Soil erosion prediction using RUSLE for rain fed crops under Conservation Agriculture practices in the Lake Alaotra region in Madagascar

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Abstract

Soil erosion of productive top soils is an obstacle for achieving an increased food production in a more sustainable way. The three principles of Conservation Agriculture (CA) of no tillage, permanent soil cover and crop rotations, are often seen as a promising solution. This study was undertaken within the framework of the CA2AFRICA project which aims at understanding the physical effects of CA and the reasons of its (non)adoption in Africa. A field level modeling approach was chosen to assess the effect of three types of CA cropping systems on soil loss, compared to a traditional cropping system for the region of Lake Alaotra in central Madagascar, using the Revised Universal Soil Loss Equation (RUSLE).

The most accurate method for estimating erosivity *R* was based on daily effective rainfall data, resulting in a value of 8487 (SI units). For erodibility *K*, the average of five estimation methods was taken, resulting in a value of 0.038 (SI units). Three slope scenario's were chosen, with *LS* values ranging from 0.6 to 4. Together, these factors form a potential erosion of about 484 $ton \cdot ha^{-1}yr^{-1}$.

The crop cover *C* was divided into a crop component estimated with percentage of canopy cover, and a mulch component estimated with the Mulch Factor. *C*-values were determined at half month time intervals for four cropping systems: 1) 'Traditional', a two year rotation of upland rice and maize with an average *C* of 0.56; 2) 'Stylo 1', a three year rotation including *Stylosanthes guianensi* at test field yielding an average *C* of 0.04; 'Stylo 2' as Stylo 1, but for situation at farmers' fields, yielding an average *C* of 0.14 and 3) 'Dolichos', a two year rotation including *Dolichos lablab* with an average *C* of 0.13. Support practice values *P* were set at 0.4 and 0.1 for respectively the traditional and the CA cropping systems.

Resulting annual soil loss ($ton \cdot ha^{-1}yr^{-1}$) was about 87 for 'Traditional', 2 for 'Stylo 1', 5.5 for 'Stylo 2' and 9 $ton \cdot ha^{-1}yr^{-1}$ for 'Dolichos. Although validation with a Unit Plot is necessary, the estimated parameters give an indication of the effect of CA on soil loss and allow for future scaling up of soil loss quantification.

Table of contents

Abbreviations and glossary

BV-lac	Bassins Versants Lac Alaotra, or Watersheds of Lake Alaotra
CA	Conservation Agriculture
CA2AFRICA	Conservation Agriculture in Africa : Analysing and FoReseeing its Impact, Comprehending its Adoption
CC	Climate Code
CIRAD	Centre de coopération internationale en recherche agronomique pour le développement, or Centre for International Cooperation in Agronomic Research for Development
FAO	Food and Agriculture Organization of the United Nations
Lavaka	Big gully in Malagasy language
MAR	Mean Annual Rainfall
MF	Mulch Factor
NDVI	Normalized Difference Vegetation Index
RSI	Rainfall Seasonality Index
(R)USLE	(Revised) Universal Soil Loss Equation
SCV	Systèmes de culture sur couverture vegetale, or Direct Seeding mulch based systems
SI units	Standard International units — For erosivity *R* this is $MJ \cdot mm \cdot ha^{-1} h^{-1}$; For erodibility *K* this is $ton \cdot h \cdot MJ^{-1} mm^{-1}$
TAFA	Tany sy Fampandrosoana, or Earth and Development
Tanety	Hill in Malagasy language
Unit Plot	A reference experiment plot for applying the RUSLE, see also p. 20
USDA `	United States Department of Agriculture

1 Introduction

This study was undertaken in the framework of the CA2AFRICA project, a project that is a reaction to several environmental problems of today. Africa is facing an increasing population pressure and food demand that have already led to large scale land use changes (Lal, 1985; 2007). Increasing pressure on land and water resources is resulting in a worsening of land degradation but also in the decreasing of biodiversity. This research is about a main contributor to land degradation in sub Saharan Africa: soil erosion by water.

This introduction will give some general information about the study area as far as relevant for soil erosion (1.1), about the greater context of CA2AFRICA (1.2), about the more specific context of Conservation Agriculture in the study area (1.3), and about modeling soil erosion with RUSLE (1.4). This leads to a problem statement and to the three related study objectives (1.5).

1.1 Lake Alaotra and soil erosion

The research was done in the region of Lake Alaotra in the centre of Madagascar. This part of the country is known as the 'granary' of Madagascar because of its abundant rice cultivation. The vast majority of rice production takes place in the flat rice paddies, called *rizières*: Over 90 000 ha of rice paddies around the lake, both under irrigated and rain fed conditions with a production of more than 200 000 tons per year (CIRAD Madagascar, 2011).

The hills around these rice fields, locally called *tanety,* are very susceptible to soil erosion. On the one hand this is translated in the huge and very visible gully's, locally called *lavaka*, that are characteristic for this area. On the other hand it is translated in the gradual and rather invisible erosion of agricultural fields which is the focus of this study.

The susceptibility to soil erosion is partly an intrinsic characteristic of the region of Lake Alaotra. The loamy yellow and red ferral sols are susceptible to soil erosion. The rainfall is concentrated in five months leading to high intensities, especially during cyclones. The slopes can be very steep and long. However, the susceptibility to soil erosion is also a result of management decisions. Cropping systems based on zero tillage and permanently covered soils have been introduced in this area, but most of the area is still traditionally cultivated with pluvial rice in a rotation with maize, beans or cassava. These fields are prepared by plowing manually or with animal (zebu) force, and there are no common conservation practices (expert interviews).

Quantitative research on soil erosion for the *tanety* of Lake Alaotra dates back to the early fifties and sixties, during and immediately after the French colonization period. In the following decades there has not been quantitative erosion research in the region of Lake Alaotra except for the big *lavakas* . Since 2003 however, a joint effort for integrated land management is embodied in the organization *Bassins Versants – Lac Alaotra* (BV-lac). This information, research and dissemination bureau is under responsibility of the *Ministère de l'agriculture, de l'élevage et de la pêche* of Madagascar, financed by the *Agence Française de Développement* (AFD), and implemented by the *Centre de Coopération Internationale en Recherche Agronomique pour le Développement* (CIRAD).

1.2 Conservation Agriculture in Africa

These efforts stand in a greater context of trying to get Conservation Agriculture (CA) to work in Africa and to achieve resource efficient agricultural crop production, based on integrated management of soil, water, biological resources and external inputs. It is the mission of the CA2AFRICA project (Conservation agriculture in Africa: Analysing and FoReseeing its Impact - Comprehending its Adoption) to shed light on this matter on the continental scale. Its overall objective is to examine the agro-ecological, socioeconomic and institutional conditions that determine success or failure of CA throughout Africa based on past and on-going CA experiences (CA2AFRICA, 2009).

Conservation Agriculture is based on three principles that may take very different shapes and forms, adapted to local customs. These principles are:

1. Continuous minimum mechanical soil disturbance.
2. Permanent organic soil cover.
3. Diversification of crop species grown in sequence or associations.

(FAO, 2010).

Conservation Agriculture is increasingly seen as a promising alternative for coping with the need to increase food production on the basis of more sustainable cropping practices. It has been a great success in Brazil and the United States during the last decades (Bolliger *et al.*, 2006). However, the adoption of CA in Africa seems very limited, and is subject to critique (CA2AFRICA, 2009). Critical publications state that CA does not address a need identified by the farmer, but rather that of policymakers and scientists. Furthermore, it is not clear which principles of CA, and under which conditions, actually contribute to the effects sought. And it is questionable if the preconditions for adoption actually exist in the parts of Africa where CA is promoted (Giller *et al.*, 2009; Bolliger *et al.*, 2006).

1.3 Conservation Agriculture in Madagascar

The CA2AFRICA project is, so far, active in two research sites in Madagascar. In Antsirabe a socio-economic perspective was chosen for identifying constraints and opportunities for the implementation of CA. In the region of Lake Alaotra, the current study area, a modeling perspective is chosen for identifying the impact of CA cropping systems on soil loss.
This corresponds to a specific objective of the CA2AFRICA project, that is *the testing and validation of bio-physical, socio-economic and conceptual models of innovation systems for analyzing the impact and adoption of CA in Africa* (CA2AFRICA, 2009).

In the region of Lake Alaotra, BV-lac is disseminating several cropping systems on the basis of *Semis-direct sous Couverture Végétal permanentes* (SCV) as an alternative to traditional systems. In the formal definition (AFD and FFEM, 2007) SCV does not necessarily include a crop rotation, but in the lake Alaotra region all SCV systems are multi-year rotations and can therefore be considered to be CA systems.
In this study four cropping systems are considered. One traditional system is compared with three CA cropping systems as briefly explained below.

1. Traditional. A two year rotation where upland rice is grown the first year and maize the second year. The crop residues are often removed after harvest. After some years the field is left fallow.
2. Stylo 1. A three to four year rotation on the basis of the *Stylosanthes Guianensi* (stylo). Stylo is introduced the first time in association with e.g. Ground Nut. The second year the Stylo grows alone to a height of about 1.5 meter. The third year upland rice is grown in the mulch of stylo. The fourth year maize is grown as the stylo mulch disappears and new stylo starts to grow again. Data is obtained from test fields.
3. Stylo 2. In theory the same as 2, but with data from farmers´ fields. The main difference is the weeding frequency and the sowing density.
4. Dolichos. A two year rotation as Traditional, but with a basis of *Dolichos Lablab* (dolichos). Dolichos is sown with maize the first year. The second year the upland rice is planted in the mulch of Dolichos.

The expected advantages are basically that soil loss is reduced by increasing the crop canopy cover or the mulch cover in times that erosive storms are frequent. In theory this can go hand in hand with an increased production, soil fertility and a healthy organic balance in the top soil.

1.4 RUSLE, modeling soil erosion

Through the modeling of soil erosion, specific insight can be gained in the relation between CA and its 'clearest benefit': soil erosion control.

There is a long tradition of modeling soil erosion that goes back to 1940 (Morgan 2005). Three often used models are the Morgan, Morgan and Finney (MMF) model, the Water Erosion Prediction Project (WEPP) model, and the Revised Universal Soil Loss Equation (RUSLE). The RUSLE, one of the first quantitative soil loss models, is relatively easy and has been applied in and modified for many regions in the world. It has also been used in the study area during the fifties and sixties, therefore the RUSLE was selected for this research.

In this study it has been tried to approach the RUSLE model both as a scientist, by being critical and trying to improve the logic of the RUSLE parameters, and as an engineer, by coming up with results for this specific context.

RUSLE's predecessor USLE was developed in the USA in the sixties and is sometimes known under the not so flattering nickname 'USELESS' because of its empirical character and the supposed high rates of guesswork. But if the estimation methods are selected according to available data the model is very well capable of roughly estimating soil loss and evaluating the impact of conservation measures on soil erosion.

Although the overall formula stayed the same throughout the years, the composition and calculation of the individual factors by other authors have led to the development of the RUSLE. It has been applied in and modified for situations in Asia, Australia, Africa and the America's (Roche, 1954; Yin *et al.*, 2006; Angima *et al,.* 2003 and many others). It has proven to be a very useful planning tool.

The RUSLE model is appropriate for the field level and can be aggregated to the whole watershed. It takes into account both rill and interrill erosion, but not the erosion from accumulated flow. It calculates a yearly average of soil loss by multiplying five factors as in equation 1-1. These factors can be roughly divided into the potential erosion factors and the management factors.

$$A = R \times K \times LS \times C \times P \qquad \text{eq. 1-1}$$

The potential erosion is given by a product of the erosivity of the rains (R), the erodibility of the soil (K) and the slope length and steepness (LS) factors. These are specific characteristics for a location and cannot be changed easily. Terracing can change *LS*, but as this was not the case for the study area, *LS* is included in the potential erosion. The management factors are the cover-management (C) and the supporting practices (P) factors. These are subject to farmers' decisions. The definitions of these factors and the methods of estimation will be extensively discussed in chapter 2.

1.5 Problem statement and objectives

In many places in the world, including most CA2AFRICA countries, quantitative soil erosion research is limited by the quality and quantity of available data. Installing and maintaining a Unit Plot is necessary for proper determination of RUSLE variables, but is often too costly and time consuming. The many alternative estimation methods are of empirical nature, and therefore not directly applicable in every situation. As with every model, the output is as good as the input, where 'good' does not only refer to a good fit with the physical conditions, but also to a balance of available and necessary data.

For accurate estimation of the RUSLE parameters in Lake Alaotra region, there is a need for careful selection from available estimation methods. Only the rainfall erosivity factor R was available from literature, but it dates back to as far as the fifties and may be changed. The other factors were not mentioned in literature (Andriamapianina, 1997).

Moreover, there is a need for understanding the dynamics of Conservation Agriculture concerning soil erosion. The logical hypothesis is that soil loss will decrease under the CA cropping systems compared to a selected traditional cropping system.

In the light of CA2AFRICA it is important to explore the possibilities and the limits of the RUSLE model in a context of limited data. Is it a suitable tool for assessing the impact of CA on soil loss?

These observations lead to the threefold objectives of this study in the Lake Alaotra region of Madagascar:

1) To compare estimation methods for and determine values of potential soil loss parameters *R, K* and *LS* of the RUSLE without installing a Unit Plot;
2) To evaluate the impact of three CA rotations on the rate of soil loss with the *C* and *P* parameters of the RUSLE without installing a Unit Plot;
3) To formulate some recommendations for the use of RUSLE in other CA2AFRICA countries.

2 Materials and methods

This chapter presents the study area and describes the available climate and soil data (2.1).
In the method section all the methodologies for estimating RUSLE factors will be presented. The RUSLE factors can be divided according to the objectives into the potential erosion and the effect of the Conservation Agriculture cropping systems. The potential erosion includes the rainfall erosivity *R* (2.2) the soil erodibility *K* (2.3) and slope length and steepness *LS* (2.4). The effect of the Conservation Agriculture cropping systems is assessed with the RUSLE's cover management *C* (2.5) and Support Practices *P* (2.6).

2.1 Study area

2.1.1 General

The selected study area is situated about 175 km north-east of the capital Antananarivo, in the province of Tamatave (figure 2-1). It is the region of the biggest lake of the country, Lake Alaotra, roughly between Ambatondrazaka and Imerimandroso. The longitude is comparable with that of Harare (Zimbabwe), Brasilia (Brazil) or the north of Australia.
The whole Lake Alaotra region is more than 17 000 km^2, of which 380 km^2 are *lavaka*, and about 7600 km^2 are the *tanety*. The rest of the surface is made up of rice paddies and reforestation. The altitude is mostly between 750 and 790 meters above sea level, while the *tanety* can reach 1450 meters (Raveloarisoa, 1998).
Estimation of population is about 500 000 people in 1996. Rice production is the main economic activity. Production is estimated to be 200 000 ton/yr of which 80 000 ton is exported to the capital Antananarivo and to Tamatave (CIRAD Madagascar, 2011).
Mean annual rainfall is close to 1056 mm/yr (2.1.2), concentrated in a 5 month rainy season from November to March in which cyclones can occur. The average yearly temperature is around 21^{o}C (Oldeman, 1990).

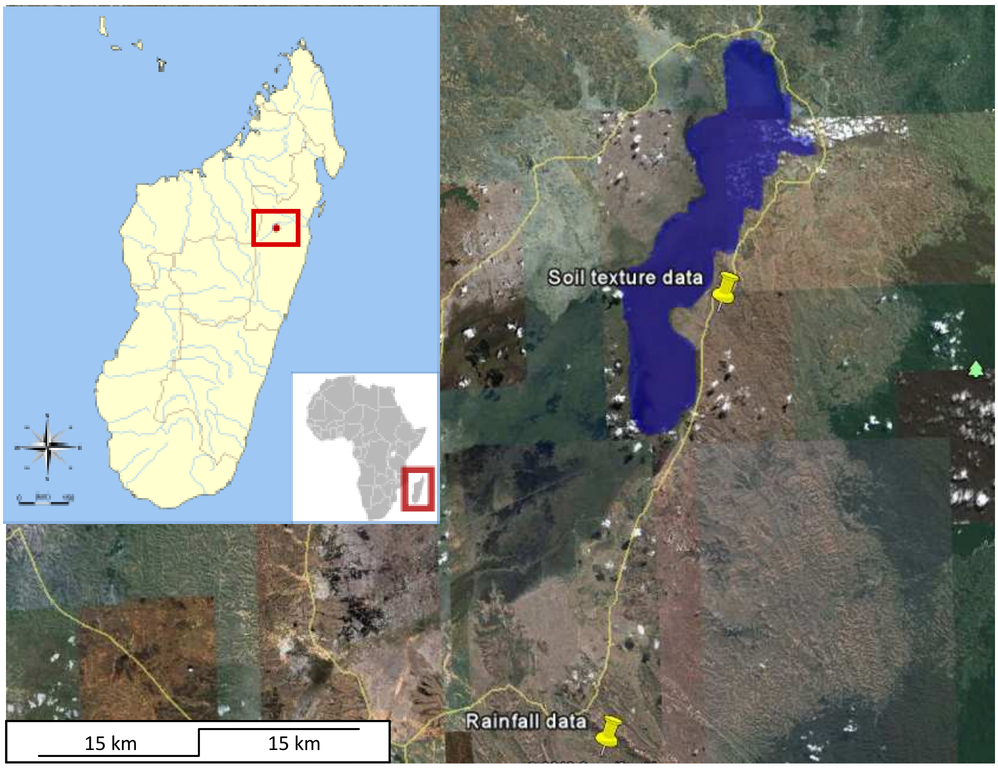

Figure 2-1 The region of Lake Alaotra and its location in Madagascar, sources of soil texture and rainfall data are indicated

2.1.2 Sources of climatologic data

Two climatologic data sets were used from two different stations. The hourly fixed interval rainfall data was obtained from the *Cimel* dataset from the *Ambohimiarina* weather station of BV-lac, located seven kilometers south-east of Ambatondrazaka. Measurements were taken from February 2006 until January 2010. The coordinates of the station are LAT: 17° 53' 56'' and LONG: 48° 25'28''. From the same station, data on daily temperature was used for calculating the temporal variability of the erodibility *K*.

The other dataset was a daily rainfall dataset for the period of 1941 to 1992 located at CALA station. Only the 46 years from 1942 to 1988 were used in the calculations because data from the other years was incomplete. This dataset was used for determining the daily rainfall, the daily effective rainfall (= rainfall exceeding the erosive runoff threshold of 12.7 mm/day, according to Wischmeier and Smith, 1978), the monthly rainfall, the monthly effective rainfall, and the yearly rainfall. In table 2-1 you can find these monthly averages.

Table 2-1 Rainfall and effective rainfall distribution throughout the year

Month	Rainfall (mm)	Percentage (%)	P_{eff} (mm)
Jan	244	23	205
Feb	201	19	163
Mar	190	18	152
Apr	44	4	30
May	10	1	4
Jun	7	1	2
Jul	6	1	1
Aug	7	1	3
Sep	3	0	1
Oct	26	2	18
Nov	109	10	81
Dec	203	19	165
Total	1051	100	824

Source: measurements of CALA station for the 1942-1988 period

2.1.3 Sources of soil texture data

For estimating the soil erodibility *K*, soil property information was used from a site of TAFA as collected by the Laboratory for Radio-isotopes in Antananarivo (Razafimbelo *et al.*, 2010). The site was located on LAT: 17°32'5" and LONG: 48°32'17", east of Lake Alaotra. Data from five *tanety* plots was used. The plots differ in the type of management (tillage, no tillage and fallow) and in the texture class (sandy clay loam and loam). The differences in rate of organic matter (OM) are very small (Table 2-2).

It would make no sense to separate these plots in the analysis, not only from a statistical point of view, but also because of the relatively low accuracy of the estimation methods. Therefore the average of these five plots was used in the analysis.

Table 2-2 Description of the five tanety plots

	Management	Texture class	Organic Matter (%) of upper 40 cm
Plot 1	Tillage	Sandy clay loam	1.5
Plot 2	Tillage	Sandy clay loam	1.4
Plot 3	No tillage	Loam	1.6
Plot 4	No tillage	Loam	1.5
Plot 5	Fallow	Loam	1.7

Source: Test fields of TAFA (Razafimbelo et al., 2010)

The soil texture was available in both the texture classification system of the United States Department of Agriculture (USDA) and another as shown in table 2-3 and table 2-4. The average from the five plots was used in the analysis.

Table 2-3 Soil texture description of the five *tanety* plots at TAFA test fields, according to an unknown classification system.

Soil type	Particle size(m)	Plot 1 (%)	Plot 2 (%)	Plot 3 (%)	Plot 4 (%)	Plot 5 (%)	Average (%)
Clay	0 - 0.002	26	22	15	14	17	19
Fine silt	0.002-0.02	3	8	29	26	25	18
Course silt	0.02-0.05	13	14	10	11	12	12
Fine sand	0.05-0.2	24	21	19	20	18	20
Coarse sand	0.2-2	34	35	27	30	28	31

Table 2-4 Soil texture description of the five *tanety* plots at TAFA according to USDA classification system

Soil type	Particle size (m)	Plot 1 (%)	Plot 2 (%)	Plot 3 (%)	Plot 4 (%)	Plot 5 (%)	Average (%)
Clay	0 - 0.002	26	22	15	14	17	19
Silt	0.002 - 0.05	16	22	39	37	37	30
Very fine sand	0.05 - 0.1	16	16	15	15	15	16
Sand	> 0.1	42	40	31	34	30	35

2.2 RUSLE - Erosivity factor R

2.2.1 Introduction

The *R*-factor in RUSLE is an erosivity index. It represents the erosive effect of raindrop impact on the soil. Bailly *et al.* (1976) calculated an *R*-value of 8153 $MJ \cdot mm.ha^{-1}h^{-1}$ for the region of Lake Alaotra. This was done in the 'Vallée Temoin' for the period of 1962-1968. This is the only reference found for *R* estimation in the region. Since the estimation equations have been updated, the *R*-value has been recalculated. Several estimation methods were applied to determine monthly *R*-factors. The methods and their necessary input data are summarized in table 2-5, and are described in more detail in the rest of this section. Hopefully this overview can be of use in other countries where the CA2AFRICA project is active.

Besides RUSLE's *R*-factor, there are many other erosivity indicators like Fournier's p^2/p index (1960), Hudson's KE > 1 index (1971), Lal's Aim index (1976), Smithen's $m.p_i/p$ Burst Factor (1981), and Onchev's P/St universal index (1985). The RUSLE science documentation (USDA-ARS *doc*, 2008) argues that only RUSLE's *R* should be used in the model, and not other erosivity indicators, as RUSLE's *R* is also used in the definition of *K*. These other erosivity indices can be used in RUSLE, but only after relating them mathematically to RUSLE's *R*, like has been done with a modified (Arnoldus, 1980) version of Fournier index (USDA-ARS *doc*, 2008) or with Smithen's Burst Factor (Smithen and Schulze, 1982).

Table 2-5 Overview of erosivity estimation methods and the required rainfall data

Method	Necessary rainfall data	Key variable	Other variables	Key publication
Original RUSLE (2.2.3)	Breakpoint rainfall data (intervals in which rainfall intensity is constant)	**I_{30} (mm/h)** Maximum 30-min intensity	**E (Mj/ha)** Rainfall energy which is a function of I_{30}	Renard *et al.,* 1997
Conversion from fixed interval rainfall (2.2.4)	**Hourly** rainfall amount (or smaller ΔT if available)	**$I_{30\,\Delta T}$ (mm/h)** Maximum 30-min intensity	**E (Mj/ha)** Rainfall energy which is a function of I_{30} **C** Conversion factor	Yin *et al.,* 2007
Regression equation of daily rainfall (2.2.5)	**Daily** rainfall amount exceeding 12,7 mm	**R_k (mm)** daily effective rainfall	***α,β,η*** and ***ω*** model coefficients, depending on climate	Yu and Rosewell , 1996
Modified index of Fournier (2.2.6)	**Monthly** and yearly rainfall amounts	**F (mm)** Modified index of fournier	**a_F** and ***b*** model coefficients, depending on climate	Arnoldus, 1980; Renard and Freimund, 1994
Regression equation of yearly rainfall (2.2.7)	**Yearly** rainfall amount	**P (mm)** Yearly rainfall amount	-	Roose, 1977

2.2.2 Variability of R in time

It is important that any method used to estimate erosivity from precipitation amount takes into account how the relationship between precipitation and intensity varies over time (USDA-ARS *doc*, 2008). Two storms of the same erosivity will lead to different rates of soil loss depending on the time of the year and the corresponding crop cover.

For estimation based on hourly and daily rainfall data there is already variability in time. However, for the yearly *R*-factor from literature (Bailly *et al.,* 1976), modified index of Fournier (Renard and Freimund, 1994), and yearly rainfall (Roose, 1977) , the lack of seasonality presents a problem for accurate estimation of soil loss. Therefore, the *R*-factor is assumed to be proportional with the precipitation. This means that for a month in which 12% of the yearly rain falls, it is assumed that the *R*-factor for that month is 12% of the yearly *R*-factor. This assumption is supported by Morgan (2005).

2.2.3 Original RUSLE method

After many decades of field and laboratory experimentation and data collection, it has become clear that the 'erosiveness' of a storm is very well described by the product of its energy *E* and its maximum 30-min intensity I_{30}, bringing together respectively the particle detachment and the transport capacity. The erosivity of a single event is best described with equation 2-1 (Wischmeier and Smith, 1978; Renard *et al.,* 1997)

$$R_s = EI_{30} \qquad \text{eq. 2-1}$$

in which R_s is the R-factor for a specific storm (MJ·mm·ha^{-1}h^{-1}), *E* represents the energy of the storm (MJ·ha^{-1}) and I_{30} is the maximum 30-min intensity (mm·h^{-1}). The R-factor in RUSLE is the average of the yearly sum of the storms EI_{30} values over a period of at least 20 years, expressed in

MJ·mm·ha^{-1}h^{-1}.yr^{-1}. Renard *et al.* (1997) suggest this threshold of 20 years to account for apparent cyclical rainfall patterns.
The rainfall energy E is a function of the rainfall intensity as proposed by Brown and Foster (1987) and modified by Renard *et al.* (1997). A storm is divided in m periods for which the rainfall intensity is considered constant. The rainfall energy is the sum of all products of the unit energy and the depth of water per period k. This is mathematically represented in equation 2-2

$$E = \sum_{k=1}^{m} 0.29\,[1 - 0.72\,exp(-0.082 i_k)] * (\Delta V)_k \qquad \text{eq. 2-2}$$

in which E is the rainfall energy (MJ·ha^{-1}), i_k is the rainfall intensity for the k^{th} period (mm·h^{-1}), and ΔV is the total depth of rainfall for the k^{th} period (mm). The fraction "$0.29[1 - 0.72\exp(-0.082 i_k)]$" is often referred to as the unit energy e_k.
Storms of less than 12.7 mm and separated from other storms by a period of 6 hours in which the total depth of rain is less than 1.25 mm, are not included in the computations because they add very little to total erosivity, while analysis may be costly and time-consuming (Renard *et al.,* 1997).

2.2.4 Conversion from fixed interval rainfall

Fixed interval rainfall data is far more available and much cheaper than the rainfall data required for the official RUSLE method. For the Lake Alaotra region, the BV-lac weather station provided 60 minutes interval rainfall data for the four year period of February 2006 to January 2010. The normal RUSLE methodology was applied to determine the storms' erosivity R_s and then corrected with a conversion factor c, as in equation 2-3.

$$R_s = EI_{30} \times \mathrm{c} \qquad \text{eq. 2-3}$$

Yin *et al.* (2006), confronted with the same discrepancy between available and necessary data, have determined conversion factors from fixed interval EI_{30} ($EI_{30\Delta t}$) to breakpoint EI_{30} (EI_{30bp}) for 5 sites throughout China at different Δt. For the regression relationships between EI_{30bp} values and $EI_{30\ \Delta t=60}$ they found an impressive r^2 of 0.93. This even becomes 0.99 if the fixed intervals are reduced to 15 minutes.
Yin *et al.* report conversion factors of $EI_{30\ \Delta t=60}$ to EI_{30bp} ranging from 1.568 for Anxi and 1.814 for Yuèxi. These two places correspond both to the climate of the Lake Alaotra region, but reciprocally differ the most. Therefore the average conversion factor of 1.73 was chosen.

To compensate for too wet or dry years in this relatively short four year period, a relation between the monthly erosivity R and the monthly effective rainfall P was determined in Microsoft Excel. This relation was then extrapolated to the 46 year period of available monthly effective rainfall data.

2.2.5 Regression equation of daily rainfall data

Yu and Rosewell (1996$_a$, 1996$_b$) developed a new erosivity model to estimate the monthly R-factor for New South Whales and for the whole of South Australia. It is based on the effective daily rainfall and five model coefficients. What is especially interesting for Madagascar and other CA2AFRICA countries, is the repetition of this calculation for 41 stations in the tropics of Australia by Yu (1998). Equation 2-4 is the mathematical representation

$$R_j = \alpha(1 + \eta\, cos(2\pi f_j - \omega)) \sum_{k=1}^{N} R_k^{\beta} \qquad \text{eq. 2-4}$$

in which R_j is the R-factor for month j and α, β, η and ω are model coefficients. R_k is the daily rainfall (mm) exceeding the threshold of 12.7 mm and f_j is the frequency of 1/12 to describe the seasonal variation. The coefficient ω is held constant at π/6 which implies that the relative rainfall erosivity will be highest for January.
The climate characteristics for the stations are very well described, making them suitable for accurate comparison with other tropical countries. They are described by their exact location, the

mean annual rainfall (MAR), a climate code (CC) and a rainfall seasonality index (RSI). CC is the number of wet months defined as having more than 100 mm of rain. Half a wet month is allocated if rainfall is 60-100 mm. RSI is calculated with equation 2-5

$$RSI = (S - W)/(S + W) \qquad \text{eq. 2-5}$$

in which *S* is the total amount of rainfall in summer (Nov-Apr) and *W* is the total amount of rainfall in winter (May-Oct).

2.2.6 Modified index of Fournier

The original index of Fournier (1960) is given by equation 2-6

$$F = p^2/P \qquad \text{eq. 2-6}$$

in which *p* is the rainfall (mm) of the month with the highest rainfall, and *P* is the average annual rainfall. Arnoldus (1980) found that this was poorly correlated to values of *R* for US data, which he explained with the illogical possibility of an increasing annual rainfall leading to a *decreasing* index of Fournier. He proposed the modified index of Fournier as in equation 2-7

$$F = \frac{\sum_{j=1}^{12} p_m^2}{P} \qquad \text{eq. 2-7}$$

in which *F* is the modified index of Fournier (mm), p_m is the average precipitation for month *j* (mm), *j* is an index for each month, and *P* is the annual precipitation (mm). With this equation the found *F* will always increase with increasing *P*.
The relation between the modified index of Fournier and RUSLE's *R*-factor is nonlinear, taking a form like equation 2-8 (USDA-ARS *doc,* 2008)

$$R = a_F \times F^b \qquad \text{eq. 2-8}$$

in which a_F and *b* are coefficients that vary with climate characteristics and can be determined by fitting the equation to observed data. For Marocco, Arnoldus (1980) used the relation given in equation 2-9 in which *R* is presumably in metric units ($MJ\cdot mm\cdot ha^{-1}h^{-1}$).

$$R = 0.264F^{1.5} \qquad \text{eq. 2-9}$$

Renard and Freimund derived equation 2-10 based on US data for *F* values of less than 55 mm,

$$R = 0.07397F^{1.847} \qquad \text{eq. 2-10}$$

while for *F* values above 55 mm equation 2-11 was best.

$$R = 95.77 - 6.081F + 0.4770F^2 \qquad \text{eq. 2-11}$$

For the composite of equation 2-10 and 2-11 (the last two) Renard and Freimund report errors in soil loss estimation of more than 50% for values of *R* around 8000 $MJ\cdot mm\cdot ha^{-1}h^{-1}$ (Appendix A).

2.2.7 Regression equation of yearly rainfall

Renard and Freimund (1994) have determined regression equations to relate the *R*-factor with the average annual rainfall. For annual rainfall of more than 850 $mm\cdot yr^{-1}$ they recommend equation 2-12

$$R = 587.8 - 1.219P + 0.004105P^2 \qquad \text{eq. 2-12}$$

in which *P* is the mean annual rainfall (mm).
It was found that *R*-factor estimation errors can have large effects on predicted soil loss, especially for the smaller values of *R*. The *R*-factor for Lake Alaotra presumably lies around 8100 MJ·mm·ha^{-1}h^{-1}.yr^{-1} (Bailly *et al.,* 1976). For this *R*-factor, Renard and Freimund (1994) found soil loss estimation errors of 10-15% for a composite of the two regression equations based on the average annual rainfall (Appendix A).

Roose (1977) has found another more simple relationship between annual rainfall data and the *R*-factor. A conversion factor from US customary units to SI units was added , see equation 2-13

$$R = [(0{,}5 \ \pm 0{,}05)P] * 17{,}02 \qquad \text{eq. 2-13}$$

in which *R* is the yearly erosivity factor (MJ·mm·ha^{-1}h^{-1}) and *P* is the average annual rainfall. It has been found valid for twenty stations in Ivory Coast, Burkina Faso, Senegal, Niger, Chad, Cameroun and Madagascar with an error of 5%. It was not accurate for stations in mountainous or coastal areas. The station of validation in Madagascar was Béfandriana (presumably North) which had an annual rainfall of 2030 mm. It was based on one year of measurements in 1971. What is attractive about this equation is the simple nature which allows for quick estimations of the range of *R*.

2.2.8 Discussion and method selection

The alternative methods described in this paper cannot give more than an estimation of *R*. The difference in the iso-erodent maps between Arnoldus (1980) and Roose (1977) illustrate the effect of the chosen method to the obtained R-factor. The graph in Appendix A illustrates the effect of the *R* on errors in soil loss estimation (Renard and Freimund, 1994).

Because of the high correlation found by Yin *et al.* (2006) for the estimation of EI_{30} with hourly rainfall measurements, this method is considered very accurate and useful where such data is available. The weak point in this method is that hourly data is not available everywhere. In the study area only four years of hourly measurements were available, making it necessary to extrapolate the results to a longer time span. Moreover, the conversion factor *c* is not easily determined. Although theoretically strong, this method based on hourly rainfall was not used for further calculation.
The method based on the modified index of Fournier is also theoretically correct and easily applicable with only monthly rainfall data. The weak point of this method lies in the equations that relate the modified index of Fournier F_m with the erosivity *R*. This relation should be known to obtain reliable results, but there is no indication that the relations found in literature for Morocco and the USA are valid in the study area. This makes the results at forehand questionable and not useful for soil loss estimation. For assessment of the relative impact of crop and management decisions it can however be used with care.

The method based on the yearly rainfall from Roose (1977) presents a range of possible erosivities. The limits of application (mountains, shore) have been explored in several studies. If the annual erosivity is transformed to monthly erosivity according to monthly precipitation, this method is very useful for a first assessment of erosivity, although it remains a rough estimate.

The method of Yu and Rosewell (1996_a) as applied in the tropics of Australia by Yu (1998) is considered to be a very useful method for estimating R in tropical regions where daily rainfall data is available. The variety and high number of stations in combination with the three climate descriptors CC, RSI and MAR allow for easy and accurate application of the model in other tropical regions like that of Lake Alaotra, Madagascar. This method was therefore selected for calculating the potential erosion for this study.

2.3 RUSLE - Erodibility factor K

2.3.1 Introduction

The soil erodibility factor *K* represents the influence of soil properties on the ease with which soil is eroded. For the region of Lake Alaotra the *K*-factor was not known from literature. Because of the time consuming and costly nature of adopting and maintaining a Unit Plot, the original method (section 2.3.3) was out of reach. Alternatively, the *K*-factor was estimated by its relation with soil characteristics. The erodibility estimation methods and their necessary data are presented in the overview table 2-6 and are described in more detail in the rest of this section.

It is important to remember that it is impossible to develop one universal soil erodibility equation. This is stressed by Mulengera and Payton (1999) and is also quite logical as different soils react differently on erosive storms. Approximation methods of empirical nature have been applied on and validated for different soils throughout the tropics and can thus provide an indication of *K*.

Table 2-6 Overview of erodibility estimation methods and the necessary input data

Method	**Key variable**	**Necessary data**	**Other variables**	**Key publication**
Original RUSLE method	**R (MJ·mm.ha^{-1}h^{-1})** Rainfall erosivity **A (ton·ha^{-1}yr^{-1})** Soil loss	Quantity of soil loss for Unit Plot conditions	-	Renard *et al*. (1997)
Soil nomograph version 1	**M** Soil texture variable	Percentage modified silt (0.002-0.1 mm) and percentage silt + sand (0.002-2 mm)	**OM (%)** Organic matter content **S (1-5) and P (1-6)** Structure and permeability class	Renard *et al*. (1997)
Soil nomograph version 2	**k_t** Soil texture variable	Percentage silt (0.002-0.05 mm), percentage very fine sand (0.05-0.1) OR percentage sand (0.05-2 mm), and percentage clay (≤ 0.002 mm)	**OM (%)** Organic matter content **S (1-5) and P (1-6)** Structure and Permeability class	USDA-ARS *doc* (2008)
Soil texture regression from world soils	**Dg** Geometric mean particle diameter	Soil texture data in whatever classification	-	Renard *et al.* (1997)
Soil texture regression from tropical soils	**M_n or M_o** Soil texture parameters	Percentage silt (0.05-0.002 mm), percentage sand (0.2-0.10 mm) and percentage very fine sand (0.05-0.1 mm).	-	Mulengera and Payton (1999)
Soil texture regression Hawaï (Appendix B)	**X_1** Unstable aggregates **X_2-X_5** Soil texture parameters	Percentage silt (0.002-0.01 mm), Percentage silt (0.002-0.01 mm), percentage sand (0.2-0.10 mm) and percentage very fine sand (0.05-0.1 mm).	-	Dangler and El-Swaiffy (1976)

2.3.2 Variability of K in time

The erodibility of soils is not constant but variable in time. This behavior may be understood from its dynamic definition in terms of soil loss rate (A_U) per unit of rainfall erosivity (EI_{30}) that results from rewriting equation 2-15. A unit of erosivity will, for example, cause more erosion to a warm soil than to the same soil when it is cold. In RUSLE, the daily soil erodibility variability throughout the year is assumed to vary only with temperature and precipitation (RUSLE *doc.*, 2008). This empirical relation is expressed in equation 2-14

$$K_j/K_n = 0.592 + 0.732(P_j/P_s) - 0.324(T_j/T_s) \qquad \text{eq. 2-14}$$

in which K_j/K_n is the ratio of the average daily soil erodibility factor value for the j^{th} day (K_j) and the yearly soil erodibility value (K_n), P_j/P_s is the ratio of the average daily precipitation (P_j) and the average precipitation (P_s) for the whole RUSLE summer period, and T_j/T_s is the ratio of the average daily temperature for the j^{th} day (T_s) and the average temperature (T_s) for the whole RUSLE summer period. Units for temperature and precipitation can be both American and 'normal' SI units as they are neutralized by the quotient.

The RUSLE summer period is defined for temporal soil erodibility purposes as the period when average daily temperature exceeds 40°F (≈4.5 °C) . For our study area this implies a constant summer.

2.3.3 Original RUSLE method

Soil erodibility is the sensivity of a soil to the combined effect of soil detachment and transport by raindrop impact and surface flow. It is an empirical measure experimentally determined, which means that it is not *directly* related to specific erosion processes and it is not a soil property like texture (USDA-ARS *ref*, 2008).

The *K*-factor is defined by the amount of erosion per unit rainfall erosivity EI_{30} for Unit Plot conditions like in equation 2-15.

$$A_U = EI_{30}K \qquad \text{eq. 2-15}$$

In this equation A_U is the amount of erosion (ton·ha^{-1}yr^{-1}) for Unit Plot conditions, EI_{30} is the rainfall erosivity (MJ·mm·ha^{-1}h^{-1}) and K is the soil erodibility (ton·h·MJ^{-1}mm^{-1}). A Unit Plot is 22.1 meters long, has a 9% slope on which no crop is grown and which is tilled up and down hill (Wischmeier and Smith, 1978).

2.3.4 Soil nomograph version 1 and 2

The soil erodibility nomograph was developed by Wischmeier *et al.* for the USLE in 1971. It is mostly known as the fancy multigraphical figure in which the erodibility can be graphically determined (figure 2-2).

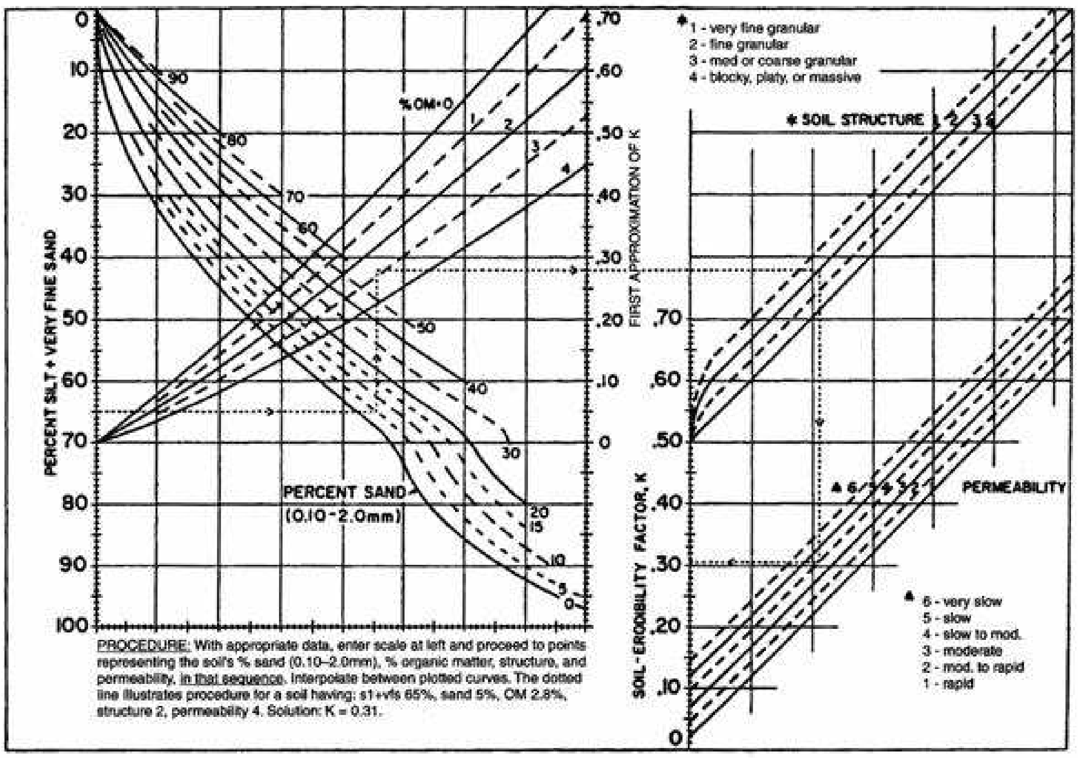

Figure 2-2 Soil erodibility nomograph. Source: Wischmeier et al. (1971)

There are two different mathematical representations of this nomograph. The first (version 1) can be found in an article of Renard *et al.* (1997) as showed in equation 2-16.

$$K = \frac{[2.1\,.10^{-4}(12-OM)M^{1.14}+3.25(s-2)+2.5(p-3)]}{100} * 0.1317 \qquad \text{eq. 2-16}$$

In this equation the soil erodibility *K* is given in SI units as a function of the percentage organic matter OM, the structure class *s* and the permeability class *p*. Soil texture is represented as *M*, which is the product of the percent modified silt (0.002-0.1 mm) and the percent silt + sand (0.002-2 mm).
The structure classes are defined as in table 2-7 and the permeability classes are defined as in table 2-8.

Table 2-7 Size and shape classes of soil structure S_s

Size classes (S_s)	Shape of the structure			
	Platy (mm)	Prismatic and Columnar (mm)	Blocky (mm)	Granular (mm)
1	< 1	< 10	< 5	< 1
2	1 – 2	10 – 20	5 – 10	1 – 2
3	2 – 5	20 – 50	10 – 20	2 – 5
4	5 – 10	50 – 100	20 – 50	5 – 10
5	> 10	> 100	> 50	> 10

Source: USDA soil survey manual (1993)

Table 2-8 Permeability classes as input for permeability sub factor

Permeability class	Description	Definition (mm/h)
1	Rapid	> 127
2	Moderate to rapid	63.6 – 127
3	Moderate	20 – 63.6
4	Slow to moderate	5 – 20
5	Slow	1 – 5
6	Very slow	< 1

Source: Whischmeier et al. (1971)

The second mathematical representation of this nomograph (version 2) can be found in the RUSLE Science documentation concept and is given in equation 2-17

$$K = \left(k_t k_o + k_s + k_p\right)/100 \qquad \text{eq. 2-17}$$

in which k_t is the texture sub factor, k_o is the organic matter sub factor, k_s is the soil structure sub factor and k_p is the soil profile permeability sub factor. We will have a look at all these factors.

First, if the portion of silt plus the portion of very fine sand is lower than 68%, the texture sub factor is described by equation 2-18

$$k_t = 2.1[\frac{\left(P_{sl}+P_{vfs}\right)(100-P_{cl})^{1.14}}{10000} \qquad \text{eq. 2-18}$$

in which P_{sl} is the percentage silt (0.002-0.05 mm), P_{vfs} is the percentage very fine (0.05-0.1 mm) and P_{cl} is the percentage clay (≤ 0.002 mm).

If the percentage very fine sand P_{vfs} has not been measured, it can be calculated from the percentage sand P_{sd} (0.05-2 mm) as in equation 2-19.

$$P_{vfs} = (0.74 - 0.62P_{sd}/100)P_{sd} \qquad \text{eq. 2-19}$$

The organic matter sub factor is calculated as in equation 2-20

$$k_o = (12 - OM) \qquad \text{eq. 2-20}$$

in which OM is the percent inherent soil organic matter. Inherent organic matter is the organic matter content of the soil in Unit Plot conditions.
The soil structure sub factor is a function of structure class, related as in equation 2-21.

$$k_s = 3.25(S_s - 2) \qquad \text{if}(k_t k_o + k_s) \geq 7$$

$$k_t k_o + k_s = 7 \qquad \text{if}(k_t k_o + k_s) < 7 \qquad \text{eq. 2-21}$$

In this equation S_s represents the soil structure class. The structure class depend on the structure shape and size as is shown in table 2-7.
Finally, the permeability sub factor is a function of the permeability class *P* as in equation 2-22.

$$k_p = 2.5(P_r - 3) \qquad \text{eq. 2-22}$$

Here P_r is one of the six permeability classes ranging from '1-rapid' (very low runoff potential) to '6-very slow' (very high runoff potential) as shown in table 2-8.

2.3.5 Soil texture regression from world soils

Renard *et al.* (1997) have developed a regression equation for estimating the erodibility based on global published data from 225 soils. This resulting relationship (R^2 0.983), which is based on the geometric mean particle diameter D_g (mm), is shown in equation 2-23.

$$K = 0.1317 * 7.594\left\{0.0034 + 0.04\exp\left[-\frac{1}{2}\left(\frac{\log(D_g)+1.659}{0.7101}\right)^2\right\}\right. \qquad \text{eq. 2-23}$$

Here the erodibility factor K is given in SI units of ton·h·MJ^{-1}mm^{-1}, and D_g (mm) is defined as in equation 2-24

$$D_g = \exp\left(0.01 \sum f_i \ln m_i\right) \qquad \text{eq. 2-24}$$

where f_i is the primary particle size fraction in percent and m_i is the arithmetic mean of the particle size limits of that size. It is mainly useful when available soil texture classifications differ from the required classification.

2.3.6 Soil texture regression from tropical soils

Mulengera and Payton (1999) have developed some equations for erodibility estimation for tropical soils. They defined six soil parameters and searched empirically for statistical correlation with erodibility. Surprisingly, they found that organic matter content and structure code class were not significantly related with erodibility. There were two texture parameters that had a quite good relation to erodibility, called M_n and M. To prevent confusion with the texture parameter M from the nomgraph version 1, Mulengera and Payton's M will be called M_o. They are defined in equation 2-25.

$$M_n = S_i(S_i + S_a) \qquad \text{eq. 2-25}$$

$$M_o = \left(S_i + S_{vfs}\right)\left(S_i + S_{vfs} + S_a\right) \qquad \text{eq. 2-26}$$

In this definition, S_i is the percentage silt (0.05 - 0.002 mm), S_a is the percentage sand (0.2 - 0.10 mm) and S_{vfs} is the percentage very fine sand (0.05 - 0.1 mm).
They relate to the erodibility K as in, respectively, equation 2-26 and 2-27

$$K = 1.333 \times 10^{-4} + 2.459 \times 10^{-5} \times M_n \qquad \text{eq. 2-27}$$

$$K = 1.82247 * 10^{-5} M_o + 0.0045 P_e - 0.0097 \qquad \text{eq. 2-28}$$

where the soil erodibility K is given in SI units (ton·h·Mj^{-1}mm^{-1}) and P_e is the permeability class as in table 2-8.

2.3.7 Discussion and method selection

The highly empirical nature of the erodibility K has the logical implication that estimation measures are very different, not only in terms of the final equation, but also in the principle approach.
The RUSLE methodologies are to incorporate all elements that in theory could influence the rate of soil loss, including permeability, soil structure, aggregate stability and soil texture. This results in very complex calculation procedures and a lot of necessary data. The relation between *OM* and soil loss, for example, is not linear and may differ per geographical or climatologic area.
The regression from tropical storms, however, assumes on the basis of empirical findings that a texture parameter is sufficient to estimate the erodibility of a soil in the tropics.
The absence of experimental data or an erodibility value for the study area in literature makes it impossible for this study to compare several estimation methods and select the "best". The criteria to *a priori* select a best option is normally a method´s match between available and necessary data. But because of the highly empirical nature, this cannot be done.

Therefore, in order to obtain an erodibility value *K* for further calculation, the average of the four methods is taken.

The calculation of the temporal variability is not likely to be very accurate because equation 2-14 was derived from a specific area in the USA, which could only accidentally correspond to the tropical conditions of the Lake Alaotra region. The continuous summer period for the study area in the model terms also suggests a primary applicability in temperate climates. Moreover, the temporal variability of erodibility has not been studied much, so references or studies in similar situations are lacking. Because of this notion of uncertainty, the temporal variability will be presented, but only the annual average will be used in calculation of the actual soil loss.

2.4 RUSLE - Slope factor LS

2.4.1 Introduction

The factor *LS* is a combination of the effect of slope length *L* and slope steepness *S* on soil loss. The *LS* factor is always relative to the Unit Plot conditions where the slope is 9% and the slope length is 22.13 meters.
There are several methods to determine the slope factor *LS*. The more traditional methods are the nomographs of Wischmeier and Smith (1978) and the equation of Roose (1977). An often used method is that of Arnoldus (1980), see equation 2-29. At catchment scale the most often used method is based on a Digital Elevation Model in a Geographical Information System environment.

For a study at the field level, like this present study, it is sufficient to estimate the scope of likely *LS* values in the region and how it impacts the potential erosion, rather than exactly determining the *LS* factor. The often used method of Arnoldus (1980) was selected to estimate *LS* for three scenario's.

2.4.2 Applied method

The way in which the slope length and slope steepness effect soil loss is described by Arnoldus (1980) as in equation 2-29

$$LS = \left(\frac{\lambda}{22.13}\right)^n (0.0065 + 0.045\,S + 0.0065S^2) \qquad \text{eq. 2-29}$$

where λ is the slope length (m), exponent *n* is a changing variable related to the slope steepness, and *S* is the slope steepness (%).
Measurements in the field and samples in Google Earth provided for field length and steepness data to which equation 2-29 could be applied. The combination of the length and steepness measurements have been used to construct three realistic scenario's of *LS* for the study area.

2.5 RUSLE – Cover management factor C

2.5.1 Introduction

Two principles of Conservation Agriculture are considered in the *C*-factor. These are the crop rotations and the maintenance of a (semi-)permanent organic soil cover consisting of a growing crop or dead mulch of crop residues. The minimum or zero tillage is considered in the *P*-factor.

The crop and management factor *C* reflects the effectiveness of cropping and management practices, like mulching, to reduce the rate of soil loss. Different sets of crops and management practices can be compared, taking into account the different growing stages and the development of the canopy cover in relation to erosive rainfall. The result is represented as a value between 0 and 1, where 1 is the reference soil loss for Unit Plot conditions and 0 means 'no erosion' (Stone and Hilborn, 2000).

For the Lake Alaotra region there does exist some literature about soil erosion under different crops (Bouchier, 1959; Roche, 1954; Roche and Dubois, 1959; Bailly *et al.*, 1976), although expert interviews have made clear that the crops and rotations have changed over time. The recently proposed CA systems are certainly different, but can still be compared with forage plots of 100% cover, Unit Plots and other historical rotations.

The original RUSLE methodology as briefly described in section 2.5.2 requires a lot of data which is readily available in the many databases for the USA, but seems rather far-fetched for application to the agricultural and climatic conditions in the tropics (Mulengera and Payton, 1999).
In section 2.5.3, two common methods that could not be used for this study are briefly described. These methods may be useful in other CA2AFRICA countries. These methods are based on Remote Sensing or the Food and Agriculture Organization (FAO) crop factor K_c. In section 2.5.4, the method used to estimate RUSLE's *C*-factor for this study in the region of Lake Alaotra is explained.

2.5.2 Original RUSLE method

The original RUSLE method is based on seven sub-factors as in equation 2-30

$$C = c_c \times g_c \times s_r \times r_h \times s_b \times s_c \times s_m \qquad \text{eq. 2-30}$$

where *C* is the cover-management, c_c is the canopy cover, g_c is the ground (surface) cover, s_r is the soil surface roughness, r_h is the ridge height, s_b is the daily soil biomass, s_c is the soil consolidation, and s_m is the antecedent soil moisture. These factors and their meaning are described in more detail In the RUSLE User's reference guide (USDA-ARS *guide*, 2008).
All these factors should be determined on a daily basis, with the help of dozens of empirical parameters and equations. The factors are highly related with each other. The effect of mulch, for example, is represented in the ground surface cover g_c, the soil surface roughness s_r and in the soil biomass s_b, making it difficult to assess the impact of a certain rate of mulching.

2.5.3 About C-factor estimation

Estimations of RUSLE's *C*-factor are always made on the basis of crop cover, which in its turn can be estimated in different ways. An increasing crop cover leads to a decreasing *C*-factor and thus a decreasing rate of soil loss. It must be noticed that the canopy cover is not a perfect indicator for the effect of crops and management on soil loss. Canopy cover reduces the rainfall energy from impact, but it does not necessarily influence the amount or velocity of runoff. This depends more on the ground cover and roughness. The big advantage compared to the original method is of course the ease of application, especially on the greater scale.

The first way in which the crop cover is often estimated is through vegetation indices that are derived from Remote Sensing images. Most often the Normalized Difference Vegetation Index (NDVI) is used as vegetation index, which allows to transform the reflectance patterns of green vegetation into a percentage of cover (Jensen, 2000) as in equation 2-31

$$NDVI = (NIR - red)/(NIR + red) \qquad \text{eq. 2-31}$$

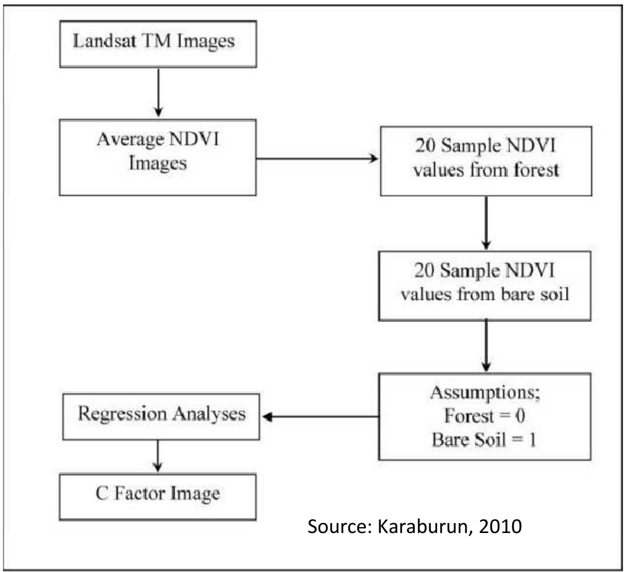

Figure 2-3 Common procedure of determining crop cover C through Remote Sensing images

where NIR is the Near Infra Red part of the spectrum and red is, logically, the red part of the spectrum. The process for *C*-factor estimation is schematically represented in figure 2-3.

Recently, Zhongming *et al.* (2010) have developed a stratified vegetation cover *(C_s)* index, which considers the canopy cover and vegetation structure of different strata instead of just the upper canopy cover. This method was not applied because there were simply no useful Landsat images.

Another method that can be used to estimate the development of canopy cover is with the FAO crop coefficients (Allan *et al.*, 1998). The fraction of canopy cover at each growing stage of the crop is estimated as in equation 2-32

$$Fc = \left(\frac{K_{cb} - Kc_{min}}{Kc_{max} - Kc_{min}} \right)^{(1+0.5h)} \qquad \text{eq. 2-32}$$

where *Fc* is the effective fraction of soil surface covered by vegetation, K_{cb} is the value for the basal crop coefficient for the particular day or period, Kc_{min} is the minimum *Kc* for dry bare soil with no ground cover, Kc_{max} is the maximum *Kc* and *h* is the mean plant height (m). Because these crop coefficients were determined in a sub-humid climate with moderate wind speed, they need to be adapted. This method was not applied for two reasons: 1) The crop coefficients of Stylosanthes, pluvial rice and weeds were not available; and more in general 2) The exact and more complicated nature of the method does not match the accuracy of available data for the study area.

2.5.4 Applied method

The *C*-factor was divided into a crop component C_{crop} and a mulch component C_{mulch} for every month *i* as in equation 2-33, corresponding to the last two principles of Conservation Agriculture. The mulch component was estimated with the Mulch Factor, and both components were based on cover estimations of several experts and extension workers. The crop canopy cover was defined as the sum of all vegetation present on the field at a certain time, with a maximum of 100%. The mulch cover was considered per mulch type which allows the total mulch cover to exceed 100%. Although this will not happen very often, it will be considered in the analysis.

$$C_i = C_{c_i} \times C_{m_i} \quad \text{eq. 2-33}$$

The *C*-factor and its components are calculated on a monthly basis and on a yearly basis. To evaluate the extent to which the *C* coincides with the erosivity, the monthly calculation is weighted with the monthly erosivity *R*.

Crop component of C-factor

For monthly calculation of the crop component C_c, the crop cover is related to the canopy cover as in equation 2-34

$$C_{c_i} = (1 - F_{c_i}) \quad \text{eq. 2-34}$$

in which C_{ci} is the crop component of the *C*-factor value for month *i* and Fc_i is the fraction of canopy cover in the same month. In reality the relation between canopy cover and the C-factor is not that simple, but for the available data it is the best estimation.

Calculating a yearly *C*-factor was done with equation 2-35 in which the crop component is corrected with the fraction of total erosivity P_i. This allows the *C* to vary according to erosivity, even when the canopy cover stays constant.

$$C_c = \sum_{i=1}^{12} (1 - F_{c_i}) P_i \quad \text{eq. 2-35}$$

Two different Conservation Agriculture cropping systems were compared with a traditional system. The cropping system 'Traditional' was a two year rotation of upland rice alternated with Maize. The cropping systems 'Stylo 1' and 'Stylo 2' were four-year rotations with the leguminous *Stylosanthes Guianensi* as cover crop, for either the situation on a test fields (Stylo 1) or on farmers' fields (Stylo 2). The cropping system 'Dolichos' was a two-year rotation as Traditional, but with the leguminous *Dolichos Lablab* as cover crop. According to the extension worker, the upland rice variations used in the region were Sebota 68, 403 and B22.

The different cropping systems as also described in section 1.3, are presented in a cropping calendar (figure 2-4), and the development of crop and mulch cover for the four cropping systems is given in figure 3-4 to 3-7.

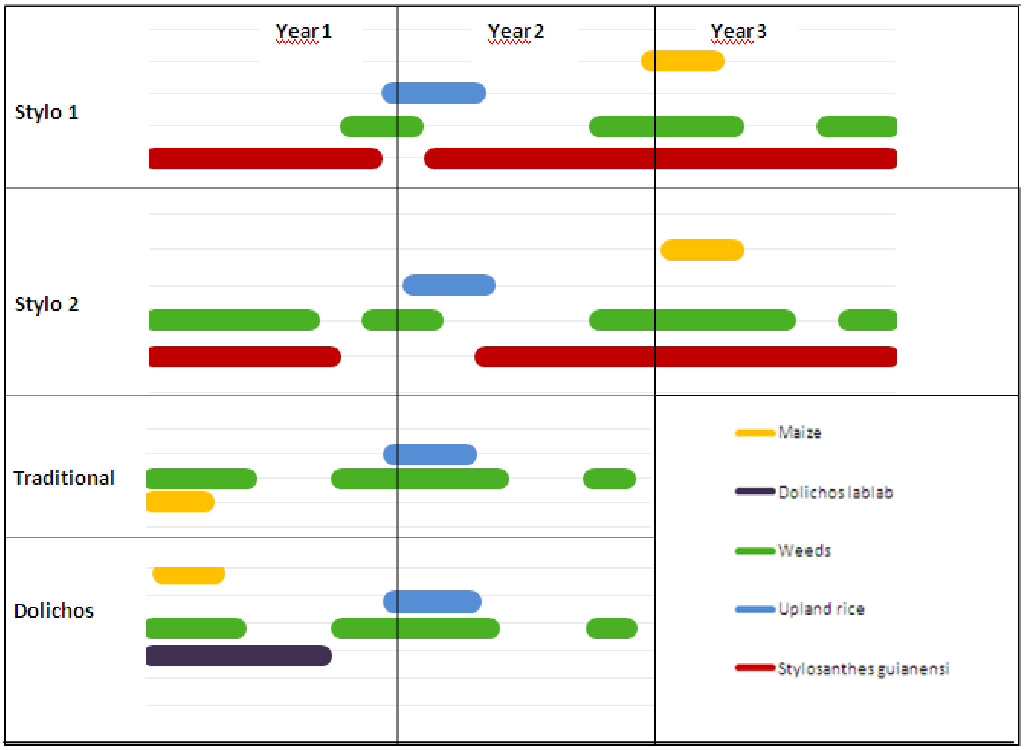

Figure 2-4 Cropping calendar for the four considered Cropping systems, based on extension workers

Mulch component of C-factor

Mulch is very well capable of reducing runoff and soil loss. This effect of mulch on soil loss changes with the percentage of cover, the type of mulch, plot length, slope gradient and soil type (Smets et al., 2008). The non-linear relation between soil loss and mulch cover is very well captured in the exponential Mulch Factor (MF) as given in equation 2-36.

$$C_{m_i} = MF_i = e^{-b\,F_{m\,i}} \qquad \text{eq. 2-36}$$

In this Mulch Factor the exponent *b* reflects the effectiveness of the mulch type to reduce soil erosion, usually ranging from 0.01 to 0.1, and F_m is the fraction of mulch cover for every month *i*. Smets *et al.* (2008) present an overview of 41 studies investigating the effects of mulch cover on soil erosion by water. From this overview four *b*-values were selected for the four mulch types. The *b*-value of stylo was thought to correspond to cut grasses, the *b*-value of rice was thought to correspond to straw, the *b*-value estimation of dolichos was based on leaves, soybean and sorghum, and the *b*-value of maize was present in the table as maize.

A yearly *C*-factor can be based on the monthly mulch component that is weighted for the monthly fraction of total erosivity P_i as in equation 2-37. The mulch component of the *C*-factor is calculated with the Mulch Factor *MF* and the fraction of total erosivity $R_{i.}$

$$C_m = \sum_{i=1}^{12} MF \times R_i \qquad \text{eq. 2-37}$$

The easiest way, but maybe not the most accurate way of calculating the mulch component is by applying equation 2-36 where *i* is simply one year instead of one month.

2.6 RUSLE - Support practices P

2.6.1 Introduction

The *P* factor in RUSLE represents the effect of a series of support practices on soil loss, relative to a regime of up and down slope tillage. These support practices may include contour tillage, strip cropping, terracing and vegetation strips. The contour tillage and contour cultivation modifies the flow patterns and reduces the detachment and transport capacity. The strip cropping and vegetation strips reduce runoff and trap sediments. Terracing is primarily considered in the slope length and steepness *LS* but is also influencing the *P* factor as the terraces have different shapes and therefore the terrace shape breaks the slope into shorter slope lengths.

Under Unit Plot conditions the support practices factor *P* is 1 and under influence of very progressive conservation measures this can be reduced to values close to 0. The effect of a support practice on the rate of soil loss depends on the slope grade.

2.6.2 Applied method

The way in which support practices relate to the soil loss are extensively described in the RUSLE science documentation (USDA-ARS *doc,* 2008). Renard *et al.* (1997) present tables with common support practices and the corresponding *P* values. Most *P* values refer to mechanical ways of tillage or the mechanical introduction and maintenance of support practices. For tropical conditions, however, not much is known about values of *P*.

The *P* factor is sometimes called the 'most uncertain RUSLE factor' (Renard *et al.*, 1997). Some authors set the *P* value to 1 in absence of data (Kouli *et al.,* 2009). However, for this study it was thought that an estimation of the author would be more reliable than ignoring the *P* value. This is a precarious attempt because of the multiplication structure of RUSLE (equation 1-1) that attributes as much weight to the *P* factor as to the other factors that have been calculated more carefully. This can be seen as a weakness of the RUSLE model to which author estimation is the best response until validation is possible.

3 Results and discussion

In this chapter the results are divided into the potential erosion (3.1) as related to the first objective, and the actual erosion (3.2) as related to the second objective. The erosivity *R,* erodibility *K* and crop cover *C* will have both a yearly and a monthly result. The slope length and steepness *LS* and support practices *P* only have yearly values.

3.1 Potential soil loss

The potential soil loss is reflecting a region's susceptibility to erosion. It was estimated by multiplying the three RUSLE factors erosivity *R*, erodibility *K* and Slope length and steepness *LS*. First the individual outcome of these factors are given in 3.1.1 to 3.1.3. The multiplication of the three and therefore the estimation of potential soil loss is given in 3.1.4.

3.1.1 Erosivity factor R

The erosivity values resulting from the four estimation methods and their variability in time are presented in figure 3-2. The table presenting the same data is given in Appendix C. We continue with other (sub) results and a discussion on the results below.

Conversion from hourly rainfall

Based on the hourly rainfall data, the erosivity R has been calculated like explained in 2.2.4. The resulting yearly erosivity R was 7595 in SI units. The variability throughout the year is shown in figure 3-2 as 'hourly rainfall' . To account for relative wet or relative dry years in the 48 month period from February 2006 to January 2010, two relations were determined.

- The relation between the monthly effective rainfall P_{eff} and the monthly erosivity *R* resulted in a R^2 of 0,937 with *n*=48, which is shown in figure 3-1.
- The relation between the monthly rainfall *P* and the monthly erosivity *R* resulted in a R^2 of 0,912 and was not used.

After extrapolation to monthly effective rainfall data of the 46 year period of 1942 to 1988, the yearly erosivity *R* was 5605 in SI units. The variability throughout the year is shown in figure 3-2 as 'hourly rainfall (extrapolation)'.

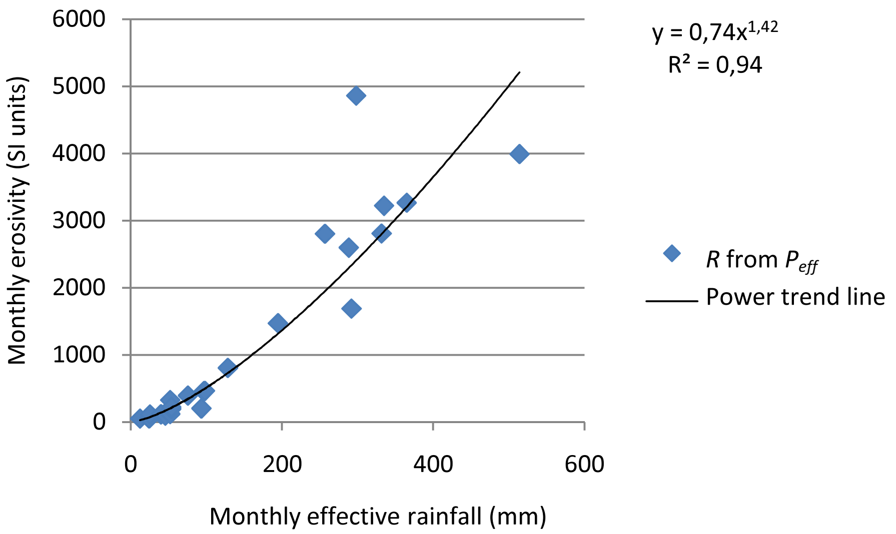

Figure 3-1 Relation between monthly erosivity and monthly effective rainfall, based on the 48 months of hourly erosivity calculation

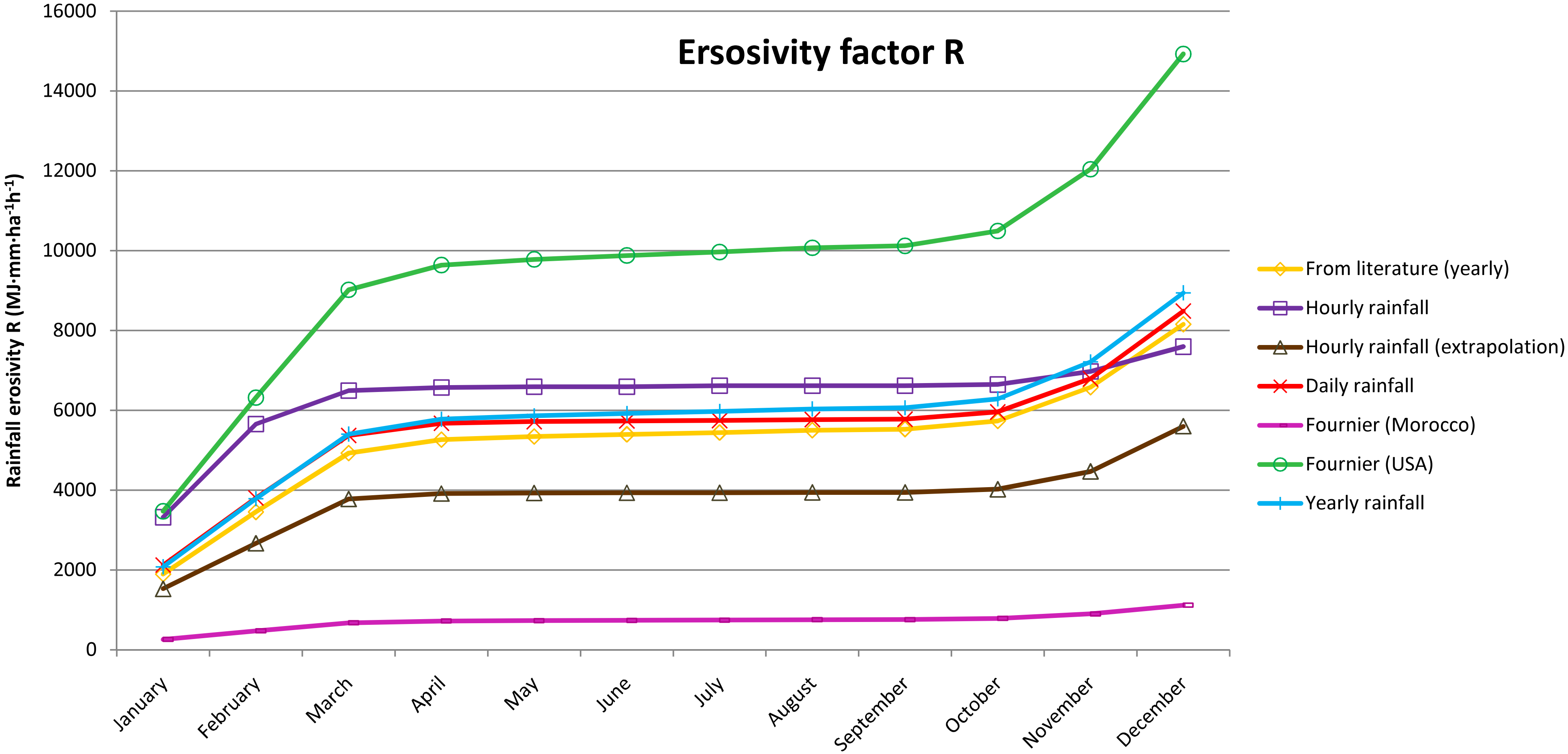

Figure 3-2 Cumulative erosivity *R* outcomes for different estimation methods

Regression from daily rainfall
For using the erosivity model of Yu and Rosewell (1996_a) it was necessary to determine the values of the climate specific model coefficients. This was done by selecting one of the weather stations in the tropics of Australia that corresponds best with the situation in the study area according to the definitions described in 2.3.5.

The Lake Alaotra climate has a Climate Code of 5, a Rainfall Seasonality Index of 0.90 and a Mean Annual Rainfall of 985 mm. This matches best with station 14400 called *Maningrida* in the tropics of Australia, having a CC of 5, a RSI of 0,97 and a MAR of 939 (Yu, 1998). The corresponding model coefficients are: α = 7,61, β = 1±0,05 and η = 0,280±0,135.

The resulting yearly erosivity *R* ranges from 5623 to 11352 with an average of 8487, all in SI units. The variability throughout the year is shown for the average of the two in figure 3-2 as 'daily rainfall'.

Modified index of Fournier
Based on the 1942 to 1988 monthly rainfall data, the modified index of Fournier was calculated according to equation 2-7 as 183 mm. Transforming this erosivity index into RUSLE's *R* was therefore done with equation 2-9 and equation 2-11 resulting in a yearly erosivity of 1114 and 14927 in SI units. The variability throughout the year is shown in figure 3-2 under the name 'Fournier Morocco' and 'Fournier USA'. The big difference in the results is not surprising, it corresponds with the discussion about the method (section 2.2.8). More research is needed to relate the index of Fournier to erosivity in this specific study area.

Regression from yearly rainfall
The simple equation for estimation the yearly erosivity *R* on the basis of yearly precipitation resulted in yearly *R* values between 8048 and 9837 in SI units. The average of the two is 8944 in SI units. The variability throughout the year of the average is shown in figure 3-2 as 'yearly rainfall'.

Discussion
Following the discussion based on the methodology, the calculation method from daily rainfall would be the most reliable. Results confirm this *a priori* statement as the outcome is really close to the erosivity value from literature. Method nor results have raised questions on the suitability and accuracy of this model, although a validation with contemporary erosivity would be the only way to prove this.
The calculation based on the hourly rainfall is definitely in the most sophisticated and accurate way. The extrapolation relation from the four year period to the necessary 20 years or more (in our case 46 years) proved to be very accurate (R=0.94). However, the determination of a proper conversion factor *c* is still to be done. In this case the conversion factor *c* should be higher than the values determined for the considered ´comparable´ regions in China.
As expected, the index of Fournier provides very disputable results. An empirical equation to relate the modified index of Fournier of 183 mm to an erosivity value should be determined in order to use this indicator of erosivity.
Surprisingly, the regression from yearly rainfall results in a range of values that correspond highly to the erosivity found in literature. This is by far the easiest method, and if this yearly value is transformed into monthly values according to rainfall, monthly erosivity values could very well be used. However, it should be considered whether this applies to all CA2AFRICA countries.

3.1.2 Erodibility factor K

An overview of the erodibility values resulting from the four estimation methods and their variability in time is given in figure 3-3. The table presenting the yearly values is given below (Table 3-1), together with other results and a discussion.

Nomograph version 1 and 2

The necessary input for the RUSLE nomograph is the organic matter content, the soil structure class, the permeability class and soil texture. For both representations of the nomograph, version 1 and version 2, the average *OM* in the top 40 cm of the soil ranged between 1.4 and 1.7%. The soil structure consisted of granular particles of about 2 mm, corresponding with a structure code 2. The permeability was classified as 'moderate', class 3, with infiltration between 20 and 63.6 mm/h.

For the first representation of this nomograph according to Renard *et al*. (1997) the texture class *M* had values of 1848 for plot 1 to 3770 for plot 3. The average *M* was 3042. With equation 2-16 an average annual erodibility *K* of 0.027 ton·h·$MJ^{-1}mm^{-1}$ was calculated (Table 3-1) .

For the second representation of this nomograph according to the RUSLE science documentation (USDA-ARS *doc*, 2008) the texture parameter k_t ranged from 1.46 for plot 1 to 3.13 for plot 3 (Table 3-1). The resulting average annual erodibility *K* was 0.035 ton·h·$MJ^{-1}mm^{-1}$.

The variability of these erodibilities in time is given in figure 3-3 as, respectively, 'Nomograph 1' and 'Nomograph 2'.

Regression from world soils

The estimation of the soils erodibility *K* with the regression equation from 220 world soils according to Renard *et al.* (1997) makes use of the geometric mean particle diameter D_g. D_g ranged from 5.8 $.10^{-2}$ mm for plot 1 to 6.3.10^{-2} mm for plot 2. The resulting erodibility ranged from 0,036 for plot 2 to 0.040 for plot 3 and plot 5 with an average of 0.038 ton·h·$MJ^{-1}mm^{-1}$. The temporal variability of this average value is shown in figure 3-3 as 'World soils'.

Table 3-1 Yearly *K*-factors for the 5 plots as a result of different estimation methods

	***K*-factor (SI units of ton·h·$MJ^{-1}mm^{-1}$)**					
Method	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Average
2.2B Nomograph (version 1)	0.015	0.020	0.035	0.034	0.032	0.027
2.2A Nomograph (version 2)	0.020	0.026	0.043	0.043	0.041	0.035
2.3 Regression from world soils	0.037	0.036	0.040	0.038	0.040	0.038
2.4 Regression from tropical soils with $\mathbf{M_n}$	0.023	0.033	0.067	0.064	0.062	0.050
2.4 Regression from tropical soils with $\mathbf{M_o}$	0.047	0.044	0.074	0.072	0.070	0.061
						0.038

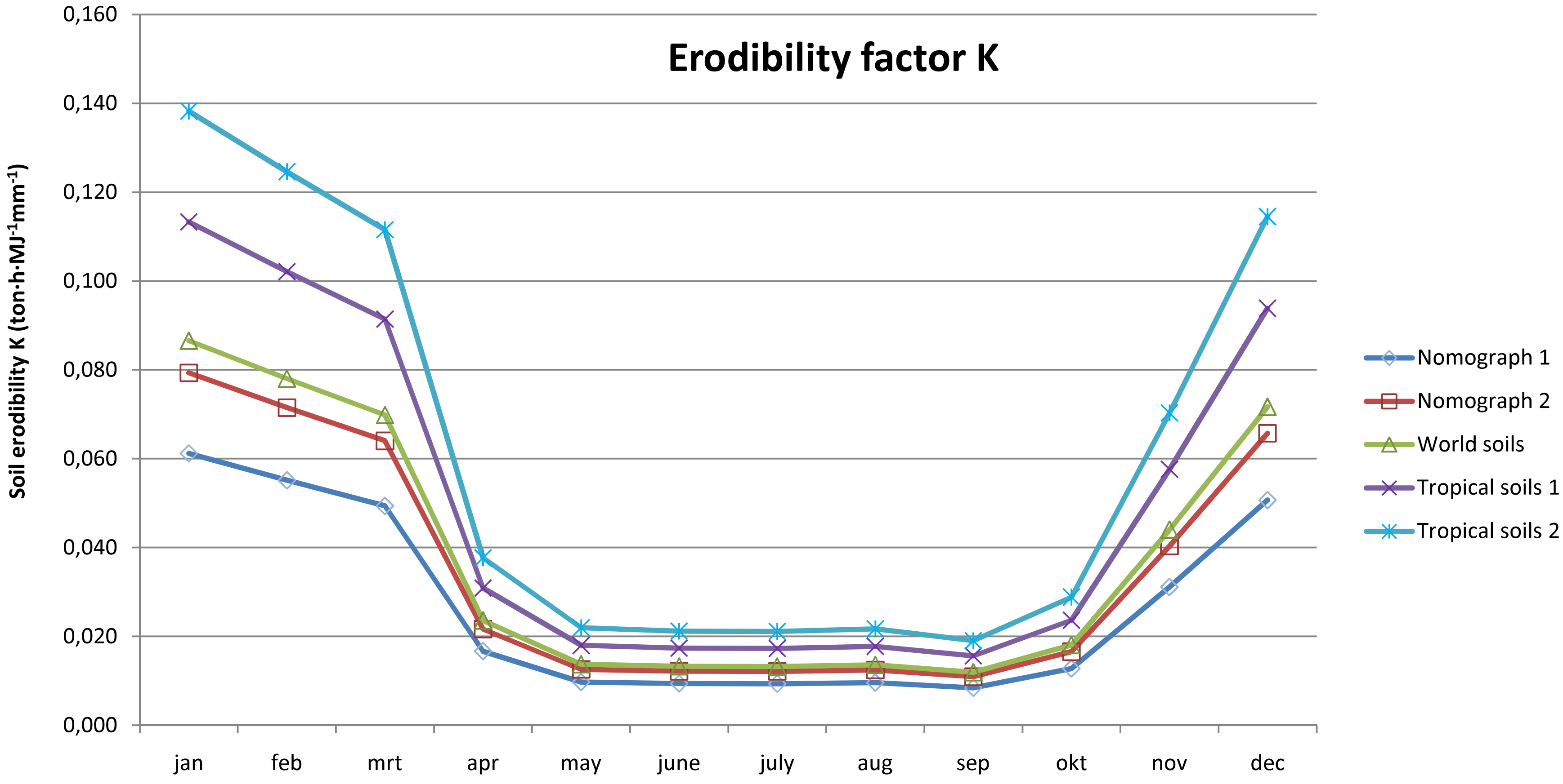

Figure 3-3 Temporal variability of soil erodibility *K* for five estimation methods

Regression from tropical soils

The selected regression equations from tropical soils according to Mulengera and Payton (1999) are only based on the soil texture parameters M_n and M_o. The texture parameter M_n ranged from 937 for plot 1 to 2729 for plot 3, resulting in erodibility values ranging from 0.023 for plot 1 to 0.067 for plot 3 with an average of 0.050 ton·h·$MJ^{-1}mm^{-1}$ (Table 3-1).

The texture parameter M_n ranged from 2345 for plot 1 to 4577 for plot 3, resulting in erodibility values ranging from 0.023 for plot 1 to 0.067 for plot 3 with an average of 0.061 ton·h·$MJ^{-1}mm^{-1}$ (Table 3-1). The temporal variability of the average annual values is given in figure 3-3 as, respectively, 'Tropical soils 1' (with M_n) and 'Tropical soils 2' (with M_o).

Discussion

The erodibility results can be discussed per method or per plot. Starting with discussing the methods, we see that the results are all in the broad range from 0.015 (very low) to 0.072 (very high). The lowest estimations are based on the nomograph, the highest are based on the regression from tropical soils. The basic difference between the two methods is not only the empirical structure of relating soil texture to erodibility, but also the inclusion or exclusion of other parameters as soil structure, permeability and *OM*. Therefore, the found difference may indicate that in the Lake Alaotra region the nature of the 'other parameters' is responsible for reducing the soil erodibility. However, the permeability, soil structure and *OM* were not drastically low or high, but rather average. Another explanation may be more appropriate, namely that the origin of the nomographs in the USA preordains low erodibility values in a tropical context.

If we look at the variability between the plots, we see no correspondence between the management situation (tillage/ no tillage/ fallow) and the resulting erodibility values. It could be expected that the no-tillage practices (plot 3 and 4) or the fallow (plot 5) would yield the lowest erodibility as soils would be more structured and stable, but the contrary is the case. Plot 3 yields highest erodibility values, followed by plot 4 and 5. The management effect would probably be more represented in the method of Dangler and El-Swaiffy (1976; Appendix C) as it takes into account the stability of soil aggregates. Resulting erosivity values seem to be mainly related to the proportion of fine silt (in the unknown classification; Table 2-3) or the proportion of silt (in USDA classification; Table 2-4).

The variability in time of the erodibility shows an expected dynamic, that is low erodibility in the dry and cold period, and high erodibility in the warm and wet period. Observed differences that go up to 85% between the two periods (figure 3-3) should not be mistrusted at once. The examples found in RUSLE User's Reference Guide (USDA-ARS *guide,* 2008) include similar percentages. This may be understood by the definition in terms of amount of soil loss per unit erosivity. However, because of the reasons mentioned in section 2.3.7 there is no solid ground to use this result, although it is interesting.

3.1.3 Slope factor LS

The low, medium and high LS classes and the corresponding values are shown in table 3-2, together with an example of typical slope gradient (%) and slope length (m).

Table 3-2 The three selected *LS* scenario's with an example from the study area

		An example from the study area	
Scenario	**LS**	**Slope length (m)**	**Slope steepness (%)**
Low	0.6	40	5.0
Medium	1.5	40	9.8
High	4	20	22

Farmers generally maintain some kind of vegetation strip that divide the different fields. On the slopes this leads to some modest formation of terraces. These terraces however are not maintained with the purpose of erosion control and are not designed in a way that they can stop or convey all the runoff. Especially during extreme weather events as the cyclones, a terrace is only functional if it is designed and maintained well. In the study area the very steep slopes on the top of the *tanety* tend to be not very long, while modest slopes are often longer.

3.1.4 Potential soil loss

The potential soil loss was determined for the three *LS* scenario's 'low', 'medium' and 'high'. This was calculated in two ways. First it was calculated with monthly *R* and *K* values and yearly *LS* values as is shown in table 3-3. But, as we saw in the methodology discussion in section 2.3.7, the temporal variability of the erodibility *K* is not likely to be very accurate. So the potential soil loss was also calculated with the monthly *R* and with yearly *K* and *LS* values as in table 3-4. This leads to the same results as a simple multiplication of only yearly values.

Table 3-3 Potential soil loss (ton·ha^{-1}yr^{-1}) for three *LS* scenario's based on monthly *R* and *K* values

Month	Erosivity R	Erodibility K	Potential erosion (ton·ha^{-1}yr^{-1})		
			LS =0,6	LS = 1,5	LS = 3
January	2122	0.086	110	274	731
February	1680	0.078	78	196	522
March	1566	0.069	65	163	435
April	307	0.023	4	11	29
May	42	0.014	0	1	2
June	17	0.013	0	0	1
July	9	0.013	0	0	0
August	25	0.014	0	0	1
September	8	0.012	0	0	0
October	182	0.018	2	5	13
November	831	0.044	22	55	146
December	1700	0.071	73	182	485
Total			355	887	2366

Table 3-4 Potential soil loss (ton·ha^{-1}yr^{-1}) for three *LS* scenario's based on monthly *R* and yearly *K* values

Month	Erosivity R	Erodibility K	Potential erosion (ton·ha^{-1}yr^{-1})		
			LS =0,6	LS = 1,5	LS = 3
January	2122	0.038	48	121	322
February	1680		38	96	255
March	1566		36	89	238
April	307		7	17	47
May	42		1	2	6
June	17		0	1	3
July	9		0	0	1
August	25		1	1	4
September	8		0	0	1
October	182		4	10	28
November	831		19	47	126
December	1700		39	97	258
Total	8487	0.038	194	484	1290

The potential erosion from monthly *R* and *K* is 355, 887 and 2366 ton·ha^{-1}yr^{-1} for respectively the low, medium and high *LS* scenario's. The months of high erosivity correspond to the months with high erodibility.
The use of a yearly *K* decreases the potential erosion to about 55% of the calculation based on the monthly *K*, resulting in 194, 484 and 1290 ton·ha^{-1}yr^{-1} for the three respective *LS* scenario's.

Discussion
A big difference can be observed between the results of different slope length and steepness *LS* scenario's. This is because the *LS* values were not systematically chosen, but rather arbitrary. They do, however, relate to the real situation in the field and give an indication of the influence of the slope length and steepness.
The values from monthly erodibility *K* seem to be unrealistically high, as we could be expecting on the basis of previous discussion. A comparison in literature from Madagascar (Bailly *et al.,* 1976; Rakotomanana, 1987; Goujon *et al.,* 1968) shows that measured soil loss rates of 86 to 258 ton·ha^{-1}yr^{-1} on a Unit Plot can occur. A multiplication of this highest value of 258 with our *LS* scenario values results in potential soil losses of 206, 390 and 1030 ton·ha^{-1}yr^{-1}. So even the highest values in literature are about half of the value found in this study if a variable erodibility *K* is used. Outcomes with a yearly erodibility, however, seem to be more within the range of possibility.

3.2 Influence of CA on soil loss

Values in this paragraph are based on four years for the cropping systems Stylo 1 and Stylo 2, consisting of the implementation year (year 1) and a typical three year cycle (year 2-4). For the cropping systems Dolichos and Traditional, values are based on a two year rotation.

3.2.1 Cover management factor C

Before giving the final results of the Cover management *C*, attention is given to the crop component C_c and the mulch component C_m. As already explained in the methodology this is done on a monthly basis, either weighted with *R* or not weighted, and on a yearly basis.
Both sub factors are based on cover percentages. The evolution of crop and mulch cover of the four cropping systems is shown on a monthly basis for a five year period in figure 3-4 to 3-7.

Crop component C_c

In table 3-5 the resulting crop component C_c is given for two calculation methods and the four cropping systems over a four year period as calculated with equation 2-34 or 2-35. The calculation of a yearly C_c from yearly cover values is not shown as it would result in the same values as the un-weighted calculation from monthly cover. This is due to the nature of the relation between cover and the crop component C_c as shown in equation 2-34.
A value close to 1 indicates very low percentages of crop canopy cover, while a value close to 0 indicates a full and permanent crop cover.

Table 3-5 Yearly crop components C_c for four cropping systems from monthly cover data (weighted and un-weighted)

	Yearly C_c from monthly cover (**not weighted**)			
Year	**Stylo 1**	**Stylo 2**	**Dolichos**	**Traditional**
1	0.14	0,56	0,38	0,70
2	0.13	0,34	0,73	0,77
3	0.48	0,70	0,38	0,70
4	0.32	0,29	0,73	0,77
Average	0.27	0.47	0.55	0.74
	Yearly C_c from monthly cover (**weighted**)			
1	0.15	0.38	0.40	0.43
2	0.22	0.36	0.47	0.51
3	0.29	0.50	0.40	0.43
4	0.20	0.22	0.47	0.51
Average	0.21	0.37	0.44	0.47

As we can see in table 3-5, the crop components for the weighted situation are lower than those of the un-weighted situation. This means that the crop cover is higher when erosive rainfall is occurring. For the un-weighted situation, the average C_c is 0.27, 0.47, 0.55 and 0.74 for, respectively, Stylo 1, Stylo 2, Dolichos and Traditional. For the weighted situation the average C_c is 0.21, 0.37, 0.44 and 0.47 for the same cropping systems.
The biggest difference between the weighted and un-weighted situation is observed for the traditional cropping system (36% lower when weighted) meaning that the timing of dense crop canopy cover for the traditional cropping system corresponds very well with erosive rainfalls. The smallest difference was observed for the Dolichos cropping system (20% lower when weighted) meaning a relative ‘bad timing’ of the crop cover. If only the canopy cover is considered, we see that there is only a very small difference between Dolichos and Traditional and the crop canopy of Stylo 1 is reducing soil loss the most.

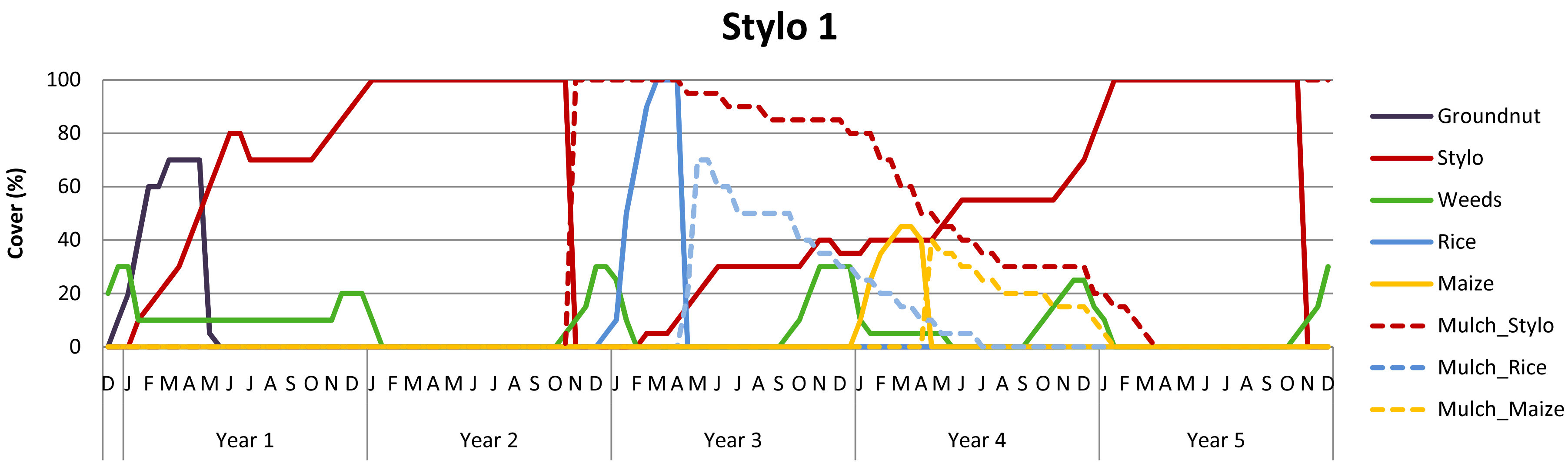

Figure 3-4 Stylo 1, situation on the test plot; percentages of crop canopy cover (sustained line) and mulch cover (dotted line) for a five year period

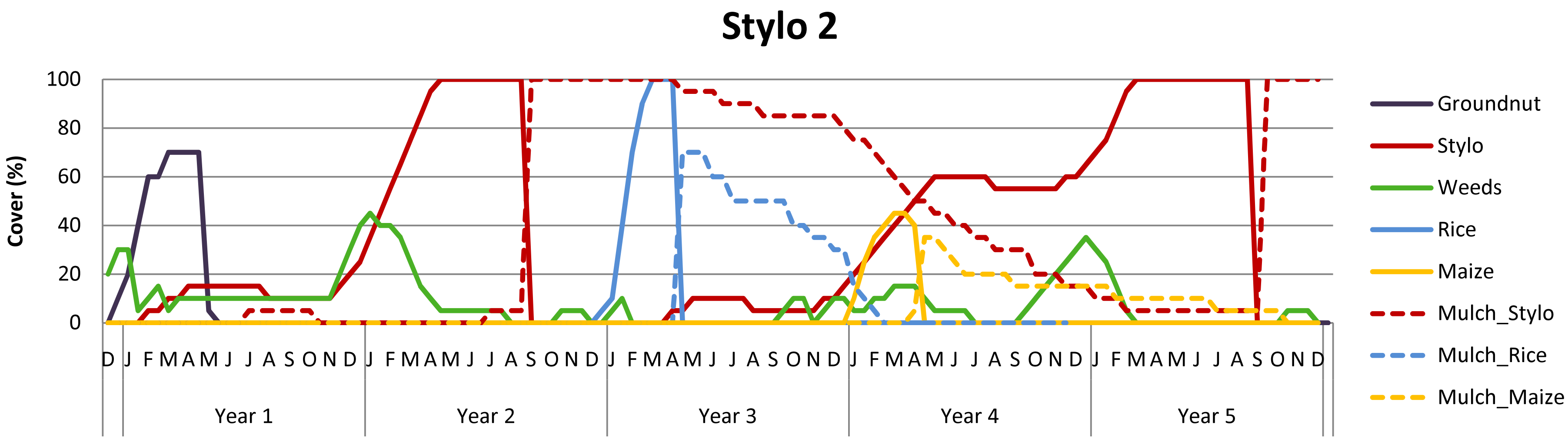

Figure 3-5 Stylo 2, situation on the farmers' field; percentages of crop canopy cover (sustained line) and mulch cover (dotted line) for a five year period

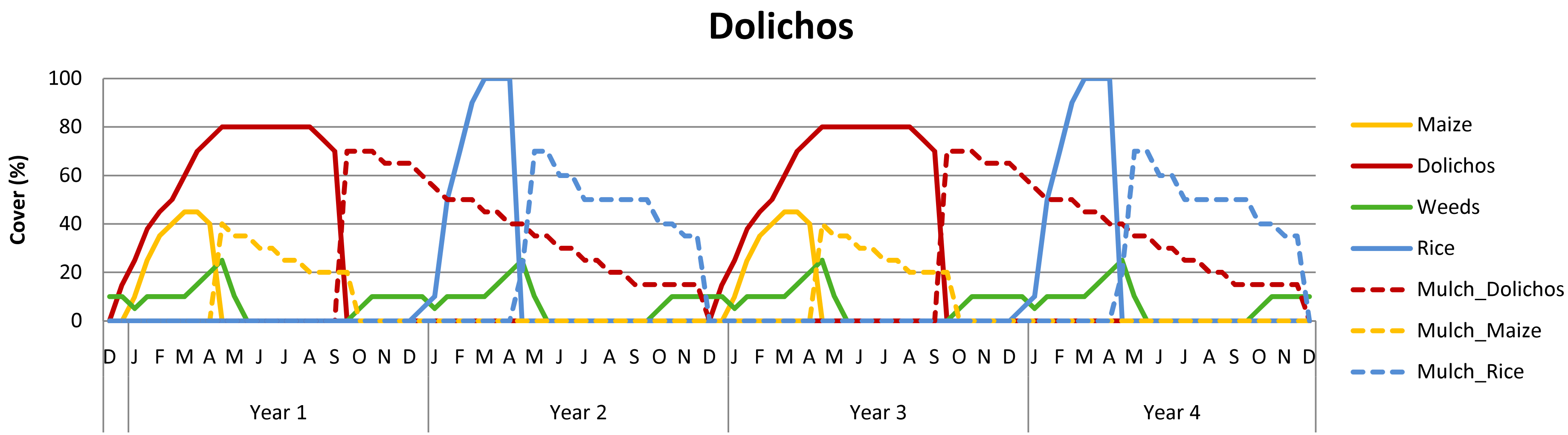

Figure 3-6 Dolichos; percentages of crop canopy cover (sustained line) and mulch cover (dotted line) for a four year period

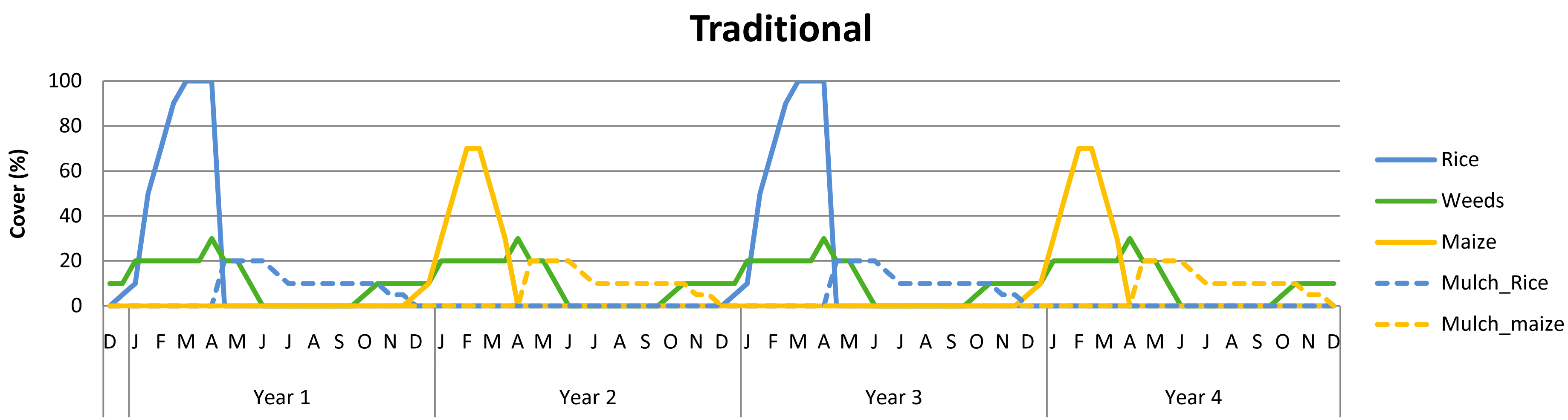

Figure 3-7 Traditional; percentages of crop canopy cover (sustained line) and mulch cover (dotted line) for a four year period

Mulch component

The selected *b*-values for determining the effect of mulch cover are 0.044 for stylo, 0.035 for dolichos, 0.031 for maize and 0.027 for rice (Smets *et al.*, 2008). These *b*-values and the corresponding Mulch Factors for seven hypothetical mulch cover percentages are given in table 3.6.

Table 3-6 Mulch Factor as a function of mulch type and percentage of cover

	Mulch Factor			
Cover (%)	Stylo, b=0.044	Dolichos, b=0,035	Maize, b=0,031	Rice, b=0.027
0	1.00	1.00	1.00	1.00
20	0.41	0.50	0.54	0.58
40	0.17	0.25	0.29	0.34
60	0.07	0.12	0.16	0.20
80	0.03	0.06	0.08	0.12
100	0.01	0.03	0.05	0.07

Own calculation using equation 2-36

The Stylo mulch type appears to be the most effective in reducing soil loss as it corresponds to a low MF. At a cover of 40%, soil loss is reduced with 83% for stylo mulch, with 75% for dolichos mulch, with 71% for maize mulch and with 66% for rice mulch.

In table 3-7 the resulting mulch component C_m is given for three calculation methods and the three cropping systems over a four year period as calculated with equation 3-8 or 3-9.

Table 3-7 Yearly mulch components C_m for three cropping systems from monthly data (weighted and un-weighted) and yearly cover data.

		Yearly C_m from monthly cover (not weighted)		
Year	**Stylo 1**	**Stylo 2**	**Dolichos**	**Traditional**
1	1.00	0.94	0.50	0.83
2	0.75	0.40	0.22	0.81
3	0.01	0.01	0.50	0.83
4	0.10	0.14	0.22	0.81
Average	**0.46**	**0.37**	**0.36**	**0.82**
		Yearly C_m from monthly cover (weighted)		
1	1.00	1.00	0.69	0.97
2	0.46	0.32	0.35	0.97
3	0.01	0.01	0.69	0.97
4	0.09	0.13	0.35	0.97
Average	**0.39**	**0.37**	**0.52**	**0.97**
		Yearly C_m from yearly cover averages		
1	1.00	0.94	0.34	0.81
2	0.48	0.19	0.16	0.79
3	0.01	0.01	0.34	0.81
4	0.07	0.1	0.16	0.79
Average	**0.30**	**0.31**	**0.25**	**0.80**

This table shows us that for the un-weighted calculation from monthly cover and for the calculation from yearly cover averages, it is Dolichos that results in the lowest C_m values of, respectively, 0.36 and 0.25.

However, the biggest difference between the weighted and un-weighted situation is also observed for the Dolichos system, yielding a 44% higher C_m of 0.52. This indicates that much of the mulch of the Dolichos cropping system occurs outside the rainy season. Both stylo rotations yield the lowest C_m values for the weighted situation with respectively 0.39 and 0.37.

For Stylo 1 this value is lower than the un-weighted value of 0.46 which indicates that the timing of mulch in the stylo cropping systems occurs more when erosive rains occur and therefore yields higher impact in reducing soil loss than the un-weighted situation. For Stylo 2 there is no difference between the weighted and un-weighted situation, indicating a distribution of mulch through the year corresponding with the distribution of erosive rains. The average C_m for *Traditional* is around 0.8 for un-weighted calculation, but reaches almost 1 for the weighted calculation. It can be concluded that the mulch of rice and maize is not very effective and mainly occurring outside the erosive season. An implication of this result is that these mulches could be used as fodder without compromising on the protective effect against erosion.

Resulting overall Crop cover C

When crop canopy cover and the mulch cover are combined, we find our interpretation of RUSLE's cover management factor *C* which is an estimation of the fraction of potential soil loss that remains occurring on the field. The cover management factor *C* was calculated from a monthly time interval according to equation 3-5, resulting in average yearly C values of respectively 0.04, 0.14, 0.13 and 0.56 for Stylo 1, Stylo 2, Dolichos and Traditional, see table 3-8. The variability throughout the year of this Crop Cover *C* is shown in figure 3-8.

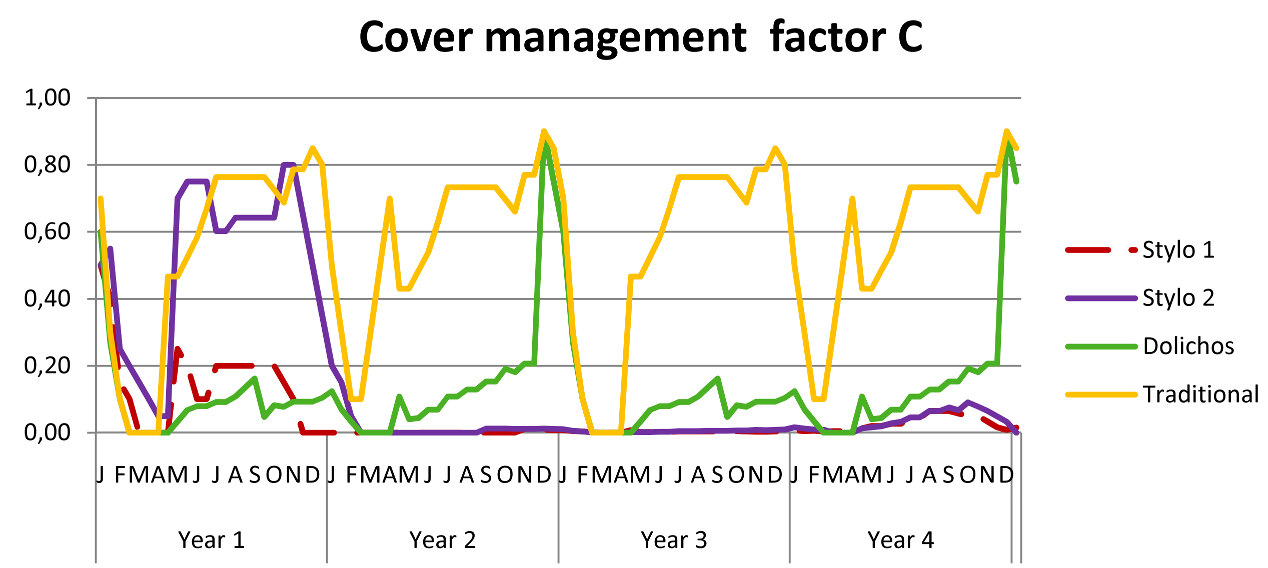

Figure 3-8 Variability of the C-factor throughout the years of rotation, for four cropping systems

Table 3-8 shows that *C*-factor calculation that is weighted for the percentage of erosivity, yields values of 0.04, 0.11, 0.18 and 0.44 for the four respective cropping systems, while a calculation from the yearly averages yields respectively 0.06, 0.16, 0.13 and 0.59.

For Stylo 1 both the weighted and the un-weighted situation yield an average *C* of 0.04, meaning that the potential soil loss is reduced with 96%. Stylo 2 yields 0.14 for the weighted situation and 0.11 for the weighted situation. This means that the protective cover from crop and mulch is occurring slightly more in the erosive season than outside.

Table 3-8 Yearly cover management factor *C* for four cropping systems calculated from monthly (weighted or un-weighted) and yearly crop- and mulch cover

		Yearly C from monthly cover (not weighted)		
Year	Stylo 1	Stylo 2	Dolichos	Traditional
1	0.14	0.51	0.10	0.54
2	0.00	0.02	0.16	0.58
3	0.00	0.00	0.10	0.54
4	0.02	0.03	0.16	0.58
Average	**0.04**	**0.14**	**0.13**	**0.56**
		Yearly C from monthly cover (weighted)		
1	0.15	0.38	0.15	0.40
2	0.00	0.05	0.22	0.48
3	0.00	0.01	0.15	0.40
4	0.01	0.02	0.22	0.48
Average	**0.04**	**0.11**	**0.18**	**0.44**
		Yearly C from yearly cover averages		
1	0.14	0.52	0.13	0.57
2	0.06	0.08	0.12	0.60
3	0.00	0.00	0.13	0.57
4	0.02	0.03	0.12	0.60
Average	**0.06**	**0.16**	**0.13**	**0.59**

Dolichos on the contrary yields 0.13 for the un-weighted and 0.18 for the weighted situation, indicating that some of the protective cover of crop and mulch is 'ineffective' for soil loss control because it occurs in times of little erosive rainfall. This difference is very clear in the first year of the rotation. This first year the Dolichos system yields a *C* value that almost equals that of the Traditional system. The Traditional cropping system yields a value of 0.44 for the weighted situation and 0.56 for the un-weighted situation.

3.2.2 Support practices P

In the Lake Alaotra region two support practices can be identified. The first is a no-tillage management which is specifically linked to the Conservation Agriculture systems. The second is a line of vegetation on the field borders that is mostly introduced to separate fields but also effects runoff and soil loss. For final calculation of *P* values, a difference was made between the three CA cropping systems and the traditional cropping system. Resulting *P* values are shown in table 3-9 and explained more below.

Table 3-9 Values for support practices *P* in the region of Lake Alaotra for traditional and CA cropping systems

Support practices	Traditional cropping system	CA cropping systems
Mechanical tillage (reference)	1	1
Non mechanical tillage	0.7	
No-tillage		0.2
Vegetation borders	0.6	0.6
Total	0.4	0.1

Tillage and no-tillage

In the traditional system tillage is mostly performed with zebus and sometimes by hand. This cannot be compared, from the erosion perspective, with mechanical seedbed preparation. Mechanical seedbed preparation leaves the soil practically without structure, whereas after animal tillage there remain relatively large soil aggregates. Moreover, tillage is done on the contours rather than up and down the slope. After an erosive rain the seedbed without structure will be very prone to soil loss, while the aggregated surface will start disintegrating into smaller aggregates and thus intercepting

some of the rain's energy. This is why the *P* value for tillage under the traditional system was given a value lower than 1.
The no-tillage regime is a very important element of the CA cropping systems, mainly aiming at restoring a balance in the top soil through the dynamics of OM, nutrient and water management. It also aims at gaining a good soil structure by replacing tillage with natural processes of turn-over and aeration through macro fauna. Such stable top soils are not easily detached by drop impact and are given a *P* value of 0.2. It is difficult to estimate such a value, because it also takes time to achieve such a state of equilibrium.

Vegetation borders
The border between fields was already mentioned in relation with the slope length and steepness *LS* in section 3.1.3. We saw that the vegetation can trap sediments leading to modest terraces. This vegetation is often *Bracaria* or *Setaria* that can both be used as fodder.
However, even at the test fields the strips were not sufficient to stop the erosive force of runoff because of interruptions in the vegetation and the lack of a solid ridge. Moreover, the vegetation borders are not present on all fields.
No difference was seen in occurrence of vegetation borders between the cropping systems. So to both the traditional and the CA cropping systems a support practices *P*-value of 0.6 was attributed.

3.2.3 Influence of CA on soil loss

In order to see the influence of crop cover C and support practices P on the soil loss, we assume the medium *LS* scenario of the potential soil loss. The calculation with a constant yearly erodibility *K* was selected, as shown in table 3-4, because the calculation of the temporal variability is too uncertain. The selected crop cover *C* values were the un-weighted monthly and yearly data. If these are put together we are able to compare the rates of soil loss under different cropping systems.

The actual soil loss in ton per hectare per year is given in table 3-10 as it is resulting from the two calculation methods from either monthly (un-weighted) crop cover *C* or the yearly average crop cover *C.*

Table 3-10 Actual soil loss (ton·ha^{-1}yr^{-1}) from monthly or yearly crop cover C for the respective years of the rotation

Cropping system	**Year**	**Soil loss from monthly cover management *C* (ton·ha^{-1}yr^{-1})**	**Soil loss from yearly cover management *C* (ton·ha^{-1}yr^{-1})**
Stylo 1	1	7.2	6.9
	2	0.1	3.0
	3	0.2	0.2
	4	0.5	1.1
	Av.	2.0	2.8
Stylo 2	1	18.4	25.3
	2	2.5	3.7
	3	0.3	0.2
	4	0.8	1.5
	Av.	5.5	7.7
Dolichos	1	7.3	6.4
	2	10.6	5.7
	Av.	9.0	6.1
Traditional	1	79	110.5
	2	94.1	116.6
	Av.	86.6	113.6

As table 3-10 makes clear, the cropping systems Stylo 1 and Stylo 2 are the most effective in reducing soil loss, yielding averages of 2.0 and 5.5 ton·ha^{-1}yr^{-1} (monthly calculation), followed by Dolichos with an average soil loss of 9.0 ton·ha^{-1}yr^{-1}. The Traditional cropping system results in an average soil loss of 86.6 ton·ha^{-1}yr^{-1}. Compared to the Traditional system, this means a reduction to only 2.3% for Stylo 1, to 6.9% for Stylo 2 and to 10.3% for Dolichos.
If we compare this with values in literature, we see comparable rates of soil loss (Andriamapianina, 1997). Near Ambatondrazaka a four-year rotation of groundnut, a leguminous crop, maize and fallow yielded erosion rates of 16 ton·ha^{-1}yr^{-1} for the first four-year cycle. What is striking is the decline of this soil loss in the second cycle to 12 ton·ha^{-1}yr^{-1} and to 8 ton·ha^{-1}yr^{-1} for the third cycle. It is difficult to compare because little is known about the circumstances of slope, management etc., but we can see that the rates of soil loss will probably be reduced after several rotations.
The rate of soil loss of the Traditional cropping system is much higher than for the CA cropping systems. In the field there is off course more variation in traditional cropping systems than is possible to represented in this thesis. But are the values realistic? If we compare it again with literature in Madagascar (Rakotomanana, 1987), we find measured soil loss rates of 86 to even 258 ton·ha^{-1}yr^{-1} on a Unit Plot. Multiply this rate with our *LS* of 1.5, a *C* of 0.56 and a *P* of 0.4 and we would find a soil loss of 29 to 87 ton·ha^{-1}yr^{-1}. Again, the circumstances are not exactly clear, but at least the results are within a range of possibility.

Stylo 1 and Stylo 2 reach relatively high rates of soil loss during the year of implementation of respectively 7.2 and 18.4 ton·ha^{-1}yr^{-1} (monthly calculation). Relative to the traditional rotation this still means a reduction of 89% for Stylo 1 and 77% for Stylo 2. The other years' soil losses fall within the assumed tolerable soil loss of 2 ton·ha^{-1}yr^{-1}.
The calculation resulting from yearly crop cover *C* results in higher values for all systems except for the Dolichos system where the yearly calculation average is only 67% of the monthly calculation. To understand this difference we have to look back at the separate crop and mulch component of the Dolichos system. There is quite some crop and mulch cover through the year, but of all rotations it is the least effective because parts of the cover occurs outside the rainy season. For the other rotation this difference was not so big.
This dynamic could not have been seen if only yearly *C*-values were calculated. On the other hand it is uncertain to what extent this found variability in the year corresponds with the real situation.

The monthly cumulative soil loss is graphically shown in figure 3-9 for the CA cropping systems and in figure 3-10 for the traditional system. The graphs are based on the average crop cover *C* of the whole rotation from monthly calculation.

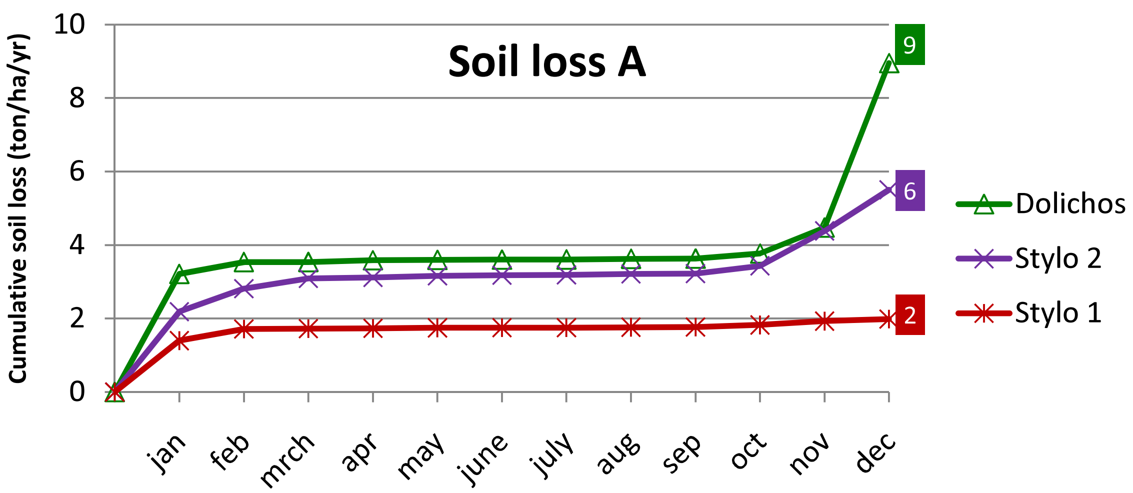

Figure 3-9 Average monthly cumulative soil loss for the three CA cropping systems

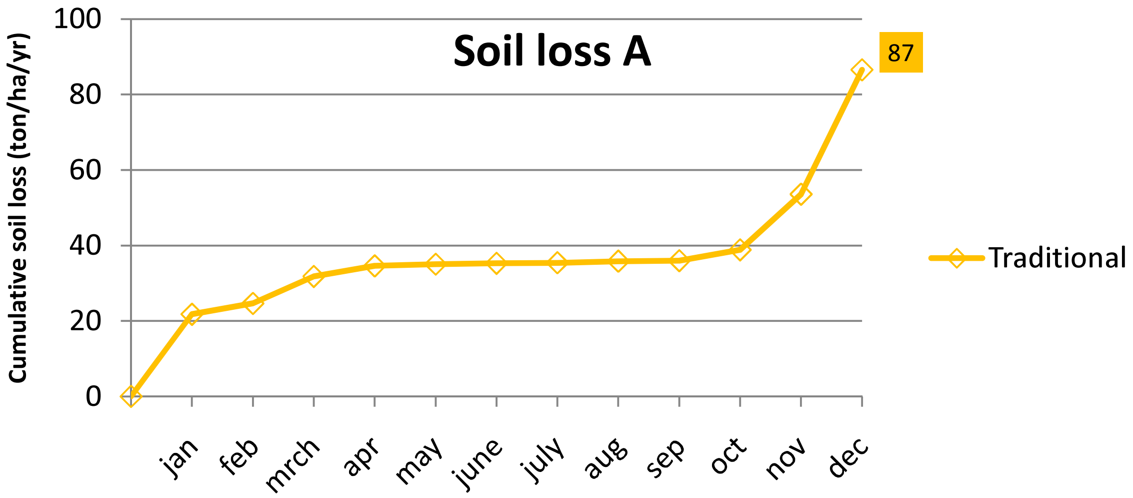

Figure 3-10 Average monthly cumulative soil loss for the Traditional cropping system

It is striking that at the end of November there is practically no difference between Stylo 2 and Dolichos, while eventually the difference is 3 ton·ha^{-1}yr^{-1}. This difference that is acquired in December can be explained by a combination of two elements. In December we have calculated the second highest monthly potential soil loss, that is 97 ton·ha^{-1}yr^{-1}, and there is a complete lack of crop or mulch cover in December of every second year.

4 Conclusions and recommendations

This research was done within the framework of the CA2AFRICA project, which seeks answers to the question why the adoption of Conservation Agriculture is limited so far in Africa.

The *tanety* (rainfed hills) in the region of Lake Alaotra are susceptible to soil erosion by water through a combination of intrinsic susceptibility (climate, soils, topography) and management (cropping systems, tillage practices). Three CA cropping systems that are disseminated in the region to improve sustainable management, are assessed for their influence on soil loss.

The RUSLE model was deployed with the following objectives:

1) Analyzing the potential soil loss, defined in RUSLE terms as the rainfall erosivity *R*, soil erodibility *K* and slope length and steepness *LS*;
2) Evaluating the impact of three CA rotations on the rate of soil loss with the *C* and *P* parameters of the RUSLE without installing a Unit Plot;
3) Formulating some recommendations for the use of RUSLE in other CA2AFRICA countries.

This objective structure is also followed in the following conclusions.

4.1 Potential soil loss

For the rainfall erosivity *R,* available data in the study area had a good match with the estimation method of Yu and Rosewell (1996_a). It proved to be possible to select model parameters for a weather station in the tropics of Australia with characteristics similar to the study area. Together with 46 years of daily effective rainfall measurements, a yearly average *R* could be calculated of 8487 $MJ·mm·ha^{-1}h^{-1}$. The problem faced when applying other estimation methods was the difficulty of relating erosivity indicators, like the modified index of Fournier, to RUSLE's *R.* Such empirical relations need more validation in well described tropical circumstances.

Estimation of soil erodibility *K* was difficult because of its empirical nature and the different texture classes. Therefore an average of five estimation methods was selected, resulting in a yearly average *K* of 0.038 $ton·h·MJ^{-1}mm^{-1}$. Taking into account the temporal variability would lead to big differences in potential soil loss estimations. Because of its methodological questionability, this was not taken into account for calculating the potential soil loss.

Three slope length and steepness scenario´s were determined, yielding *LS* factors of 0.6, 1.5 and 4 corresponding to the low, medium and high erodibility compared to the Unit Plot.

Potential soil loss for the respective *LS* scenario's was 194, 484 and 1290 $ton·ha^{-1}yr^{-1}$. Such values, although high, are within the range of possibilities when compared with previous studies in the study area on Unit Plots.

CA2AFRICA recommendation:

- If there is a history of daily rainfall data, accurate determination of monthly and yearly erosivity *R* is possible with Yu and Rosewell (1996_a).
- For estimating erodibility *K*, apply as many estimation methods as possible and take the average of them until validation is possible.

Lake Alaotra recommendation:

- The existing parcel borders may be the basis of more structural vegetation borders to reduce soil erosion in the study area.

4.2 Impact of CA on soil erosion

The impact of the CA cropping systems Stylo 1, Stylo 2 and Dolichos on soil loss was compared with the cropping system Traditional.

The crop management factor *C* was divided into a crop component and a mulch component. This approach reveals in a transparent manner the respective contribution of crop and mulch cover in reducing soil loss. Results indicated that Stylo 1 is most effectively reducing soil loss through both crop and mulch. The difference between Stylo 1, situation at test fields, and Stylo 2, situation on farmers' fields, lies in the crop cover rather than the mulch cover. The impact of the Dolichos cropping system can be attributed to the mulch, because there is little difference with Traditional if only crop cover is considered. Mulch of rice and maize are not adding much to erosion prevention. Mulch of Dolichos has a 'bad timing' with respect to erosive rains compared to mulch of stylo. Average outcomes of crop management *C* are 0.04, 0.14, 0.13 and 0.56 for the four cropping systems: Stylo 1, Stylo 2, Dolichos and Traditional.

The two Support Practices considered in this study were the linear vegetation borders and the no-tillage. Overall P values were 0.4 for the Traditional cropping system and 0.1 for the CA cropping systems. Although the weight of this P factor is equal to the other factors, it is methodologically weaker.
For the traditional cropping system an actual soil loss of 86.6 ton·$ha^{-1}yr^{-1}$was found for the medium LS scenario. The impact of CA on actual soil loss relative to Traditional, measured in ton·$ha^{-1}yr^{-1}$, is a reduction to 2.0 (2.3%) for Stylo 1, to 5.5 (6.9%) for Stylo 2 and to 9 (10.3%) for Dolichos.

Scientific recommendation:

- It would be interesting to see the variability in time of Support Practices. The *P* factor just after tillage will be absolutely different from just before, and the effectiveness of linear vegetation elements will probably increase in the growing season.

Lake Alaotra recommendation:

- The outcome of the modeling suggests that the Dolichos rotation can easily be improved by establishing more cover in December.

4.3 RUSLE's applicability in CA2AFRICA

Let us go back to the sub objective of CA2AFRICA that is *the testing and validation of bio-physical, socio-economic and conceptual models of innovation systems for analyzing the impact and adoption of CA in Africa* (CA2AFRICA, 2009). This study shows that RUSLE is a workable model for a situation with limited data and no direct possibilities of installing a Unit Plot.
The primary use of a model like RUSLE is to relatively compare cropping systems, rather than accurately estimating a soil loss quantity, especially when the model parameters have not been calibrated.
Three important CA elements are very well captured in the RUSLE model: The cover crops used in CA cropping systems; the use of mulch; and the no-tillage management.
However, RUSLE does not take into account the long-term changes in the soil equilibrium in terms of structure and soil fauna, even though these are important elements in CA. Also, previous soil loss studies in the region show that protective cropping systems become more effective after several years, which is not modeled in RUSLE.

In conclusion, estimation methods for RUSLE have been assessed, parameters have been determined, and recommendations were made. Although validation with a Unit Plot remains necessary, the estimated parameters give an indication of the effect of CA on soil loss and allow for future scaling up of soil loss quantification.

CA2AFRICA recommendation:

- The monthly time scale for both crop as well as mulch cover, allows for good overview of cover dynamics throughout the year.
- The division of crop management *C* into a crop component and a mulch component can give very clear insight in the respective contribution of crops or mulch in reducing soil loss.

5 References

AFD and FFEM (Agence Française de Développement and Fonds Français pour l'Environnement Mondial) 2007, **Direct seeding mulch-based cropping systems (DMC), An alternative to conventional cropping systems in developing countries,** information booklet

Allan R.G., Pereira L.S., Raes D. and Smith M. 1998, **Crop evapotranspiration - Guidelines for computing crop water requirements**, on-line accessible FAO publication under the name *Irrigation and drainage paper 56*

Andriamapianina N. 1997, **Mesure des phénomènes d'érosion,** part of *Bilan et évaluation des travaux et réalisations en matière de conservation des sols a Madagascar* - FOFIFA / DRFP Madagascar

Angima S.D., Stott D.E., O'Neill M.K., Ong C.K. and Weesies G.A. 2003, **Soil erosion prediction using RUSLE for central Kenyan highland conditions,** published in *Agriculture, Ecosystems and Environment 97, pp. 295–308*

Arnoldus H.M.J. 1980, **An approximation of the rainfall factor in the universal soil loss equation,** published for *Land and water development division FAO, Rome*

Bailly M.C., Malvos M.C., Sarrailh M.J.M., Rakotomanana M.J.L., Rampanana L., Ramanahadray M. 1976, **Étude de la sensibilité des sols de Madagascar a l'érosion – Expérimentation en parcelles élémentaires**, published in *Bois et Forêts des Tropiques n° 169*

Bolliger, A., Magid, J., Amado, T.J.C., Neto, F.S., Ribeiro, M.D.D., Calegari, A., Ralisch, R., De Neergaard, A. 2006, Taking **stock of the Brazilian ''zero-till revolution'': a review of landmark research and farmers' practice**, published in *Advances in Agronomy. 91, pp. 47–110*

Bouchier B. 1959, **Mesure du ruissellement et de l'érosion**, published in *Direction des eaux et forêts et de la conservation des sols D40/4 n° 44*

Brown L.C. and Foster G.R. 1987, **Storm erosivity using idealized intensity distributions,** published in *Transactions of the ASAE 30 (2), pp. 379-386*

CA2AFRICA 2009, KBBE project program 1-2-09: **Impact and development of Conservation Agriculture techniques in developing countries- Mandatory ICPC (African ACP)**

CIRAD Madagascar 2011, website www.cirad.mg/fr/bvlac.php visited on 2-03-11

Dangler E.W. and El-Swaiffy S.A. 1976, **Erosion of selected Hawaii soils by simulated rainfall,** published in *Science Society of America Journal 40, pp. 769-773*

FAO 2010, website http://www.fao.org/ag/ca/1a.html visited on 3-12-10

Fournier F. 1960, **Climat et Erosion**, published in *Presses Universitares de France*, Paris

Giller K.E., Witter E., Corbeels M. and Tittonell P. 2009, **Conservation agriculture and smallholder farming in Africa: The heretics' view**, published *in Field Crops Research 114, pp. 23–34*

Goujon P. *et al.*, 1968, **Conservation des sols en Afrique et a Madagascar 1re partie, les facteurs de l'érosion et le équation universelle de Wischmeier,** published in *Bois et forêts des tropiques n° 118*

Goujon *et al. (i) :* Goujon P., Bailly, De Vergnette, Benoit de Cognac, Roche, M., 1968, **Conservation des sols en Afrique et a Madagascar 2eme partie, influence du couvert végétal sur le ruissellement et les pertes en terre,** published in *Bois et forêts des tropiques n^{o} 119*

Goujon P. *et al.(ii)* Goujon P., Bailly, De Vergnette, Benoit de Cognac, Roche, M., 1968, **Conservation des sols en Afrique et a Madagascar 3eme partie, influence des rotations et des pratiques culturales sur le ruissellement et les pertes en terre a Madagascar,** published in *Bois et forêts des tropiques n^{o} 120*

Jensen, J. R. 2000, **Remote sensing of the environment: An earth resource perspective**, published as *1st ed. Upper Saddel River, New Jersey: Prentice Hall, Inc.*

Karaburun A. 2010, **Estimation of C factor for soil erosion modeling using NDVI in Buyukcekmece watershed,** published in *Ozean Journal of Applied Sciences 3, no. 1*

Kouli M., Soupios P. and Vallianatos F. 2009, **Soil erosion prediction using the Revised Universal Soil Loss Equation (RUSLE) in a GIS framework, Chania, Northwestern Crete, Greece,** published in *Environmental Geology No 57 pp. 483–497*

Lal R. 1985, **Soil erosion and sediment transport research in tropical Africa**, published in *Hydrological Sciences journal 30-2*

Lal R. 2007, **Anthropogenic Influences on World Soils and Implications to Global Food Security,** Advances in Agronomy Volume 93, pages 69-93

Morgan R.P.C. 2005, **Soil erosion and conservation - third edition**, Blackwell publishing

Mulengera M.K. and Payton R.W. 1999, **Estimating the USLE-soil erodibility in developing tropical countries,** published in *Tropical agriculture (Trinidad) 76 no. 1, pp.17-22*

Oldeman L.R. 1990, **An agroclimatic characterization of Madagascar,** published as *Technical Paper 21, ISRIC Wageningen, FOFIFA Antananarivo and IRRI Los Baños*

Rakotomanana J. 1987, **Climat, érosion et techniques culturales sur les hauts-plateaux de Madagascar,** published in *Département de Recherches Forestières et Piscicoles N^{o} 580,* Madagascar

Razafimbelo T., Albrecht A., Feller C., Ravelojaona H., Moussa N., Razanamparany C., Rakotoarinivo C., Razafintsalama H., Michellon R., Naudin K., and Rabeharisoa L. 2010, **Stockage de carbone dans les sols sous systèmes de culture en semis direct sous couvert végétal (SCV) dans different contextes pédoclimatiques à Madagascar,** published in *Etude et Gestion des Sols 17,No. 2, pp. 143-158*

Raveloarisoa A. 1998, **Mise en place d'un système d'information géographique pour l'étude de l'évolution des phénomènes d'érosions du bassins versants du l'imamba (Madagascar),** published for the *Centre de formation aux sciences de l'information géographique et de l'environnement (CFSIGE)*

Renard K.G., Foster G.R., Weesies G.A., McCool D.K. and Yoder D.C. (Coordinators) 1997, **Predicting soil erosion by water - a guide to conservation planning with the revised universal soil loss equation (RUSLE)**, published as *Agriculture Handbook 703, US Govt. Printing Office, in press*

Renard K.G. and Freimund J.R. 1994, **Using monthly precipitation data to estimate the R-factor in the revised USLE,** published in *Journal of Hydrology 157, pp. 287-306*

Roche P. 1954, **Mesures de l'érosion et du ruissellement, sous différentes cultures – dans la région du Lac Alaotra, Madagascar**, presented at the *2^e^ conférence Interafricaine des Sols, Léopoldville 9-14 août*

Roche P. and Dubois B. 1959, **Mesures de ruissellement et d'érosion réalisées à Madagascar,** published for *Bureau pour le développement de la production agricole, Poo13, juin*

Roose E. 1977, **Erosion et ruissellement en Afrique de l'ouest - vingt annees de mesures en petites parcelles experimentales,** published in *Travaux et Documents de I'ORSTOM No. 78, ORSTOM, Paris*

Smithen A.A. and Schulze R.E. 1982, **The spatial distribution in Southern Africa of rainfall erosivity for use in the Universal Soil Loss Equation,** published in *Water South Africa 8 No. 2, pp. 73-78*

Smets T., Poesen J. and Knapen A 2008, **Spatial scale effects on the effectiveness of organic mulches in reducing soil erosion by water,** published in *Earth-Science Reviews No 89 pp. 1–12*

Stone R.P. and Hilborn D. 2000, **Universal soil loss equation (USLE)**, factsheet for *Ontario agricultural engineering* under *US ministry of food, agriculture and rural affairs*

USDA Soil Survey Division Staff 1993, **Soil survey manual,** published for as *Handbook 18* for *Soil Conservation Service. U.S. Department of Agriculture*

USDA-ARS *doc*, 2008, RUSLE science documentation, draft

USDA-ARS *ref*, 2008, RUSLE user reference guide, draft

Wischmeier, W.H., Johnson C.B., and Cross B.V. 1971, **A soil erodibility monograph for farmland construction sites**, published in *Journal of Soil and Water Conservation No. 26 pp. 189-193*

Wischmeier W.H. and Smith D.D. 1978, **Predicting rainfall erosion losses--a guide to conservation Planning,** published as *Agriculture Handbook No. 537, USDA, Washington*

Yin S., Xie Y., Nearing M.A., Wang C. 2006, **Estimation of rainfall erosivity using 5- to 60-minute fixed-interval rainfall data from China**, published in *Catena 70, pp. 306–312*

Yu B. and Rosewell C. J. 1996*a*, **An assessment of a daily rainfall erosivity model for New South Wales,** published in *Australian Journal Soil Research 34, pp. 139-152*

Yu B. and Rosewell C. J. 1996*b*, **Rainfall erosivity estimation using daily rainfall amounts for South Australia,** published in *Australian Journal Soil Research 34, pp. 721-733*

Yu B. 1998, **Rainfall erosivity and its estimation for Australia's tropics,** published in *Australian Journal Soil Research 36, pp. 143-165*

Zhongming W., Lees B.G., Fenga J., Wanning L. and Haijing S. 2010, **Stratified vegetation cover index: A new way to assess vegetation impact on soil erosion,** published in *CATENA No 83 Issue 1, Pages 87-93*

Appendix A Errors in soil loss from erosivity estimation

The graph below (Renard and Freimund, 1994:302) shows the effect of -inaccurate- estimation of erosivity *R* factors on soil loss. Soil loss as resulting from the estimation is plotted relative to soil loss as resulting from the real erosivity *R* (x-axis). These errors go up to more than 300% for low erosivity situations, and decrease to less than 50% when erosivity increases.

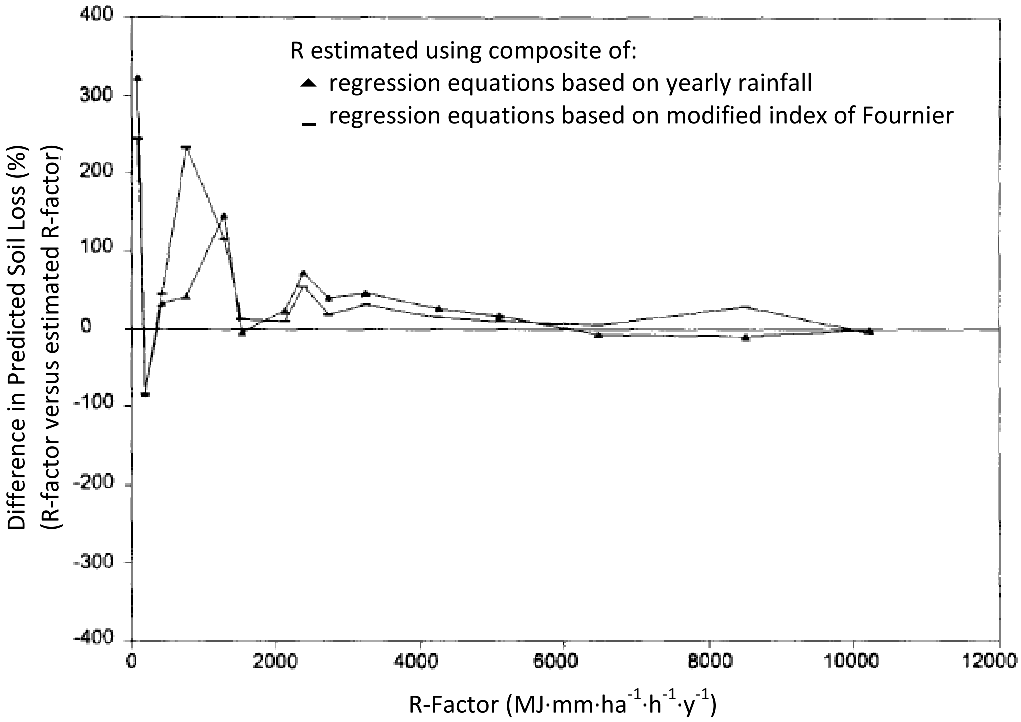

Figure A-1 Impact of potential *R*-factor estimation errors on predicted soil loss

Appendix B Erodibility estimation method El-Swaiffy and Dangler

An estimation method of El-Swaiffy and Dangler is shortly described. Although it was not used in the Lake Alaotra region it could be useful in other CA2AFRICA contexts.
For tropical soils, unstable soil aggregates, modified silt, sand, and the corresponding base saturation are used to determine K (Dangler and El-Swaiffy, 1976). Although they derived it for volcanic soils of Hawaï, it has also been used in tropical areas with feral sols.
This method makes use of the percentage modified silt (0.002–0.1 mm), percentage modified sand (0.1–2 mm), base saturation, percent unstable aggregates, and percent very fine sand. This relation is given in equation B-1

$$K = -0.03970 + 0.00311X1 + 0.00043X2 + 0.00185X3 + 0.00258X4 - 0.00823X5 \quad \text{eq. B-1}$$

where X1 is the percent unstable aggregates <0.250 mm, X2 is the product of the percent of silt (0.002–0.01 mm) and sand (0.1–2 mm) present in the sample, X3 is the percent base saturation of the soil, X4 is the percent silt present (0.002–0.050 mm), and X5 is the percent sand in the soil (0.1–2 mm).
This equation results in a K-factor with US units, thus the result was divided by 7.59 to obtain the equivalent value in SI units of $Mg \cdot h \cdot MJ^{-1} mm^{-1}$.

Appendix C Outcome of erosivity estimations

Table C-1 Monthly R-factors as a result of different estimation methods in SI units of $MJ \cdot mm \cdot ha^{-1} h^{-1}$

Month	**From literature (yearly)**	**Hourly**		**Daily rainfall**			**Monthly Fournier**		**Yearly Roose**		
		Hourly rainfall	**Hourly rainfall (extrapolation)**	**Min**	**Max**	**Daily rainfall**	**Fournier (Morocco)**	**Fournier (USA)**	**Min**	**Max**	**Yearly rainfall**
January	1895	3321	1528	1367	2876	2122	259	3470	1871	2287	2079
February	1556	2336	1140	1099	2260	1680	213	2849	1536	1878	1707
March	1476	836	1108	1030	2103	1566	202	2702	1457	1780	1619
April	338	80	136	224	390	307	46	619	334	408	371
May	78	16	16	35	50	42	11	143	77	95	86
June	53	0	4	14	19	17	7	97	52	64	58
July	47	28	2	8	9	9	6	86	46	56	51
August	58	0	8	21	28	25	8	106	57	70	64
September	27	0	1	7	8	8	4	50	27	33	30
October	203	29	79	137	227	182	28	372	201	245	223
November	844	328	447	569	1093	831	115	1545	833	1018	926
December	1578	621	1130	1111	2288	1700	216	2889	1558	1904	1731
Year	**8153**	**7595**	**5605**	**5623**	**11352**	**8487**	**1114**	**14927**	**8048**	**9837**	**8944**

Appendix D Monthly C-factor and actual soil loss

Table D-1 Average actual soil loss for the four cropping systems, assuming a medium scenario of Potential soil loss where slope length and steepness *LS* is 1.5 on the basis of monthly data

Month	Potential erosion (medium LS scenario)	Average *C* for whole rotation not weighted				P		Average actual soil loss (ton·ha^{-1}yr^{-1})			
		Stylo 1	Stylo 2	Dolichos	Traditional	Stylo & Dolichos	Tradi-tional	Stylo 1	Stylo 2	Dolichos	Traditional
Jan	121	0.12	0.18	0.27	0.45	0.1	0.4	1.40	2.18	3.22	21.77
Feb	96	0.03	0.07	0.03	0.08			0.32	0.63	0.32	2.87
Mar	89	0.00	0.03	0.00	0.20			0.01	0.28	0.00	7.14
Apr	17	0.00	0.01	0.03	0.40			0.01	0.03	0.05	2.79
May	2	0.06	0.19	0.05	0.48			0.01	0.04	0.01	0.46
June	1	0.03	0.20	0.07	0.60			0.00	0.02	0.01	0.23
July	0	0.06	0.16	0.10	0.75			0.00	0.01	0.00	0.15
Aug	1	0.07	0.18	0.12	0.75			0.01	0.02	0.02	0.42
Sept	0	0.07	0.18	0.13	0.75			0.00	0.01	0.01	0.13
Oct	10	0.06	0.21	0.13	0.69			0.06	0.21	0.14	2.87
Nov	47	0.02	0.20	0.15	0.78			0.09	0.95	0.71	14.75
Dec	97	0.01	0.12	0.46	0.85			0.06	1.12	4.47	32.94
Monthly calc total	484	0.04	0.14	0.13	0.56			2.0	5.5	9.0	86.5

Table D-2 Average actual soil loss for the four cropping systems, assuming tial soil loss where slope length and steepness *LS* is 1.5

Yearly calc sum	484	0.06	0.16	0.13	0.59	0.1	0.4	2.8	7.7	6.0	113.5