}$ (Table 2.4). POC_L for temperate soils were significantly lower. Clayey temperate soils averaged POC losses of 2.9 g C $m^{-2}yr^{-1}$ and silty soils 10.8 g C $m^{-2}yr^{-1}$, corresponding to statistically significant differences according to $P<0.05$. Furthermore, clayey soils were marked by the lowest enrichments among all soils (ER=1.6 for tropical and 1.5 for temperate), while sediments from semi-arid and sandy environments exhibited the highest SOC enrichment (ER=2.6).

The resulting yearly depletion rate of SOC_S stocks in the 0-0.1m soil layer (SOC_{DR}) was with 1.8 $\%y^{-1}$, the highest in semi-arid environments, followed by tropical environments with high soil clay content (SOC_{DR}=1.6$\%y^{-1}$). The lowest SOC_S depletion rates were observed in temperate regions with a high soil clay (SOC_{DR}=0.01 $\%y^{-1}$) (Table 2.4).

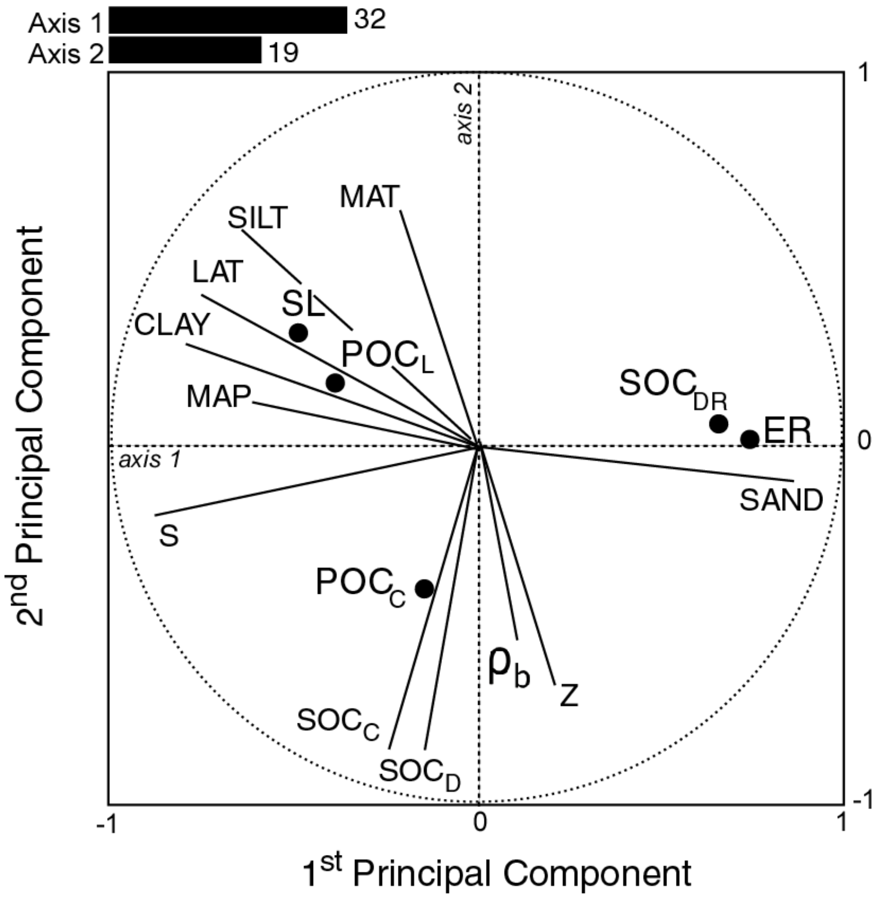

Figure 2.5. A Principal components analysis (PCA) scattergram of 'factor scores' generated using environmental and soil characteristics. POC_C, POC_L, ER and the SOC annual depletion rate by water erosion (SOC_{DR}) were included as supplementary variables (black circles). n=357 plots with a slope length below 22.1m.

Table 2.4. Median soil organic carbon stocks (SOC_S) in the 0-0.1 m soil layer, particulate organic carbon (POC) in the eroded sediment, particulate organic carbon content (POC_C) of the bulk soil, POC losses (POC_L), from micro-plots and plots in different pedo-climatic zones (estimated from the 416 considered by this study) compared to the losses to the ocean from large river basins (data from Meybeck, 1982). ER is the enrichment ratio of POC in sediments eroded from plots compared to the bulk soil, while DR, is the delivery ratio between organic carbon fluxes exported from river basins and from plots. SOC_{DR} is the yearly depletion rate of SOC stocks in the 0-0.1m soil layer, expressed as a percentage of SOC_S to 0.1 m.

Region	**Texture**	**SOC_S**	**POC_L**	**SOC_{DR}**	**ER**
		Kg C m^2	g C $m^{-2}yr^{-1}$	**% y^{-1}**	
Tropical	Clay	2.2	18.0	0.8	1.6
Temperate	Clay	3.5	2.9	0.01	1.5
Temperate	Silt	1.8	10.8	0.6	1.9
Semi-arid	Sand	0.9	16.2	1.8	2.6

2.4.8 Predicting the global trends of SOC displacement from its initial place

Since POC_L and ER showed strong correlations to several environmental and soil properties (data which were relatively easily attainable), a predictive model, using a regression analyses and plot data only was generated to further inform the global trends of SOC erosion.

Since ER was most strongly correlated to MAT, soil texture (both CLAY and SAND) and SOC_C, which are were readily available variables, a regression model (displayed in Equation 2.8) was generated to predict ER, using MAT, SAND and SOC_C.

$$ER=0.021\times MAP+0.39\times SAND-0.10\times SOC_C \qquad r^2=0.53 \qquad (2.8)$$

The model explained 53% of the data variability and since data for MAT, CLAY and SOC_C a map showing global trends in ER variation was produced (Figure 2.6). A 100 km grid resolution was used in this model.

The global trends of ER appeared to be the lowest in the equatorial zones of the Amazon Basin, Central Africa, West Africa and South-east Asia (especially Indonesia). ER revealed to be the highest in the semi-arid to arid zones of the world, such as the eastern regions of North America (more pronounced on the west coast), North Africa, South-Western Africa, Central Asia and Western Australia. In South America, the organic carbon enrichment in sediments was the highest on the entire southeast peninsula. For Europe, the ER trends ranged from Low to Moderate, the lowest enrichment was shown in Western Europe, where shallow soils with a high clay content predominate.

No attempt was made to create a further global prediction model for POC_L as the statistical significance of the regression model ($r^2<0.20$) proved to be too low.

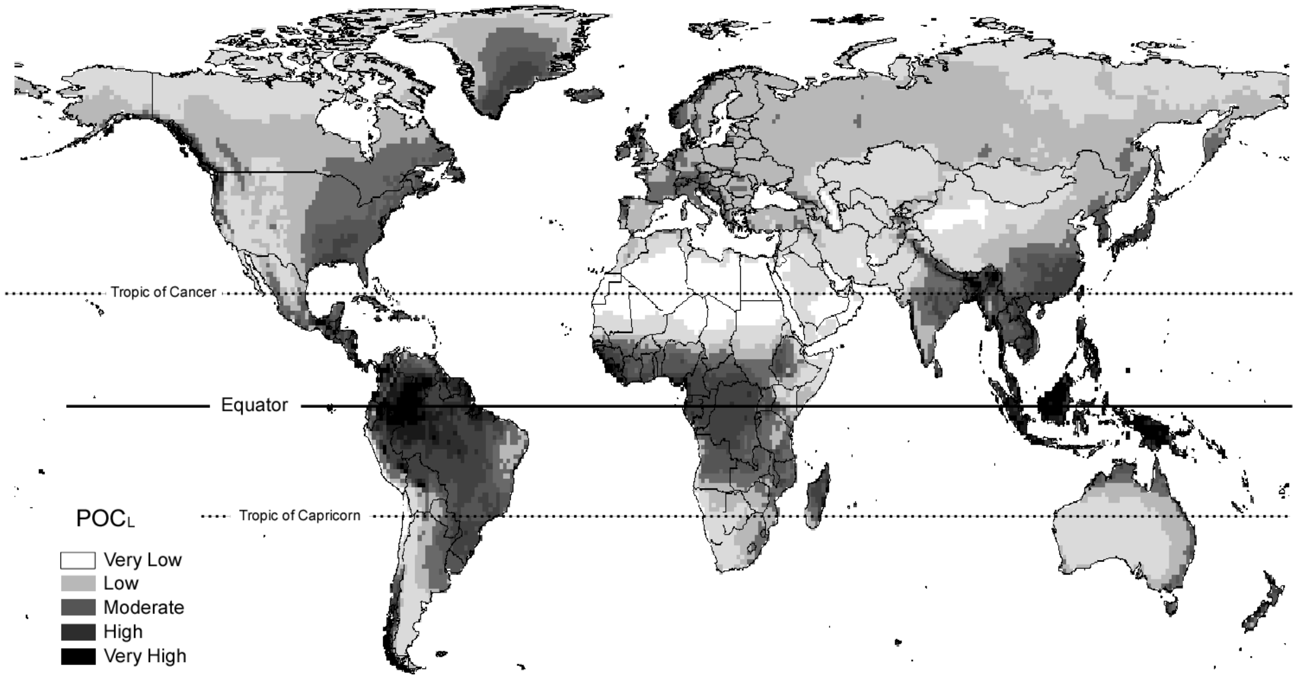

Figure 2.6. Map showing global variations in POC enrichment of eroded sediment (ER) compared to the bulk soil from where the sediments originate from. The figure was generated using Equation 2.4.

2.5 Discussion

2.5.1 Rates of SOC erosion and controlling factors

The highest particulate organic carbon loss (POC_L) rates were recorded in the tropical regions of the world. These trends were underpinned by the findings of Hontoria *et al*. (1999), who established that SOC erosion increases with increasing mean annual precipitation. The most SOC erosion happened in wet areas, especially in the tropical humid regions. This may be explained by the greater SOC stock that these soils contain, in combination with highly erosive rainfalls, but also by the erosion of entire soil aggregates, as previously shown by Chaplot et al. (2005) in the steep tropical lands of Laos. The higher SOC stock found in tropical humid soils can be explained by the conditions that these soils emanate, as humid tropical climates are highly favorable to biomass production and C input into the soils, hence supporting SOC accumulation in the soils (Bationo *et al*., 2006). Another explanation for the higher tropical SOC stocks that needs to be addressed is the rather recent conversion of natural soils to other agricultural systems compared to the temperate zone where such conversion occurred for most areas already long time ago. The semi-arid regions of the world, which are characteristic of significantly lower SOC stocks than the humid tropics, were marked by similar levels of POC losses. This trend can be explained by the highly erosive rainfalls experienced by this region with its erosivity becoming aggravated by the absence of sufficient soil surface protection (Vásquez-Méndez *et al*., 2010). Conversely, the temperate regions, which are characterized by a slighter rainfall intensity and amount, have a higher vegetation cover and displayed SOC erosion rates 20% lower than those of the tropical and semi-arid areas.

POC losses decreased with decreasing soil bulk density. This result was in accordance with the findings of previous studies (Wang *et al*., 2000; Craine *et al*., 2010). As, soil bulk density increases, the soil becomes more compacted, thus lessening the pore space volumes, which in turns diminishes soil infiltration by water and enhances overland flow and associated soil erosion (Abdel-Magid *et al*., 1987; Fleischner, 1994; Schlesinger *et al*., 1990). Moreover, as the soil becomes compacted, root growth is restricted due to poor aeration and lower soil water holding capacity, adding further to the infiltration impairment and accelerated soil erosion by water (Gyssels *et al*., 2005).

Land use and land management had a significant impact upon SOC erosion, which was supported by previous research studies (Six *et al*., 2000; Denef *et al*., 2004; Mchunu *et al*., 2011). This series of academic papers recognised the impact that land use can have on SOC erosion by water. The land use changes that take place in the transformation of natural ecosystems into cultivated lands are assumed to have induced vast reductions in the natural SOC stocks (Schlesinger, 1999). According to Lal (2004), some cultivated soils have lost as much as 75% of their initial SOC stock. The loss of SOC is commonly explained by a greater SOM decomposition rate (Lal, 1996) as a main result of tillage (Denef *et al*., 2004; Mikha and Rice, 2004) and by lower soil C inputs (Schlesinger, 2000; Tiessen *et al*., 2001). The third reason is greater soil erosion, as unprotected soils are more prone to wind and water erosion than soils protected under natural ecosystems.

Based on the data received from a total of 357 runoff plots with a slope length of less than 22.1 m and assuming the collected data give a fair representation of the global pedo-climatic and land use patterns, the total amount of SOC displaced each year by water erosion was calculated to be 0.55±0.08 Gt C. This amount, calculated by using the mean SOC_L value of

12.1 g C $m^{-2}y^{-1}$ and the total surface area of terrestrial lands, represented 0.037±0.005 % of the total terrestrial SOC stocks (SOC_S) held by soils and was estimated to be 1500 Gt (Lal, 2004). This represented also an approximated 6.5% of the annual net fossil fuel emissions (approximately 9 Gt C).

The estimated total POC_L in this study were calculated to be much lower than the 4.0-6.0 Gt C range previously reported by Lal (2003), which was estimated using global SOC yields, taken from the mouth of rivers, and assuming that 2 to 3% of the displaced SOC reaches the open ocean. Considering that between 50 and 70% of the SOC stocks are held in the 0 to 0.3 m layer of the soil (Chaplot *et al*., 2010; Bernoux *et al*., 1998) and further assuming that 25 to 35% of the SOC is present in the top 0.1 m, the annual SOC_L would represent in the range of 0.28 to 0.39% of the 0-0.1 m SOC_S. The study also pointed out high discrepancies concerning SOC_L between the different pedo-climatic regions of the world. According to the data presented in Table 2.4, semi-arid sandy soils are the most affected and vulnerable concerning SOC erosion since 0.18% of their carbon density is lost annually. These SOC_L are followed by 0.08% from tropical clayey soils, 0.06% from silty temperate soils and 0.001% from clayey temperate soils. Further research studies are needed to generate a range of “acceptable POC erosion”, needed for a sustainable functioning of soils of all concerned pedo-climatic regions. Moreover, further research is needed to synthesize the information on SOC stocks and originated from different sampling protocols and soil depths. This is important to accurately estimate the global trends in SOC depletion rate by water erosion, the present study has not been able to fully achieve.

2.5.2 Processes of SOC losses by water erosion

Plots (5 x 2m) revealed lower POC_L compared to microplots, hence follows the deduction that sheet erosion, measured on the plot scale, is a less efficient erosion mechanism, regarding SOC than splash erosion. If however sheet wash in acts in combination with splash it appeared to be yet still more efficient than splash alone for detaching and transporting SOC as suggested by the significant increase in POC_L from microplot to plot level. Thus when isolating the two mechanisms, splash erosion is the dominant erosion mechanism, regarding SOC erosion.

The average ER computed for the 357 plots was 2.5, with a median value of 1.7. In addition, 75% of the total data displayed an ER higher than 1.3, which alluded to an overall enrichment of sediments in SOC in comparison to the bulk soil. This enrichment is likely to be due to disaggregation. When water erosion removes entire soil aggregates, the content of SOC in the eroded material (i.e. sediment) is equivalent to that of the topsoil layer of the bulk soil, resulting in a organic carbon enrichment ratio (ER) of 1. The destruction of soil aggregates induces selective erosion, which either results in sediments becoming enriched or depleted in SOC, compared to the bulk soil. Depending on whether the sediments are enriched or depleted in SOC, the ER value will be above or below 1 accordingly. Because SOM is of a significantly lower density than mineral soil matter, it tends to be detached and displaced preferentially, resulting in an ER above 1. Disaggregation may be induced by the disruption caused by either, the escape of compressed air through a quick emersion in water, or through the physical raindrop impact energy. The disaggregation of the aggregate will result in the release of the hitherto encapsulated organic material. As the OM is of a lighter nature than the mineral fraction of the soil, preferential SOC erosion occurs. This is consistent with the global theory of the preferential removal of SOM by water erosion (e.g. Lal, 2003).

Figure 2.7 displays a simplified graphic representation of the soil erosion process and portraying the effect that raindrops have on the detachment and transport of SOC for different soil textures: Clayey, Silty and Sandy. The lowest sediment enrichment in organic carbon compared to the bulk soil was found under clayey soils (ER=1.6±0.1), indicating that the erosion process induced only slight selective organic carbon erosion. In contrast sandy soils (ER=3.0±0.52) and silty soils (ER=5.0±1.58) proved more conducive to selective organic carbon erosion. For instance, the eroded sediments originating from silty soils exhibit a SOC_C 500% higher in sediments than in the original bulk soil.

Furthermore, semi-arid sandy soils and temperate silty soils demonstrated the highest SOC ER values. The key role that soil texture holds in the SOC enrichment of sediments was to be expected. In fact, several authors, the likes of Le Bissonnais (2006), Dimoyiannis (1998), Tisdall and Oades (1982) as well as Dalal and Mayer (1986) have expounded on the connection between greater soil aggregate stability and increased SOC protection in clayey soils compared to sandy and silty soils, which produce aggregates of lesser rigidity. A possible explanation for the correlation between ER and soil texture can be gained from the idea postulated by Tisdall and Oades (1982), where a model explains clay particles to be bound to humic material and sesquioxydes through di- and trivalent metal cation bonds. Polysaccharides, present in the exocellular mucilages and gums produced by micro-organisms, are believed to act as potential cementing agents, principally forming micro-aggregates (2 to 20 micrometers in diameter). Macro-binding agents, such as roots and hyphae, rather, are involved in macro-aggregation. As a consequence, clayey aggregates are more resilient to breakdown and owing to their adhesive structure, entire clay aggregates are eroded. For this reason the sediment produced in clayey soil environments is only fractionally enriched in SOC.

In the same landmark study, Tisdall and Oades (1982) went on further to postulate a model proposing that aggregates form part of a hierarchical order of formation, whereby three main binding agents, known as transient, temporary and persistent, control aggregate formation and subsequent OM stabilization. This concept is founded upon the observed fact that aggregates form in a specific sequence, according to varying degrees of aggregate size and stability. Interestingly, it is in this likewise sequence that the aggregates decay (Carter *et al*., 2003), with the macro-aggregates being subject to decomposition first. At the most basic level, primary particles (<20 μm) are agglomerated to form micro-aggregates (20-250 μm) by persistent binding agents such as oxides, polyvalent metal cation complexes and aluminosilicates. These micro-aggregates may be, in turn, agglomerated through temporary binding agents, such as hyphae and roots, to form stable macro-aggregates (>250 μm) (Tisdall and Oades 1982). Macro-aggregates are generally less stable than micro-aggregates, as the transient binding agents (e.g. polysaccharides) tend to decompose quicker, thus enhancing the disaggregation potential. A study done by Carter *et al*., (2003) revealed that most of the SOC is found within macro-aggregates, yet only the SOC stored in the micro-aggregates is considered to be protected (recalcitrant). Therefore, soil water erosion, which is a main mechanism of disaggregation, will render the protected SOC more prone to be exported from the bulk soils.

Based on this, Figure 2.5 portrays a mechanistic model of the relationship between soil texture, climate and SOC erosion. Whereas the aggregation process facilitates SOC sequestration, disaggregation, brought about by the action of splash and overland flow, initiates the detachment and transport (erosion) process of SOC. Clayey soils from both temperate and tropical regions, displayed an ER value near 1, which is indicative minimal preferential SOC erosion. These low enrichment ratios are indicative of the erosion of entire stable aggregates. The higher ER for sandy and silty soils is probably the result of a lesser soil aggregate stability inherent to these soils, which is potentially conducive to greater SOC mobilization by water erosion. For all soils, the lower ER values in the interquartile range are likely to originate from land uses such as forest or conservation agriculture, while the highest values may be associated with conventional agricultural practices, which are associated with lower aggregate stabilities.

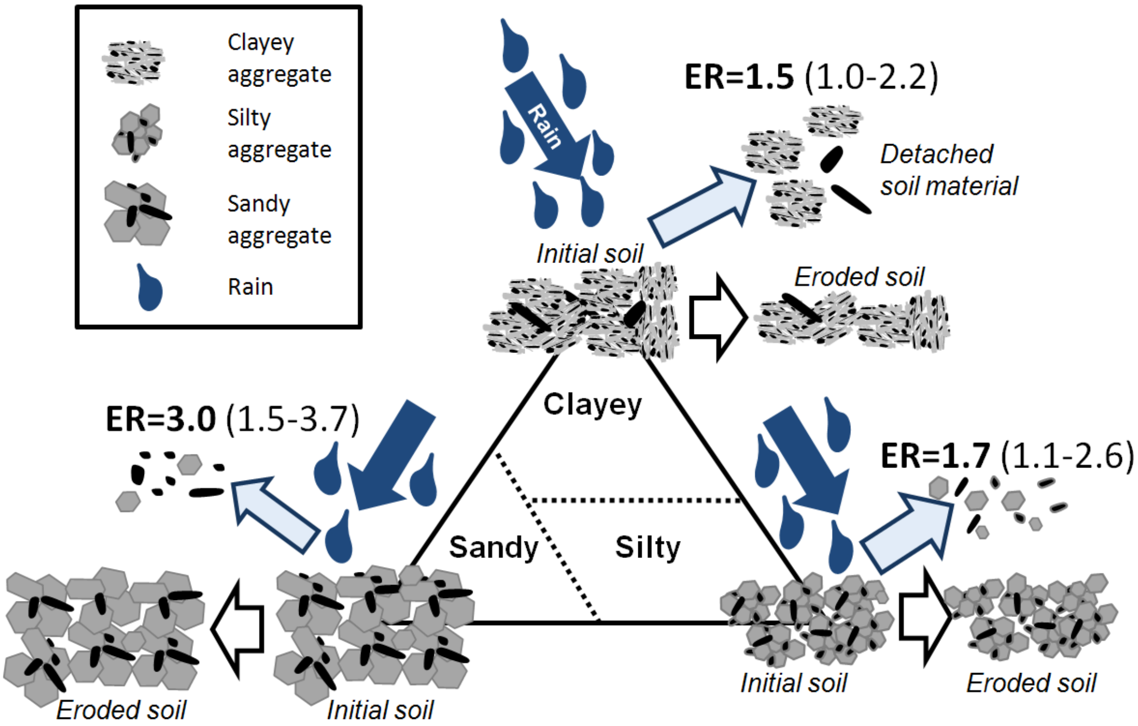

Figure 2.7. A model portraying the effect that rainfall has on enriching the sediments in soil organic carbon compared to the bulk soil, categorised into the different pedo-climatic environments studied. Median (1st - 3rd quartiles), ER is the ratio between particulate organic carbon (POC) contained by the sediments to the SOCc in the bulk soil.

As a combination of weathering processes and pedogenesis favour the formation of clayey soils in the wet and warm regions of the world, there was a significant "indirect" relationship between climate and preferential SOC erosion evident in the results. Hence, the lower ER values were found in the areas that receive the highest mean annual precipitation (MAP) and are simultaneously characteristic of high mean annual temperatures (MAT). Conversely, the areas with characteristically high sand and silt contents, such as the Sahara, the Australian Outback region, the Arabian Desert and central Mongolia, displayed high SOC enrichments in their respective sediments.

The ER values proposed by the existing studies are, however, likely to have been overestimated. Most studies calculate the SOC content in the bulk soil by sampling the upper soil horizon. The average sampling depth used to determine the SOC_C of the 357 plots investigated in this study was 0.3m. It is important to bring attention to the fact, however, that only the upper most millimeters of the soil are affected and vulnerable to be removed by water erosion. These same very first millimeters of soil are also most likely to contain a much higher SOCC than a sample taken to the depth of 0.3 meters. In their no-till study, Mchunu *et al*., (2011) showed that the ER increased from 2.3, estimated using the SOCC of the 0-0.3 m soil layer, to 1.2, when considering only the SOCC in the upper most 2 cm of the soil, which corresponded to an ER overestimation by 1.1. This appends to the notion that most of the existing ER estimations are in fact overestimations. For instance, clayey soils, which owing of their superior aggregate stability characteristics, should generally promote the erosion of entire soil aggregates. Therefore it would be more regular to receive ER values close to 1 instead of 1.6, as found in this study. Future research studies performed in this field should most definitely address the issue of ER estimation. The precision with which SOC erosion processes can be investigated addressed is influenced heavily by the accuracy regarding the calculation of this ratio. There is a need for scientists to revert from sampling to the depth of an entire first horizon when studying SOC_C enrichment in sediments, and rather focus on the upper millimeters of the soil.

2.5.3 Fate of the eroded SOC

The total amount of SOC displaced each year through water erosion globally, under the assumption that all terrestrial surfaces were sampled adequately and without bias, would represent approximately 0.59±0.09 Gt or 0.039% of the total 1500 Gt of SOC contained by the soils. However, considering that most of the data were originated from the main agro-ecosystems worldwide with lower sampling density in other ecosystems such as natural forests or deserts and mountains of low SOC erosion, this global estimate is likely to be slightly overestimated. Further investigations need to be performed in marginal lands.

The literature largely disagrees on the fate of the eroded SOC. Smith *et al*., (2001) argue that only a tiny fraction of the eroded SOC is decomposed and released as CO_2 to the atmosphere, which contradicts the initial research findings by Schlesinger (1995), suggesting that the eroded SOC is oxidized to the greatest extent. Other authors including Lal (2003) and Oskarsson *et al*., (2003) proposed decomposition rates of between 20 and 50%. The fact that up to 90% of the SOC displaced from its initial place is POC and most (approximately 90%) of the organic carbon exported to open oceans is DOC, demonstrates that the eroded POC fraction is subject to drastic transformations (likely mineralization) during its transportation. Utilizing a modest decomposition rate of 20%, annual C emissions to the atmosphere would amount to 0.33±0.06 Gt C y^{-1}, which is a much lower rate than the previous estimations proposed by Lal (2003) of 0.8-1.2 Gt C y^{-1}, which were based on the same rate. According to various authors, a rate exceeding 80% would induce gaseous net emissions amounting to 1.32 Gt C y^{-1}.

This rate may differ across the varying pedo-cliamtic regions as a result of differing degrees of microbial activity, varying availability of organic matter, disaggregation characteristics and the duration of stream transport. Several studies have demonstrated a relationship between the magnitude of SOC decomposition and organic matter quality. Land management has been shown to play a critical role in the fate of the eroded SOC. Studies conducted by Juarez *et al*. (2011) and Chaplot *et al*. (2012) revealed that less mineralization occurs in the POC eroded from zero tillage soils, compared to the POC eroded from tilled soils.

The lower ER of sediments produced from clayey soils (ER of 1.1 when considering the SOC_C in the top 1 to 2 cm of the soil) suggests that most of this SOC remains protected within soil aggregates with no more (<10% as suggested by a ER value of 1.1) additional gaseous emissions than are emitted from the bulk soil, while the re-burial of eroded SOC in hillslopes, may constitute a significant carbon sink. A greater clay content in the bulk soil leads specifically to a more effective stabilization of SOC and thus enhances the organic matter protection from decomposers (Duchaufour, 1983; Six *et al*., 2002). Water erosion in silty soils, producing sediment enrichments in SOC by as much as 500% (ER=5), is likely to induce about 400% more greenhouse gas emissions than the respective bulk soil. Finally, sandy soils exhibited an intermediate behavior (ER=3) with approximately 100% of potential erosion-induced carbon emission. The stability of soil aggregates is suggested here to be dominant in the fate of the eroded OM. An enhanced aggregate structure to improve OM protection can be achieved by implementing conservation tillage practices, as shown, for instance in a study done by Lal *et al*. (1994), spanning over a timeframe of 28 years. The general zero tillage practice is to leave the seasonal crop residue as mulch on the soil surface. The additional cover serves as protection against soil water erosion and the associated SOC erosion (Bradford and Huang, 1994; Choudhary *et al*., 1997). Crop residues create favorable conditions for biological activity, improve soil porosity, enhance soil infiltration, and hereby also lessen the effect of SOC erosion by water (Doran, 1980; Edwards *et al*., 1988; Pierce *et al*., 1994; Mchunu *et al*., 2011). Mchunu *et al*. (2011), in a study of a specific form of zero tillage, where no crop residues are left on the soil surface, observed the development of indurated crusts that are less prone to water erosion.

OM recalcitrance, OM complexation and adsorption onto minerals, which are likely to vary between the different soil textures, are other possible factors of control of OM fate that need further appraisal.

CHAPTER 3

MECHANISMS AND CONTROLLING FACTORS OF SOIL ORGANIC CARBON LOSSES THROUGH SHEET EROSION

3.1 Abstract

Although the link between sheet erosion mechanisms (namely splash, a local process and rain-impacted flow, RIF, which requires a certain slope length to be operative) and soil losses has been well studied, little is known about their role in the lateral translocation of particulate soil organic carbon (POC). The present study was conducted to identify the main erosion mechanisms and pertaining factors of control involved in POC erosion within hillslopes. Fifteen erosion plot replicates with a slope length of 1m, and 10 with the slope length of 5m (the respective dimensions being 1 x 1 m^2 for the microplots and 2 x 5 m^2 for the plots) were installed at different preselected topographic positions with differing geology, soil form and vegetation cover in the foothills of the Drakensberg mountain range of South Africa. Soil loss (SL), sediment concentration (SC), runoff water (R) and POC loss (POC_L) obtained from the runoff plots was measured in-situ subsequent to every rainfall event from November 2010 up to February 2013. Averaged out across the 32 studied rainfall events, there were no significant differences in R and POC_L between the two plot sizes but SL were markedly higher on the 5m compared to the 1m erosion plots (174.5 *vs* 27g m^{-1}), which signifies a greater efficiency of RIF as opposed to splash. This information on the mechanisms and both, *in situ* (soil surface related conditions) and *ex situ* (rainfall characteristics) factors of control involved in POC erosion is expected to contribute toward generating POC specific erosion models and thus further inform erosion mitigation..

3.2 Introduction

Soils have been shown to contain more than half the carbon in terrestrial ecosystems (Schlesinger., 2000) thus soil erosion reserves the potential to greatly influence the terrestrial as well as the global carbon cycle. Soil organic carbon (SOC), which constitutes the bulk component of soil organic matter (SOM), comprises a plethora of essential plant nutrients, improves soil structure, acts as a natural buffer against compaction and thus reduces the soils susceptibility to erosion. SOM also enhances the soils water retention capacity and provides energy for soil biota, therefore determining soil productivity and biodiversity.

Soil erosion by water is a complex process, which is largely recognised to be the principal driving force behind the lateral translocation of soil, soil nutrients and SOC in landscapes (Nadeu *et al*., 2011; Paton *et al*., 1995; Gregorich *et al*., 1998). While the processes and mechanisms involved in soil erosion have been widely investigated, little is known on the specifics of SOC erosion, which is recognised to be an essential soil constituent for the healthy functioning of natural ecosystems (Pimentel *et al*., 1995; Biggelaar *et al*., 2001; Lal., 2003).

Soils are able to retain atmospheric carbon through plant photosynthesis and sequestration of plant residues. Hence soils as a carbon sequestration has agent have the potential to offset global warming by reducing the atmospheric CO_2 concentration (Lal., 2004). SOC erosion rates have been observed to differ vastly with climatic, pedologic and topographic variables: with annual depletion rates of in SOC stock for the 0-0.3m top-soil ranging from as low as 0.01% in Spain (Rodriguez *et al*., 2004), 0.47% in India (Cogle *et al*., 2002), 1.28% in Laos (Chaplot *et al*., 2007) to as high as 15.88% in Burkina Faso (Roose *et al*., 1978).

SOC erosion by water occurs when raindrop impact disrupts soil aggregates and exposes the enclosed SOM initially to detachment, then to transportation (Gregorich *et al*., 1998) and eventually to decomposition (Chaplot *et al*., 2012). The destruction of soil aggregates by the impact of raindrops and also by rain-impacted flow (RIF) may occur as one of three desegregation mechanisms, namely: slaking, dispersion or mechanical breakdown (Le Bissonais., 1996).

Owing to its low stability, light nature and high abundance in the surface soil horizons and the existence of complex but reversible associations with the mineral soil matrix, SOM has been previously shown to be highly affected by the mechanisms of water erosion (Gregorich *et al*., 1998; Jacinthe and Lal., 2001; Chaplot *et al*., 2005). Soil disaggregation leads to the detached material becoming more enriched in SOC, in comparison to the bulk soil, as it is within the actual soil aggregates that organic matter is stabilized (Masiello *et al*., 2004; Six *et al*., 2004; Rasmussen *et al*., 2005; Mikutta *et al*., 2006; Nadeu *et al*., 2011).

Among the few available studies, Boye and Albrecht (2006) observed in Kenya that, in comparison to their original bulk soil, eroded sediments were enriched in SOC by a factor of 3.3. The SOC enrichment ratio (ER) increased to 4.3 in a study performed in Burkina Faso (Bilgo *et al*., 2006). In South Africa, under a temperate climate with sandy soil conditions the average ER ranged between 4.3 and 4.8 (Mchunu *et al*., 2011) and in a semi-arid environment with sandy soil conditions in Mali the ER was found to be as high as 10.0 (Drissa *et al*., 2004).

Much of the research on soil erosion has focused on understanding the intricate physical and chemical processes associated with soil water erosion, with little emphasis directed towards its functions regarding SOC dynamics. The present study was performed in a context where the impact of soil erosion on the global carbon cycle has been largely omitted and little is known about the impact of the main water erosion mechanisms (Stallard, 1998; Lal, 2004; Berhe *et al*., 2007; Van Oost *et al*., 2007), namely splash that dominates local erosion and rain-impacted flow (RIF), which requires a certain slope length to be operative. The main objective of this study was to quantify the impact of splash and RIF on SOC detachment and transport through water.

3.3 Methods and materials

3.3.1 General Characteristics of the study area

The research experiment was conducted in the 23ha catchment of the communal settlement Potshini (longitude: 29.36^o; latitude: 28.82^o), positioned in the greater Thukela River basin (30,000km^2) of KwaZulu-Natal, South Africa. The land is utilised by the local community as cattle grazing land. Rills and Gullies appear throughout the landscape of the catchment, suggesting poor grazing management practices. Potshini is characterised by a tropical, sub-humid climate with a summer rainfall pattern (September-March) (Schulze, 1997). The geology of the area is characteristic of an irregular sequence of fine grained sandstone, shale, siltstone and mudstone spread out horizontally, with erratic intrusions of Karoo dolerite sills. Acrisols (WRB, 2006) are the main soils found in the area, which are generally deep at the footslope and shoulder, while shallow at midslope positions. Deep yellowish Acrisols were found at the shoulder sandstone and deep reddish Acrisols at the shoulder dolerite positions. The Footslope position also had deep Acrisols whereas the midslope and terraceslope both had shallow Acrisols.

The topography of the 23ha catchment is moderate to gentle, with a mean slope gradient of 15.3^o. The hillslope on which this study was conducted has a maximum slope gradient of 29^o. The altitude within the catchment ranges from 1381m to 1492mabove sea level.

3.3.2 Climatic conditions

The Meteorological data was attained from the Bergville weather station, situated 10km east of the study site. According to the data, the mean annual temperature (MAT) of the area is 13^{o}C, the mean annual precipitation (MAP) 684mm and the potential evaporation is 1600mm year^{-1}. Meteorological records of a 30year data series, obtained from the national database, show that a rainfall events with a maximum half hour intensity of 49mm h^{-1} (I_{30}) have a probability of reoccurring every two years, with a 90% probability occurrence between 37 and 61mm h^{-1}. The reoccurrence period for a rainfall event with the maximum half hour intensity of 76mm h^{-1} is ten years and the probability for a 115mm h^{-1} intensity rain is one hundred years.

3.3.3 Experimental design

A typical catena was selected in the grassland part of the landscape with five landscape positions: Footslope (F), characterised by gentle slope and deep Acrisols; Midslope (M), characterised by steep slopes and shallow Acrisols; Terrace (T), characterised by a flat gradient and shallow Acrisols Shoulder Dolerite (SDOL), characterised by deep reddish Acrisols; and Shoulder sandstone (SST), characterised by deep yellowish Acrisols (Figure 3.1).

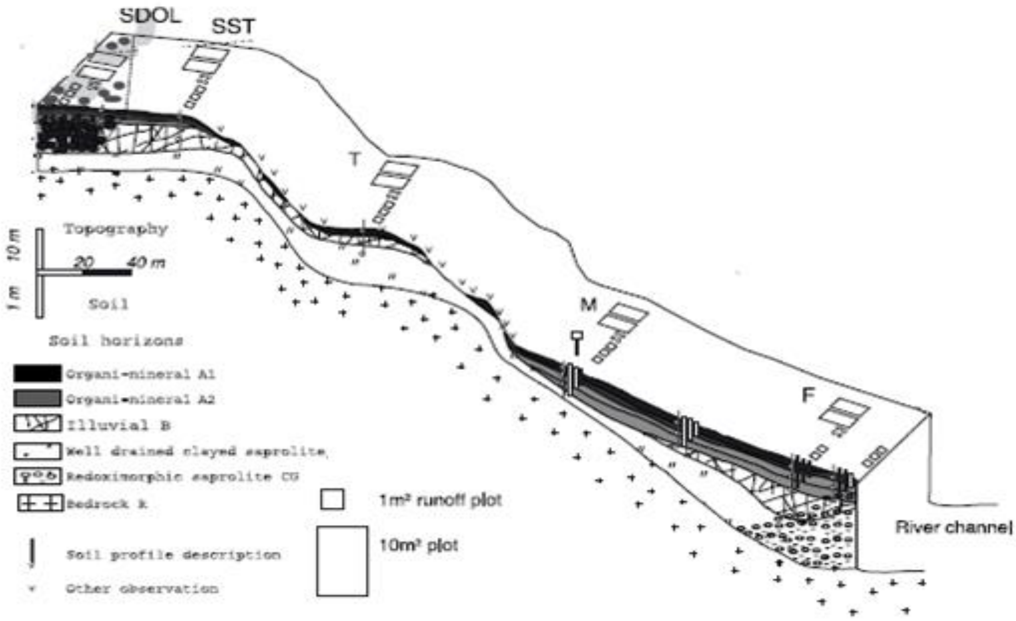

Figure 3.1. Diagram depicting a cross-section profile of the study hillslope in the Potshini research catchment of South Africa; also depicted on the profile are erosion plots of $1m^2$and $10m^2$, replicated 3x and 2x respectively for each of the hillslope positions: shoulder dolerite (SDOL), shoulder sandstone (SST), terrace (T), midslope (M), footslope (F). (Adopted from Oakes et al, 2012)

Experimental erosion plots of 1m^2 (1 m x1m) and 10m^2 (2 m x5m) were used to evaluate runoff and sediment yields from sheet erosion. The conventional 1m^2 plots were installed to specifically study local erosion processes, of which the most predominant erosion process is splash and rain impacted flow features on the local scale to a lesser degree also. The larger 10m^2 plots were installed for the evaluation of sheet or linear erosion processes, which is herein referred to as rain impacted flow transport (RIFT) erosion. The reason for the use of 5m long plots was that previous field studies have shown that eroded soil aggregates had the tendency to re-deposit in local depressions at a distance between 3 and 5m from the place of initial detachment. The use of this particular plot length also minimised the cyclic phases of 'detachment, transport and deposition', thus compensating for the underestimation of RIFT erosion processes. The orthodox Wischmeier and Smith plots would have been inappropriate for this particular study, as their slope length is conducive to rill formation, it would have interfered with and deterred from the evaluation of the lateral erosion processes. Three replicates of the 1m^2 plots and two replicates of the 10m^2 plots were installed at five preselected hillslope positions; footslope, midslope, terrace, shoulder sandstone and shoulder dolerite. The plots were orientated at parallel angles to the hillslope. Steel sheets were used as plot boundaries and anchored in the soil at a depth of 0.1 m. At the foot-end (most down slope end) of every erosion plot, a length of PVC piping connected the erosion plot to reservoir used to collect runoff and suspended sediments. Each erosion plot was also equipped with a gutter at the foot-end to trap excess sediment.

None of the plots contained significant soil cracks or rill erosion features, therefore it was assumed that measurements were made under steady-state soil loss conditions. Field measurements were made subsequent to every rainfall event occurring from the 25 November 2010 to the 8 February 2013. After each rainfall event the runoff (R) water depth in each reservoir was measured with a tape measure, in order to be able to apply a calibrated volumetric equation for the determination of R in litres. Subsequent to the depth measurement, aliquot samples (500ml) were taken, with an effort to retrieve as much of the suspended sediments as possible for lab analysis purposes. Two droplets of concentrated hydrochloric acid were dispensed into each of the aliquots in order to impede microbial activity for dissolved organic carbon (DOC) analyses purposes. The aliquots were stored in a refrigerator overnight to allow for most of the suspended sediment to settle out. On the following day, the aliquots were removed from the refrigerator and left outside until they reached room-temperature. A 10 ml sample was taken from each aliquot for the purpose of DOC analysis. The 10ml aliquot samples were poured through filter paper into viles and DOC concentration was measured using a Total Organic Carbon (TOC) analyser. The sediments remaining in the aliquots were oven-dried at 50^{o}C for approximately 12 hours or until a dry state was reached and weighed to determine the average sediment concentrations, in the cases where the turbidity meter readings were not available. Soil losses (SL), being the product of R and sediment concentration (SC), could thus be calculated. The oven-dried sediment was then analysed for total carbon and nitrogen content, by dry combustion using the LECO-TruMAC CNS analyser (LECO CORP, Michigan, USA). During this study, a total of 22 erosive events were analysed, amounting to a total number of 550 samples. Rainfall event characteristics, such as rainfall amount, maximum and average rainfall intensity were estimated, using an automatic rain gauge with a six minute step counter located at the study site. Scale ratios for SC, SL, particulate organic carbon losses (POC_L) and dissolved organic carbon losses (DOC_L) were subsequently calculated to access the level of contribution of the main sheet erosion mechanisms e.g. splash and RIF. A ratio less than one indicates more RIF than splash. Although it is possible to limit the contribution that sheet erosion has to splash erosion, by limiting the slope length of the runoff plots, it is virtually impossible to separate the contribution of splash erosion towards sheet erosion. Even calculating the contribution of splash erosion to the sheet erosion, is a highly complex task. Because the 5x2m plots had double the width as the 1x1m plots, the eroded sediment loads could thus not be easily compared. It is for this reason that two variables were chosen to represent soil losses (SL) as a total sediment mass eroded from a plot, and soil losses per width (SLW), which makes the comparison of eroded sediment yields between microplots and plots more accurate and easier.

3.4 Results

3.4.1 Soil characteristics

The environmental characteristics: Crust, average vegetation cover (Cov), clay content (Clay), average slope gradient (Slope), soil bulk density (p_b), average SOC stock across all hillslope positions recorded for a 0-5cm sampling depth (SOC_S5), SOC stocks for a 0-2cm sampling depth (SOC_S2) for the five studied hillslope positions are depicted in Table 3.1. Soil surface crusting increased as vegetational surface cover. The average Cov was 85%, ranging between 52% at the midslope and 98% at the terrace. Clay content ranged from 27% at the midslope to 54% at the shoulder dolerite position. Slope gradient averaged 20% and varied from 15% at the shoulder dolerite position to29% at midlslope. Of all the hillslope positions, the midslope, with 1.33 g cm^{-}3, had the highest P_b. The average SOC_C of the upper 2 cm of the soil (SOC_C2) was with 35.36 g C kg^{-1}, 30% greater than that of SOC_C5 (24.98 g C kg^{-1}). The average SOC_S5 was 143.5 g m^{-2}, ranging from 180g m^{-2} at shoulder dolerite to 109.9g m^{-2} at midslope. The midslope position thus had the lowest Cov and SOC_C, but the steepest slope and highest bulk density, the least vegetation cover and the greatest crusting.

Table 3.1. Soil characteristics at different hillslope positions; footslope (F), midslope (M), terrace (T), shoulder dolerite (SDOL) and shoulder sandstone (SST) of a communal grassland in Potshini, South Africa. Soil surface covered with crusts (Crust); percentage of soil surface covered by vegetation (Cov); clay content of the soil (Clay); average slope gradient (Slope): soil bulk density (ρ_b); Soil organic carbon (SOC) content for 0-2cm sampling depth (SOC_C2); SOC content for 0-5cm sampling depth (SOC_C5); SOC stocks calculated for the 0-2cm soil horizon (SOC_S2); SOC stocks calculated for the 0-5cm soil horizon (SOC_S5).

	Crust	**Coverage**	**Clay**	**Slope**	ρ_b	**SOC_C2**	**SOC_C5**	**SOC_S2**	**SOC_S5**
Position	------------------------------%-------------------------				g cm^{-3}	g C kg^{-1}	g C kg^{-1}	g C m^{-2}	g C m^{-2}
F	4	96	28	23	1.25	42.9	23.8	107.1	148.7
M	48	52	27	29	1.33	18.8	16.5	50.1	109.9
T	2	98	40	16	1.13	45	26.1	101.9	147.6
SDOL	6	94	54	15	1.02	40	35.2	82.1	180.5
SST	17	83	31	19	1.12	30.1	23.3	67.4	130.7
Mean	17	85	36	20	1.17	35.36	24.98	81.7	143.5

3.4.2 Slope length impact on soil and SOC erosion

There were significant differences between 1 and 5m long plots for R, SC, SLW, POC_C and POC_L while the differences for DOC_C, and DOC_L were not statistically significant. R was on average 15.3 L m^{-1} on 1m plots and was 48% lower (7.9 L m^{-1}) on 5m plots (Table 3.3). The highest R was generated on the midslope position, while the lowest R occurred on the footslope. The average SC was 27% higher for the 5m plots (1.5 g L^{-1}) than for the 1m plots (1.1g L^{-1}; Table 3.2).The mean SLW from the 5m long plots was 172.7g m^{-1}, which was 85% greater than 1m plots. The POC_C decreased with increasing slope length from 63.4 g kg^{-1} at the 1m plots to 51.7g kg^{-1} on 5m plots. POC_L decreased from 1.5 g C m^{-1}on 1m to 0.9g C m^{-1} on 5m, corresponding to a 40% difference. Although DOC_C and DOC_L were not statistically significant in regard to plot length, values were 12% higher on 1 m than on 5 m plots.

Higher SC values occurred on 5 m plots on all hillslope positions, with the midslope revealing the highest SC, with average values of 1.6 g L^{-1} and 2.3 g L^{-1} on the 1m and 5m erosion plots, respectively. The lowest SC values were observed for the shoulder sandstone slope and the terrace slope, both hillslope positions revealing the same average SC across the plot lengths (1.1 g L^{-1}). Significantly higher SLW was found on 5 m across all hillslope positions, the highest difference occurring at midslope, where SLW was 85% greater on 5 m plots (296.9 *vs* 44.5 g m^{-1}). The lowest POC_L of all positions was recorded for the footslope (0.9 g m^{-1} and 0.5 g m^{-1} for the respective 1 and 5 m plots), and the shoulder sandstone slopes (1m = 1.3 g m^{-1}; 5 m = 0.5).

Table 3.2. Basic statistics (SD: standard deviation; SE: standard error; CV: coefficient of variance) for runoff (R), sediment concentration (SC), soil loss calculated per metre width (SLW); particulate organic carbon losses (POC_L); dissolved organic carbon losses (DOC_L); particulate organic carbon content (POC_C) of eroded sediemnts; dissolved organic carbon content (DOC_C), for 1m^2 (n=480)and 10m^2(n=320) erosion plots set up on a communal grassland in Potshini in South Africa.

	R		SC		SLW		POC_L		DOC_L		POC_C		DOC_C	
	L m $^{-2}$		g L $^{-1}$		g m $^{-1}$		g m $^{-2}$		mg L^{-1}		g kg $^{-1}$		mg L^{-1}	
	1m^2	10m^2	1m^2	10m^2	1m^2	10m^2	1m^2	10m^2	1m^2	10m^2	1m^2	10m^2	1m^2	10m^2
Mean	15.4	16.0	1.1	1.5	26.7	172.7	1.5	1.8	87.5	72.2	63.4	51.7	12.0	8.6
SD	19.1	27.6	1.4	1.8	61.2	528.1	3.1	5.6	173.3	131.7	32.0	19.2	19.1	6.1
SE	1.6	2.3	0.1	0.2	5.1	44.3	0.3	0.5	14.5	11.0	2.7	1.6	1.6	0.5
CV	124.0	173.1	124.1	122.3	229.2	305.8	207.3	313.7	198.0	182.5	50.4	37.1	159.6	71.5
Variance	364.3	764.0	2.0	3.2	3748.0	278937.3	9.8	31.0	30033.5	17337.9	1021.9	367.9	365.9	37.6
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.2	12.5	0.0	0.2
Max	103.5	132.0	9.7	10.4	495.3	4988.3	21.9	54.0	1442.8	656.9	276.0	210.6	155.9	22.7
Quartile1	2.0	0.0	0.3	0.4	0.8	1.3	0.0	0.0	5.1	0.0	53.5	42.0	3.5	3.9
Median	8.2	3.9	0.6	0.8	4.4	17.2	0.2	0.2	26.2	2.8	56.9	54.1	6.6	8.1
Quartile3	20.3	17.8	1.4	1.8	17.3	104.5	1.0	0.8	113.9	77.9	72.5	56.4	12.3	12.6
Skewness	1.8	2.6	2.6	2.7	3.7	6.0	3.1	6.2	5.3	2.6	2.7	3.6	5.1	0.6
Kurtosis	2.7	7.2	8.3	8.1	16.1	43.9	10.7	47.7	37.3	7.8	12.1	25.5	34.1	-0.2

Table 3.3. Runoff (R), sediment concentration (SC), soil losses calculated per meter width (SLW), particulate organic carbon losses (POC_L), dissolved organic carbon losses (DOC_L), soil organic carbon enrichment ratio calculated by considering the soil organic carbon content of the 0-2cm layer(ER2) and0-5 cm layer (ER5): of a communal grassland in Potshini, South Africa at different hillslope positions; footslope (F), midslope (M), terrace (T), shoulder dolerite (SDOL) and shoulder sandstone (SST)

	R		SC		SLW		POC_L		DOC_C		ER2		ER5	
	Lm^{-1}		gL^{-1}		gm^{-1}		$g\ C\ m^{-1}$		$g\ C\ L^{-1}$		-------- ratio --------			
	1m	**5m**	**1m**	**5m**	**1m**	**5m**	**1m**	**5m**	**1m**	**5m**	**1m**	**5m**	**1m**	**5m**
F	8.9	6.3	1.1	1.6	17.9	138.4	0.9	0.5	58.2	16.6	1.5	0.6	2.7	1.1
M	19.0	10.6	1.6	2.3	44.5	296.9	1.7	1.4	20.3	14.4	2.6	2.6	2.9	3.0
T	17.1	6.1	1.1	1.1	30.0	125.4	1.9	0.7	54.0	11.8	1.6	1.0	2.8	1.8
SDOL	13.9	9.2	1.2	1.4	21.7	227.6	1.7	1.2	30.7	95.8	1.9	1.2	2.1	1.4
SST	17.6	7.4	0.7	0.9	21.1	84.0	1.3	0.5	90.0	83.7	2.2	2.0	2.8	2.6
Average	15.3	7.9	1.1	1.5	27.0	174.5	1.5	0.9	50.6	44.5	1.9	1.5	2.7	2.0

3.4.3 Correlation between soil erosion variables on 1m long plots

R proved to have a positive correlation to SL (r = 0.53), POC_L (r = 0.52), PON_L (r = 0.44) and DOC_L (r = 0.53; Table 3.7). A negative correlation between R and POC_C (r = -0.24) suggested that as the POC_C in the eroded sediment from the 1m plots increased, R decreased correspondingly (Table 3.5). SC was positively correlated to SL, PON_C, DOC_C, POC_L. SL with the highest correlations occurring for PON_C (r = 0.89), POC_L and PON_L (r = 0.99). There was a lack of correlation between SC and DOC_L. A negative relationship was revealed between erosion variables SL and POC_C for $P < 0.05$ level. POC_C showed significant correlation to PON_C and DOC_C. PON_C was positively correlated to DOC_C, POC_L and PON_L.

Table 3.5. Correlation matrix investigating erosion variables: R runoff; SC sediment concentration; SL soil losses; POC_C particulate organic carbon content of the sediment; PON_C particulate nitrogen content of sediment DOC_C dissolved organic carbon content; POC_L particulate organic carbon losses; PON_L particulate organic nitrogen losses and DOC_L dissolved organic carbon losses specifically for the 1m plots. Variables showing a significant statistical correlation at P < 0.05 are marked with a * in the table.

	R	SC	SL	POC_C	PON_C	DOC_C	POC_L	PON_L	DOC_L
R	1.00								
SC	0.50*	1.00							
SL	0.53*	0.21*	1.00						
POC_C	-0.24*	0.01	-0.24*	1.00					
PON_C	0.28*	0.89*	0.00	0.40*	1.00				
DOC_C	0.07	0.43*	0.01	0.39*	0.60*	1.00			
POC_L	0.52*	0.99*	0.26*	0.06	0.88*	0.41*	1.00		
PON_L	0.44*	0.99	0.12	0.05	0.91*	0.44*	0.98*	1.00	
DOC_L	0.53*	0.07	0.82*	-0.21	-0.07	0.10	0.10	0.01	1.00

Table 3.7. Correlation matrix comparing erosion variables (R runoff; SC sediment concentration; SL soil losses; POC_C particulate organic carbon content of the sediment; PON_C particulate nitrogen content of sediment DOC_C dissolved organic carbon content; POC_L particulate organic carbon losses; PON_L particulate organic nitrogen losses and DOC_L dissolved organic carbon losses) to specific environmental variables: Rain : cumulative rainfall per event; RI6: maximum rainfall intensity per six minutes; R3D: three-day rainfall intensity; Slope: slope gradient; Crust: soil surface covered with crusts; Cov: percentage of soil surface coverage by vegetation; ρ_b: soil bulk density; Clay: clay content of the soil; Rainc; cumulative rainfall for the entire rainfall season; SOC_C5: soil organic carbon content for the 0-5cm sampling depth; for the 1m long plots. Variables showing a significant statistical correlation at $P < 0.05$ are marked with a * in the table.

	L	**Rain**	**RI6**	**R3D**	**Slope**	**Crust**	**Cov**	**Clay**	ρ_b	**Rainc**	**SOC_C5**
R	0.40	0.56	0.34	0.46	0.36	0.28	0.00	0.22	0.42	-0.10	0.29
SC	0.98	0.48	0.14	0.60	0.76	0.43	0.08	0.46	1.00	-0.74	0.70
SL	0.11	0.22	0.18	0.18	0.16	0.32	-0.18	-0.07	0.05	0.07	-0.09
POC_C	0.11	-0.14	0.04	0.20	0.06	-0.01	0.16	0.12	0.13	-0.26	0.16
PON_C	0.82	0.37	0.08	0.51	0.66	0.28	0.12	0.36	0.85	-0.67	0.58
POC_L	0.98	0.50	0.16	0.61	0.76	0.43	0.08	0.46	0.99	-0.71	0.69
PON_L	0.99	0.48	0.12	0.59	0.76	0.42	0.08	0.46	1.00	-0.73	0.70
PON_L		0.27*	0.20	0.12	0.16	0.05	-0.05	-0.09	0.18	0.43*	-0.19
DOC_L		0.25*	0.03	-0.06	0.26*	-0.03	0.03	-0.19	0.19	0.14	-0.27*

3.4.4 Correlation between soil erosion variables on 5m long plots

R proved to be significantly positively correlated to SL (r = 0.51), PON_C (r = 0.33), POC_L (r = 0.49), PON_L (r = 0.33) and DOC_L (r = 0.64) (Table 3.7). A negative correlative relationship was revealed for R and POC_C, suggesting that as R increases the POC_C in the eroded sediment decreases. SC was positively correlated to SL and POC_L, with a r-coefficient of 0.57 and 0.59, respectively. SL correlated to R, SC, PON_C, POC_L, PON_L, DOC_L, the highest correlation occurring with POCL (r = 0.99). Surprisingly, POC_C did not correlate with the study variables. POC_L was positively correlated to R, SC, SL, PON_C, PON_L and DOC_L.

3.4.5 Temporal evolution of soil and soil carbon erosion

Figure 3.2 presents the temporal evolution of cumulative R over three consecutive rain seasons (2010-2011; 2011-2012; 2012-2013). Cumulative R increased sharply for both plot lengths during the first 2010-2011 rainfall season, which was characterised by numerous large rainfall events. Thereafter the trend-line reached a quasi-plateau until February 2012, from which month the cumulative R slightly increased again in response to further large rain events. The advent of the 2012-2013 rainfall season was marked by further large events, leading to further spikes in the trend-line. During the first rainy season cumulative R initially increased at the same pace at both plot lengths until the fourth rainfall event. Thereafter, the 1m plots steadily generated more runoff than the 5m plots. This resulted in a cumulative R over the three year seasons of 245.9 L m^{-1} on one meter long plots, and 444.1 L m^{-1} on the long plots. The cumulative SLW followed a similar trend to R, i.e. a sharp increase during the first semester of 2011, followed by a more gradual increase, but only for 5m plots (Figure 3.2B). This resulted in a cumulative three year SLW of 4275.9 g m^{-1} on long plots (5 m) and 701.4g m^{-1}on short plots (1 m). For both plot lengths POC_L increases sharply at first, yet with the end of the 2010-2011 season plateaus off over the entire 2011-2012 season to increase again along with the onset of the first events of the third rainfall season. At the end of the three seasons, the 5m plots yielded a cumulative of 41.5 g C m^{-1} and the 1m plots 37.4 g m^{-1}.

Figure 3.3 depicts the evolution of R, SLW and POC_L over time for the 1m^2 plots. In Figure 3.3A R initially increases rapidly for all hillslope positions, with the highest R at this point being delivered at the terrace slope. Half way through the second season (n = 22) however, the R generated by the midslope increased rapidly to result in it being the hillslope position that produced the greatest cumulative R over the three seasons (565.4 L m^{-1}). A similar trend was evident for SLW, where all hillslope positions responded with rapid losses during the first season, and after event 22 the midslope produced the greatest SLW (1124.1 g m^{-1}). The terrace slope yielded the second highest cumulative soil losses at 744.1 g m^{-1} (Figure 3.3B). Cumulative POC_L were highest for the shoulder dolerite (44.6g m^{-2}) and terrace slope (43.6g m^{-2}), after event 22 the midslope also increased rapidly and eventually yielded a cumulative of 41.5 g m^{-2} (Figure 3.3C). The footslope yielded the lowest cumulative values for R, SLW and POC_L.

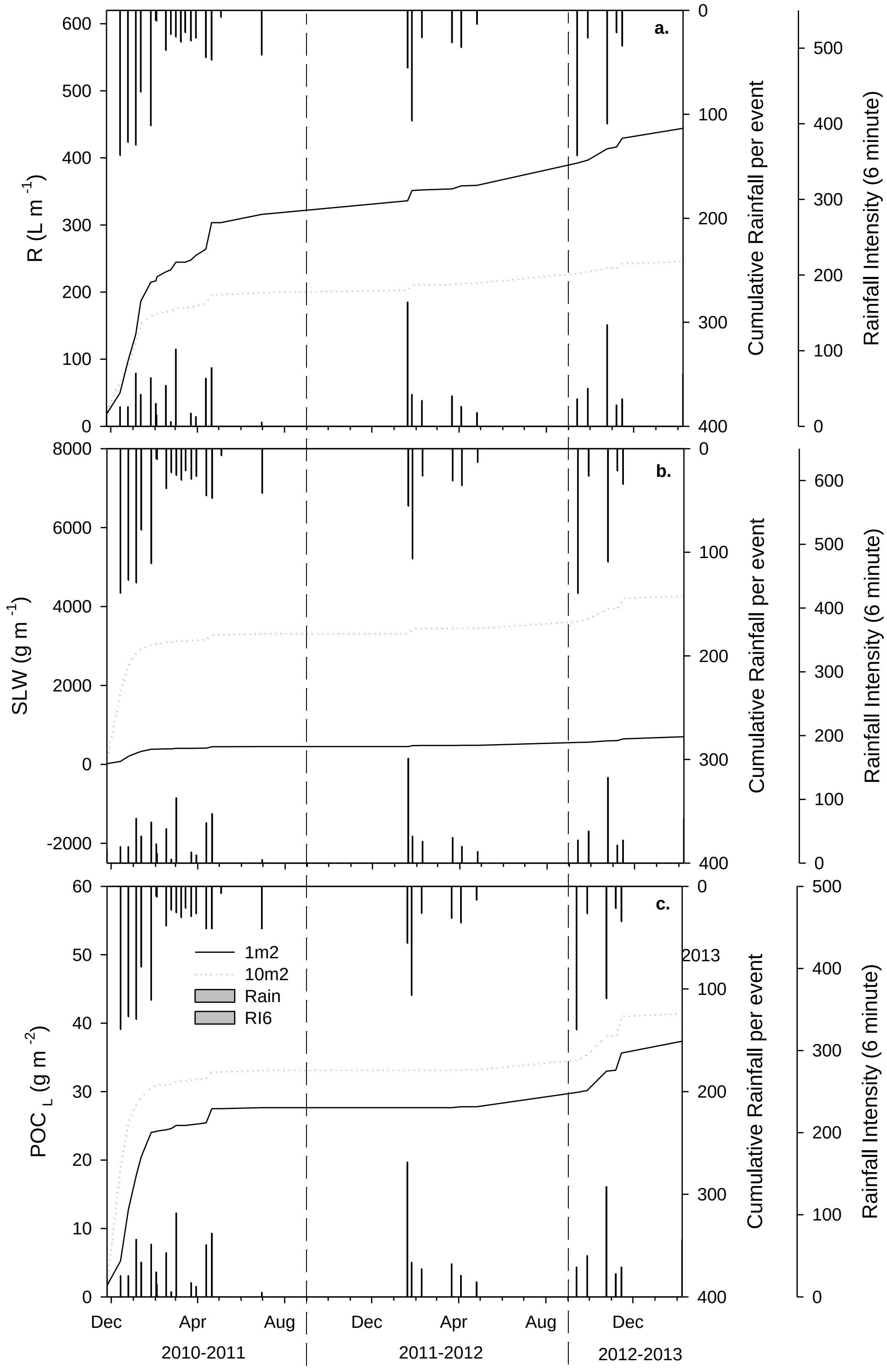

Figure 3.2. (a.) Cumulative runoff (R), (b.) cumulative soil losses and (c.) cumulative particulate organic carbon losses (POC_L) plotted for three rainfall seasons (2010 – 2013), for $1m^2$ and $10m^2$ plot sizes installed at different hillslope positions on communal grassland in Potshini, South Africa. Supplementary axes have been added to show the cumulative rainfall per event(n=32) as well as the six minute rainfall intensity in a bar-graph format.

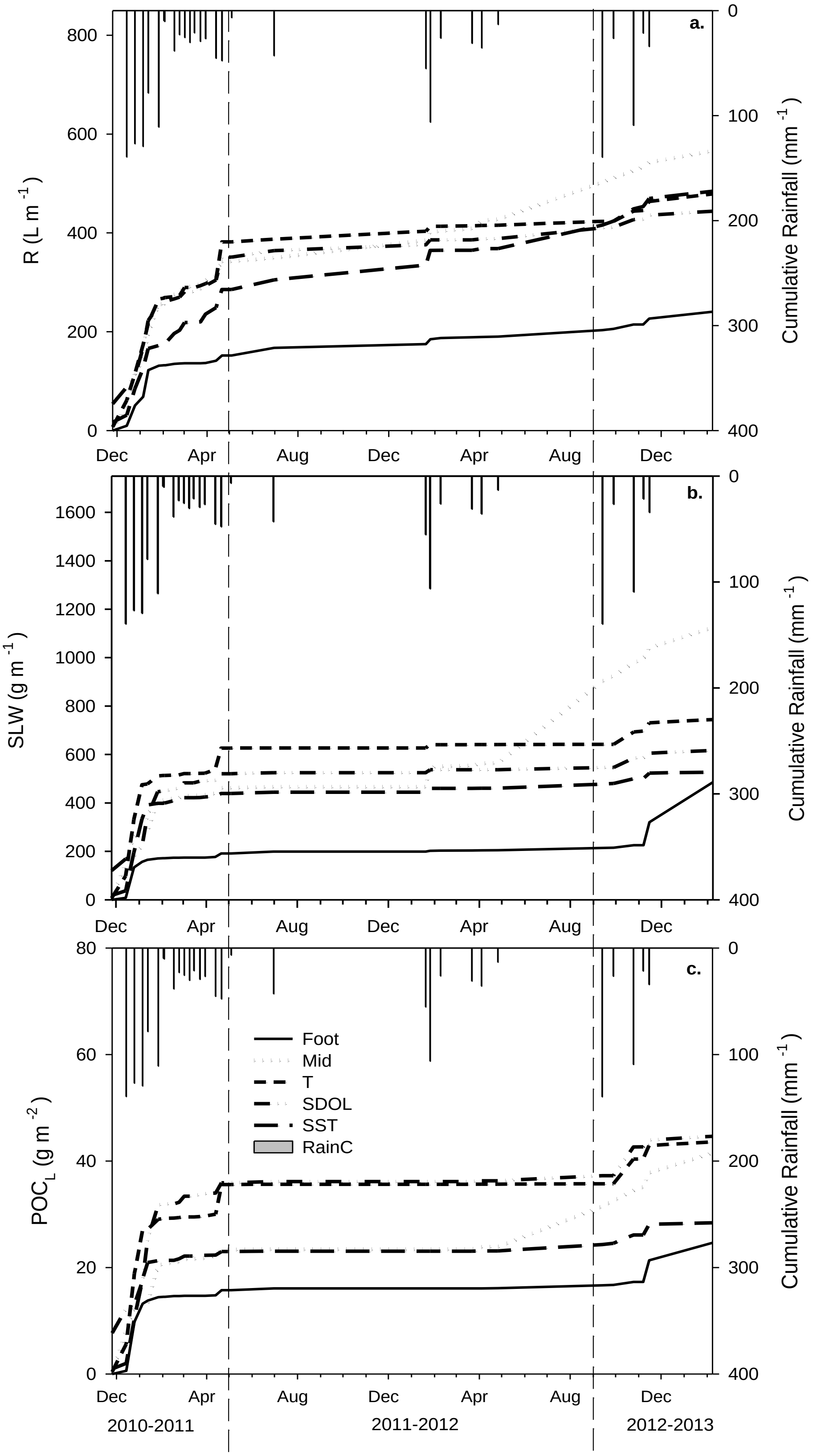

Figure 3.3 (a.) Cumulative runoff (R), (b.) cumulative soil losses (SLW) and (c.) cumulative particulate organic carbon losses (POC_L) plotted for three rainfall seasons (2010 – 2013) for1m^{2}plots installed at different hillslope positions; footslope (F), midslope (M), terrace (T), shoulder dolerite (SDOL) and shoulder sandstone (SST) on a communal grassland in Potshini, South Africa. Supplementary axes have been added to show the cumulative rainfall per event (n=32) as well as the six minute rainfall intensity in a bar-graph format.

In Figure 3.4 the evolution of R, SLW and POC_L for the 10 m^2 plots is also depicted for each hillslope position. Similar to the trend for the 1m^2 plots, R, SLW and POC_L at all hillslope positions increased rapidly with the first rainfall events of the first season. After the first few initial events, the shoulder sandstone hillslope position generated the highest amount of R and the midslope delivered the least R. However, during the second season the midslope and the shoulder dolerite steadily produced greater R to eventually result in respective values of 27.3 L m^{-1} and 262.4 L m^{-1}. The lowest cumulative R values were observed for the footslope (171.9L m^{-1}) and the terrace slope (174.3L m^{-1} ;Figure 3.4A). The SLW responded with rapid losses on all hillslope positions during the first season and it was only during the third season that the midslope produced significantly more SLW to eventually yield the highest cumulative SLW of all the hillslope positions (6383.7 g m^{-1}). The terrace slope hardly produced any further soil losses after the first season, hence the flat gradient of the line presented on the graph. The lowest SLW were revealed for the shoulder sandstone hillslope position, where the seasonal cumulative losses were 69% lower than the seasonal SLW recorded for midslope (Figure 3.4B). The POC_L initially increased rapidly for all hillslope positions during the first season, reaching a plateau with the onset of the second season. At the end of the second season, the highest cumulative POC_L came from the shoulder dolerite slope, yet with the onset of the third season, the midslope produced higher POC_L and eventually ended up producing the highest cumulative losses (59.4 g m^{-2}). The shoulder dolerite produced cumulative POC_L of 50.g m^{-2}, whereas the foot and the terrace slopes produced the lowest cumulative values of 26.1 g m^{-2} and 37.241.5 g m^{-2} respectively (Figure 3.4C).

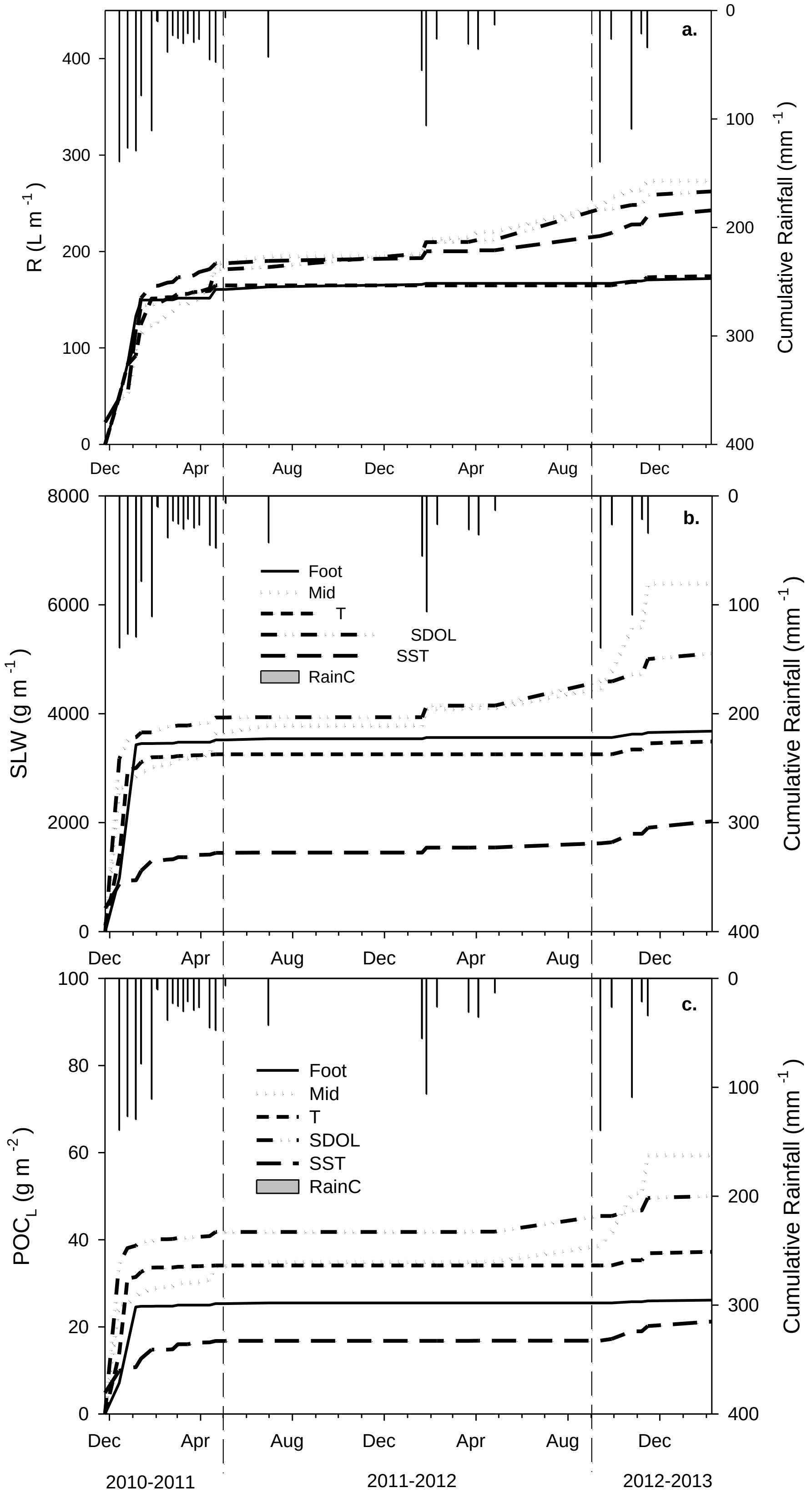

Figure 3.4 (a.) Average cumulative runoff (R), (b.) cumulative soil losses (SLW) and (c.) cumulative particulate organic carbon losses (POC_L) plotted for the duration three rainfall seasons, depicting only the $10m^2$plot size. Supplementary axes have been added to show the cumulative rainfall per event (n=32) as well as the six minute rainfall intensity in a bar-graph format.

3.4.6 Correlation between SOC erosion and selected controlling factors.

Overall, slope length significantly influenced R, SC, PON_C, POC_L PON_L (Table 3.4). L showed the highest correlations to SC (r = 0.98), POC_L (r = 0.98), PON_C and PON_L (r = 0.99), with L showing the weakest correlation to R (r = 0.40; Table 3.4).

Table 3.4. Correlation matrix comparing erosion variables runoff (R); sediment concentration (SC); soil losses (SL); particulate organic carbon content (POC_C) of the sediment; particulate nitrogen content (PON_C)of sediment, dissolved organic carbon content (DOC_C); particulate organic carbon losses (POC_L) and particulate organic nitrogen losses (PON_L) to specific environmental variables: length of slope (L); cumulative rainfall per event (Rain); maximum rainfall intensity per six minutes (RI6); three-day rainfall intensity (R3D); slope gradient (Slope); soil surface covered with crusts (Crust); percentage of soil surface coverage by vegetation (Cov); clay content of the soil (Clay); soil bulk density (ρ_b); cumulative rainfall for the entire rainfall season (Rainc); soil organic carbon content for the 0-5cm sampling depth (SOC_C5); for the 1 and 5mplots. Variables showing a significant statistical correlation at P < 0.05 are marked with a * in the table.

	R	SC	SL	POC_C	PON_C	POC_L	PON_L
L	0.40*	0.98*	0.11	0.11	0.82*	0.98*	0.99*
Rain	0.56*	0.48*	0.22*	-0.14	0.37*	0.50*	0.48*
RI6	0.34*	0.14	0.18*	0.04	0.08	0.16	0.12
R3D	0.46*	0.60*	0.18*	0.20*	0.51*	0.61*	0.59*
S	0.36*	0.76*	0.16	0.06	0.66*	0.76*	0.76*
Crust	0.28*	0.43*	0.32*	-0.01	0.28*	0.43*	0.42*
Cov	0.00	0.08	-0.18*	0.16	0.12	0.08	0.08
Clay	0.22*	0.46*	-0.07	0.12	0.36*	0.46*	0.46*
BD	0.42*	1.00*	0.05	0.13	0.85*	0.99*	1.00*
Rainc	-0.10	-0.74*	0.07	-0.26*	-0.67*	-0.71*	-0.73*
SOCc5	0.29*	0.70*	-0.09	0.16	0.58*	0.69*	0.70*

3.4.7 Dominant erosion variables investigated for 1m plots

R did not correlate significantly with all study environmental variables, except the cumulative rainfall calculated for the entire season (r=0.41) and SOC_C5 (r=-0.32). Likewise, SC negatively correlated to SOC_C5 but positively correlated to P_b and cumulative rainfall. SL showed significant correlation to Rain, event rainfall amount, S, P_b and SOC_C5, the latter being a negative correlation. POC_C negatively correlated with S and P_b, and was furthermore positively correlated with Clay and SOC_C5. PON_C and DOC_C did not reveal any significant correlation with the study variables, accept with SOC_C5 (r=0.23), in the case of PON_C, and Rain (r= -0.22) in the case of DOC_C. POC_L responded positively to the rainfall variables: Rain, six minute rainfall intensity (RI6), three day rainfall intensity (R3D) and Rainc. PON_L responded positively to Rain and Rainc; and DOC_L correlated positively to Rain and S and negatively to SOC_C5 (Table 3.6).

Table 3.6. Correlation matrix investigating erosion variables: R runoff; SC sediment concentration; SL soil losses; POC_C particulate organic carbon content of the sediment; PON_C particulate nitrogen content of sediment DOC_C dissolved organic carbon content; POC_L particulate organic carbon losses; PON_L particulate organic nitrogen losses and DOC_L dissolved organic carbon losses specifically for the 5m long plots. Variables showing a significant statistical correlation at P < 0.05 are marked with a * in the table.

	R	**SC**	**SL**	**POC_C**	**PON_C**	**DOC_C**	**POC_L**	**PON_L**	**DOC_L**
R	1.00								
SC	0.06	1.00							
SL	0.51*	0.57*	1.00						
POC_C	0.06	-0.24	-0.10	1.00					
PON_C	0.33*	0.29	0.39*	-0.03	1.00				
DOC_C	0.18	-0.14	-0.02	-0.05	0.07	1.00			
POC_L	0.49*	0.59*	0.99*	-0.06	0.39*	-0.02	1.00		
PON_L	0.33*	0.29	0.39*	-0.03	1.00*	0.07	0.39*	1.00	
DOC_L	0.64*	0.00	0.44*	-0.08	0.18	0.46*	0.41*	0.18	1.00

3.4.8 Dominant erosion variables investigated for 5m plots

The correlations on the 5m plots exhibited different trends in comparison to those obtained on 1m plots. There was a tendency for R to be affected by soil surface features (Crust and Cov) and antecedent rainfall (R3D), and SC and SL and POC_L to also respond to soil surface features and slope gradient (Table 3.8). Surprisingly, POC_C, POC_L PON_L and DOC_L were not significantly correlated to any of the controlling study factors. On the whole the correlations proved to be relatively low with the highest r value of 0.47 between SC and S.

Table 3.8. Correlation matrix comparing erosion variables to specific environmental variables for the 5m long plots. Variables showing a significant statistical correlation at $P < 0.05$ are marked with a * in the table.

	Rain	RI6	R3D	Slope	Crust	Cov	Clay	ρ_b	Rainc	SOCC5
R	-0.20	-0.30	-0.41*	0.24	0.41*	-0.41*	-0.01	0.12	0.07	-0.11
SC	-0.11	0.18	0.26	0.47*	0.44*	-0.44*	-0.23	0.46*	0.52*	-0.36*
SL	0.18	0.13	0.07	0.33*	0.40*	-0.40*	-0.10	0.27	0.21	-0.22
POCC	-0.17	-0.15	-0.25	-0.27	-0.15	0.15	0.02	-0.20	-0.18	0.01
PONC	-0.12	-0.09	-0.11	0.21	0.19	-0.19	-0.13	0.21	0.16	-0.19
DOCC	-0.29	0.07	0.04	0.36*	0.03	-0.03	-0.36*	0.23	-0.21	-0.24
POCL	0.14	0.14	0.08	0.32*	0.38*	-0.38*	-0.13	0.29	0.22	-0.24
PONL	-0.12	-0.09	-0.11	0.21	0.19	-0.19	-0.13	0.21	0.16	-0.19
DOCL	0.16	0.00	-0.08	0.20	0.31	-0.31	-0.03	0.06	-0.08	-0.07

3.4.9 The soil loss variations across the hillslope

The cumulative 5m/1m soil loss rate ratios of R, SL and POC_L are depicted in Figure 5. A lower total cumulative value indicates that splash erosion was dominating RIF erosion for a certain hillslope position. It is evident that the terrace slope had the lowest cumulative SLW ratio, followed by the midslope and shoulder sandstone positions (Figure 3.5B). The POC_L revealed the highest cumulative ratio for the midslope and the shoulder sandstone hillslope position. The lowest cumulative ratio value was revealed for terrace, followed by the footslope.

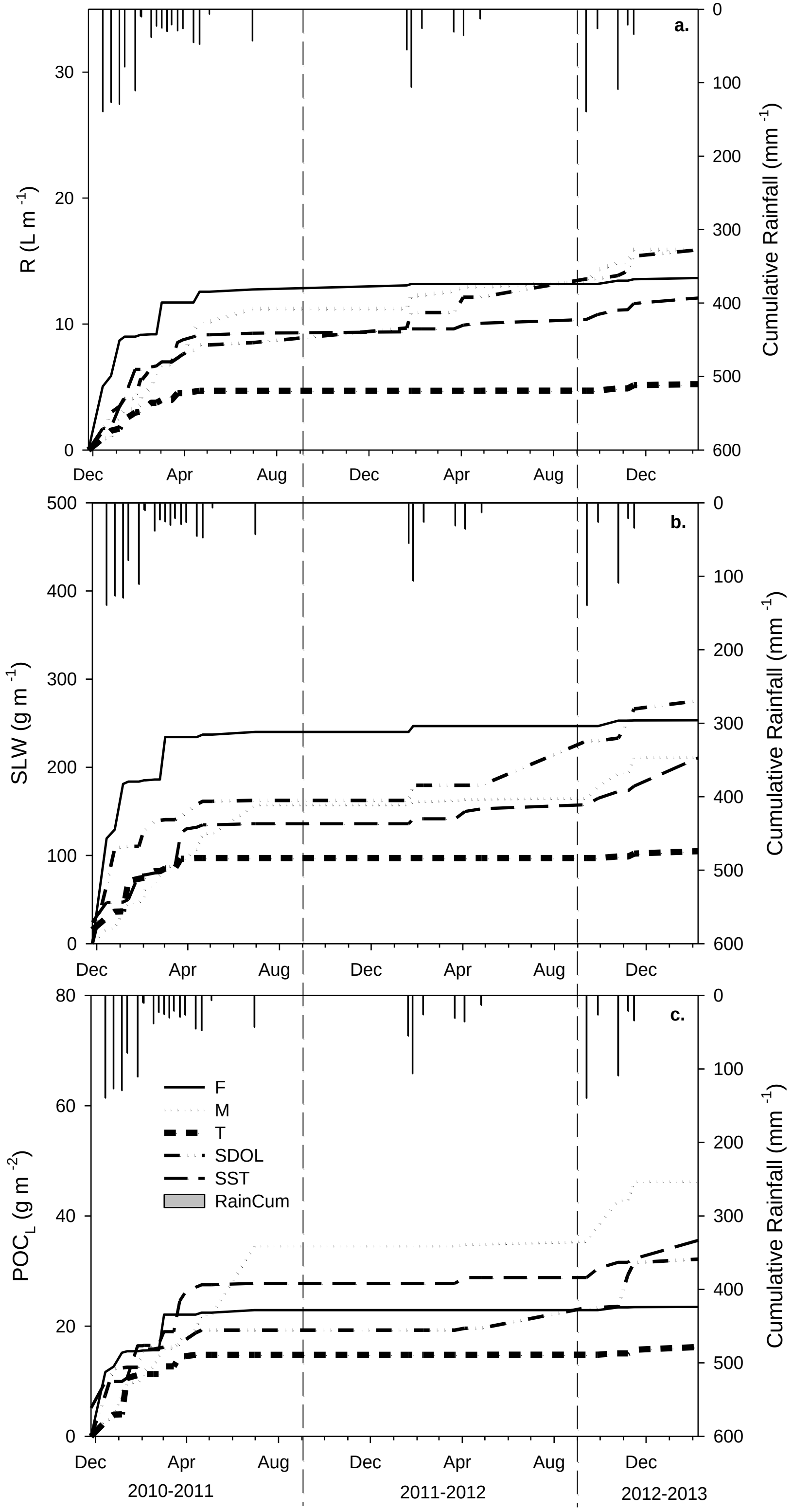

Figure 3.5. (a.)Average cumulative 10/1 runoff (R), (b.) cumulative soil losses (SLW) and (c.)cumulative particulate organic carbon losses (POC_L) plotted for the duration three rainfall seasons, depicted for the $1m^2$and $10m^2$plot size. Supplementary axes have been added to show the cumulative rainfall per event (n=32) as well as the six minute rainfall intensity in a bar-graph format.

3.5 Discussion

3.5.1 On the mechanisms of soil and SOC erosion

The cumulative soil losses (SLW) monitored for the three seasons were six fold greater for the 5m long erosion plots than on the 1m long plots. This is indicative that RIF erosion, which operates more effectively on longer slopes, is the primary mechanism of soil erosion, in comparison to splash. These findings concur with those of Oakes *et al.* (2012), who conducted a prior study at the same research site, but over 2009-2010, and by Stomph *et al*. (2002) and Chaplot and Le Bissonais (2003) under different pedo-climatic contexts. Following Kinnel (2004) the greater efficiency of soil erosion on the longer plots is facilitated by a higher flow velocity, enabling RIF erosion to be operative.

Significantly lower POC_L per meter width on the longer plots inform on the overall limitation of transport and the predominance of splash in contrast to RIF in SOC water erosion. Temporal variations were however observed. These findings were consistent with the results obtained in studies of Stomph *et al*. (2002) and Chaplot and Poesen (2012), conducted in semi-arid and tropical environments respectively. However, during the first season of our study (2010-2011), which was characterised by exceptionally high cumulative rainfall, the longer plots produced significantly higher yields of POC_L, which was indicative of a higher efficiency of RIF. The remainder of the study period was marked by POC transport limitation. Such a link between rainfall conditions and relative contribution of the erosion mechanisms needs further appraisal.

3.5.2 Factors controlling the contribution of splash and RIF erosion

The impact of rainfall characteristics on SL and SOC_L was expected (Bryan., 2000; Kinnell., 2004; Parsons and Stone., 2006), since as the event cumulative rainfall and rainfall intensity increase the efficiency of splash and RIF increases. Intense events not only increase the potential erosive energy of raindrops and enhance overland flow erosivity, but also contribute to soil erosion by increasing soil moisture, which in turn diminishes soil water infiltration, hereby enhancing the efficiency of sheet erosion (Castillo *et al*., 2003). Our results showing a stronger rise during the first season of the study and a more gradual increase later in the season, albeit large events were also present at this stage, suggest that antecedent rainfall and accompanying soil moisture strongly potentiates rainfall erosivity.

Despite our study plots not displaying a large range in slope gradient, there was however a significant increase in runoff, soil, SOC and soil organic nitrogen losses with increasing S. This was consistent with previous findings by Liu *et al*. (2001) and Koulouri and Giourga, (2007) who observed greater soil losses, runoff and SOC losses with increasing slope gradient. Furthermore the significant and positive correlation between SOC losses and SOC content in the soil concords with the fact that greater SOC contents in the top-soil , which were shown to impede soil (e.g. Tisdall and Oades., 1982; Duchaufour., 1983; Six *et al*., 2002; Vásquez-Méndez *et al*., 2010), also positively affect SOC. Increased organic matter content in the soil, of which SOC forms an important part, results indeed in a more resilient soil aggregate structure, greater soil moisture retention capacity and altogether better infiltration properties of the soil.

Since the onset of the rainy season, overall fluxes from the shorter slope lengths were affected the most by an increase in soil moisture as the season progressed, as is shown by a positive and significant relationship with Rainc (the seasonal cumulative rainfall amount). In contrast, the longest plots had fluxes principally controlled by slope gradient and soil surface features of soil crusting and cover. This strongly indicates that detachment on a local scale is controlled by soil properties associated with soil cohesion and erodibility, such as bulk density and SOC_C, as opposed to for the long plots. The POC_L for the microplots responded significantly to all rainfall variables: cumulative rainfall per event, six minute rainfall intensity, three day rainfall intensity and total cumulative rainfall. POC_L therefore, seem to be highly sensitive to rainfall, responding to the intensity, magnitude and duration of a rainfall.

Environmental factors that seemed to further determine the effectiveness of RIF erosion of soil and POC were slope gradient, percentage of the erosion plots covered with soil surface crusting and the percentage covered by vegetation. An increased slope gradient and greater surface crusting both impaired the soils infiltration capacity. As on a steeper slope gradient, just as with crusting, water has less time to infiltrate and therefore a greater volume remains on the surface to contribute to RIF (Kinnel., 2004; Puigdefabregas *et al*., 1999). Vegetation has the opposite effect, as was also revealed by the long plots in this study (Table 3.7), as it slows down the surface water flow velocity assuring greater and more effective infiltration, hence a greater surface vegetation cover decreases the effectiveness of RIF (Cammeraat., 2002; Dlamini *et al*., 2011).

3.5.3 Recommendations on the enrichment ratio

We believe that most studies over-estimate the SOC enrichment ratio when it is calculate on a sampling depth of up to 5cm (Chaplot and Poesen., 2011; Rumpel *et* al., 2011; Martinez-Mena *et al*., 2008; Boye and Albrecht., 2006). During moderate rainfall events, however, it is likely only the 0-2cm soil surface layer that is exposed and rendered vulnerable to erosion. In the current study it was found that the 0-02 m sampling depth on average contained up to 25% more SOC than the 0-05m layer, This is because the upper 0.02 m of soil is much enriched in SOC than the 0-0.3 layer, the most common reference in research papers, that published results largely over-estimate the preferential erosion of SOC. Our recommendation is thus for scientists to consider the top 0-0.02 m of the soil when assessing SOC enrichment ratios.

3.6 Conclusion

In this study in the hillslope of the Drakensberg foothills of South Africa, our main objective was to evaluate the impact of the different water erosion mechanisms, namely splash and RIF on the detachment and transport of SOC. Three main conclusions can be drawn from the data obtained at runoff plot sizes of 1×1m^2 and 5×2m^2 runoff plots installed at different topographic positions, soil types, geology and vegetation cover:

1. . The main finding of this study, was that SL were markedly higher on the 5m compared to the 1m erosion plots. RIF proved to be the least effective where soils had high vegetation coverage and most effective on steep slopes with a high prevalence of soil surface crusting. Significantly lower POC_L were observed, calculated on a per meter width basis.
2. RIF erosion, which operates more effectively on longer slopes, proved to be the dominating mechanism of soil erosion, in comparison to splash. The longer slope length of the longer plots facilitates for a higher flow velocity thus enabling RIF erosion to be fully functional. POC_L were dominated by the splash erosion mechanism and RIF proved to have a rather limited effect on SOC erosion. Temporal variations were however observed regarding the dominance in SOC erosion mechanisms, especially during the first season of our study (2010-2011), which was characterised by exceptionally high cumulative rains, the longer plots produced significantly higher POC_L, which was indicative of a higher efficiency of RIF. The remainder of the study period was marked by POC transport limitation.
3. The efficiency of sheet erosion, with the contribution of rain impacted flow (RIF), was determined largely by slope gradient, vegetation cover, soil surface crusting and soil clay content. In contrast, the efficiency of splash for SOC erosion was largely

controlled by rainfall characteristic, such as intensity and duration. At the onset of the first rainfall season, where rainfal$_l$ events were concentrated temporally and also produced the highest cumulative rainfall amount, soil erosion and POC losses increased exponentially. As the rainfall season proceeded, POC losses evened out, seemingly due to higher moisture content in the soil, therefore compromising efficiency of RIF erosion.

To effectively mitigate SOC_L through sheet erosion at the hillslope level, this study recommends increasing the soil surface vegetation cover. Sufficient vegetation cover was indeed shown to significantly reduce the efficiency of RIF, hence greatly reducing erosion efficiency. These results are finally expected be used to improve existing erosion mitigation models to further inform:

4. On the significance of SOC erosion by water in South Africa , and the associated impacts on the countries SOC stocks.
5. On the amount of SOC displaced annually through water erosion in South Africa and possible spatial variations.

CHAPTER 4
GENERAL CONCLUSION

In the preceding MSc manuscript two academic papers, both currently under revision in internationally refereed journals were presented. The quantitative review in Chapter 2 carrying the title **'Soil water erosion and the global carbon cycle: a global assessment'**, was constructed by synthesising all existing studies in the field of SOC erosion. The objectives of this study were:

- To integrate and compare the outcomes of all available *in-situ* studies focussing on SOC erosion through water on a global scale.
- To identify possibly existing global SOC erosion patterns.
- To identify the main erosion mechanisms involved in SOC erosion (i.e. splash or sheet erosion) and the pertaining factors of control dominating globally.

Based on the data received from this global review, the total amount of SOC displaced each year by water erosion was calculated to be 0.55±0.08 Gt C. The highest particulate organic carbon loss (POC_L) rates were recorded in the tropical regions of the world. The semi-arid regions of the world, which are characteristic of significantly lower SOC stocks than the humid tropics, were marked by similar levels of POC losses to the tropics. The temperate regions, displayed SOC erosion rates 20% lower than those of the tropical and semi-arid areas. This review also recognised the impact that land use and land management can have on SOC erosion by water.

Sheet wash associated with splash appeared far more efficient than splash alone for detaching and transporting SOC as suggested by the significant increase in POC_L from microplot to plot size level. Plots revealed lower POC_L compared to microplots, meaning that sheet erosion quantified at plot scale, is a less efficient SOC erosion mechanism than splash. This paper revealed research potential for further studies to generate a guide delineating a range of "acceptable POC erosion", needed for a sustainable functioning of soils of all concerned pedo-climatic regions.

Hence the third chapter, '***mechanisms and controlling factors of soil organic carbon losses by sheet erosion',*** was specific to the South African environment and investigated observable differences regarding:

- The particulate organic carbon (POC) exported in the eroded sediments from 1x1m^2 and 2x5 m^2 erosion plots, installed at pre-selected hillslope positions.
- The main erosion mechanisms involved in SOC erosion (i.e. splash or sheet erosion) and the pertaining factors of control.

The cumulative soil losses monitored for the three seasons were six fold greater for the 5m long erosion plots than on the 1m long plots. This is indicative that RIF erosion, which operates more effectively on longer slopes, is the primary mechanism of soil erosion, in comparison to splash. Significantly lower POC_L per meter width on the longer plots inform on the overall limitation of transport and the predominance of splash in contrast to RIF in SOC water erosion. These findings were consistent with the results of studies conducted in semi-arid and tropical environments, which are displayed in Chapter 2. The efficiency of sheet erosion, with the contribution of rain impacted flow (RIF), was determined largely by slope gradient, vegetation cover, soil surface crusting and soil clay content. RIF erosion operated more effectively on longer slopes and proved to be the dominating mechanism of soil erosion, in comparison to splash. The efficiency of splash for SOC erosion was largely controlled by rainfall characteristic, such as intensity and duration.

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