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SOIL EROSION IN ANDEAN CROPPING SYSTEMS:

THE IMPACT OF RAINFALL EROSIVITY

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Preface

Cassava, an important staple food and industrial crop of the low to medium-altitude tropics, is associated with soil exhaustion and degradation world-wide. Slow initial soil cover of the crop, in particular when grown without fertilizer, and the erosive nature of tropical rainstorms, combined with the increasing cultivation of marginal and steep lands are the principal factors leading first to the degradation of soils and then of rural livelihoods themselves. They are indeed the loom on which the fabric of poverty is woven.

Research focussing on the arrest or reversal of soil degradation has to take a long-term approach since damage to agricultural lands from erosion is not normally detected in a couple of years and the loss in agricultural productivity is more of a gradually progressing than instantaneous nature. Yet, capturing the magnitude of change is necessary to quantify damage and justify investment in research to find viable solutions to the problems outlined above. A special effort has therefore been made to develop a sustained, long-term research programme on factors related to soil erosion and degradation in a mid-altitude location of the tropical Andes representative of vast extensions of agricultural lands in Central- and South America.

Over a twelve-year time span (1986-1998), six individual doctoral research programmes, accompanied by numerous MSc programmes were planned and carried out in a sequential, co-ordinated way so as to explore causes and effects of soil erosion and devise conservation practices in cassava-based cropping systems of an Andean mid-altitude tropical environment. The research reported in this doctoral dissertation , the last of those six , profits greatly from the large stock of scientific data previously generated and is thus able to provide a medium-term perspective on degradation and productivity aspects as well as a solid, critical review of suitable conservation practices. Beyond this 12-year overview and synthesis, the last phase of the project focused on elucidating the role of rainfall erosivity in the context of soil erosion and conservation in this Andean environment from where no scientifically sound results were available until now. The research on rainfall erosivity implied a rigorous scientific approach to evasive and complicated to measure parameters such as raindrop size and a reassessment of the rain drop energy-rainfall intensity relationship. These and other highly demanding tasks were fulfilled with precision and perseverance. Based on the results, future researchers are now able to generate rainfall erosivity maps throughout the region based on rainfall quantity data thus providing an easy to generate and useful planning and decision support tool for agricultural development in the region.

What is left behind by this effort which went well beyond the twelve-year project phase is not only a wealth of scientific information on factors driving soil erosion and degradation in mid-altitude tropical Andean hillsides. Beyond science, and by gradually involving more and more stakeholders in the design of this research, planning tools and many practical solutions and approaches to conservation have emerged and have been taken up by local institutions, NGO's and even schools and farmers groups for whom this research was conducted.

We are most grateful to Deutsche Forschungsgemeinschaft who provided the seed money to get this programme started, and to the Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) who had the vision and the determination to support this research over the necessary length of time to make it relevant and useful to those for whom it was conducted.

Dietrich E. Leihner Rome, March 2004

Contents

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Abbreviations

A	Annual soil loss amount calculated in accordance with the USLE
AEI_{30}	Rainfall amount times kinetic energy times I_{30}
AI_{30}	Rainfall amount times I_{30}
AI_{max}	Product of rainfall amount and $I_{7.5}$
C	Crop management factor of the USLE
CENICAFE	Research Center of the Colombian Coffee Growers' Association
CIAT	Centro International de Agricultura Tropical
CVC	Corporación Regional Valle del Cauca
EI_{30}	Erosivity index of the USLE, R-Factor
EIA	Product of (Runoff volume)$^{-0.5}$ and I_{30}
E_L	Kinetic energy load per unit amount of rainfall
ER	Enrichment ratio
FAO	Food and Agriculture Organisation of the United Nations
FIDAR	Fundación para la investigación y el desarollo agricola
I_{30}	Maximum intensity during 30 minutes
IGAC	Instituto Geografico Agustin Codazzi
K	Soil erodibility factor of the USLE
KE	Kinetic energy
L	Slope length factor of the USLE
m.a.m.s.l.	meters above mean sea level
MJ	Mega joule
MON	Mondomo
NGO	Non governmental organization
O.M.	Organic matter
P	Protection measures factor of the USLE
R	Rainfall erosivity factor of the USLE
r^2	Coefficient of determination
S	Slope gradient factor of the USLE
SD	Standard deviation
STQ	Santander de Quilichao
USD	United States Dollar
USLE	Universal Soil Loss Equation

Summary

Soil erosion in Andean Cropping Systems: The impact of Rainfall Erosivity

Rationale and methods

The Andean region of Colombia, covering about one third of the country, is home to about 15% of the total population and 50% of the rural population. Due to the fact that Colombia's most fertile and flat areas are used for the production of sugar and other crops destined for industrial use or export, food crops are generally grown on the Andean hillsides. About 85% of bean, 70% of hard maize, 80% of wheat, 80% of cassava and 90% of potato production takes place in this region. Considering the extreme importance of the Andean hillsides for Colombia's food production, it is alarming that some 84% of the Andean region is affected by erosion, with close to 40% deemed to be moderately or extremely affected.

In view of this alarming situation, the University of Hohenheim, together with the Centro International de Agricultura Tropical's (CIAT) cassava program, launched an erosion research project in 1986. This had the aim of adapting and applying the Universal Soil Loss Equation (USLE) to local circumstances in order to study the effectiveness of various cassava-based cropping systems in relation to erosion control and income generation, propagate conservation measures and provide the local farming community with technical advice as well as improved germplasm. The objectives of the present study were:

a) to determine the applicability of the USLE rainfall erosivity factor to the Andean Region, particularly the energy-intensity term, the applicability of which has been questioned in relation to tropical rainfall conditions
b) to calculate long-term erosivity data for several meteorological stations in the wider research area and to create a rainfall erosivity map for the area
c) to establish the long-term erosivity of two soil types in the research area; and
d) to evaluate the yield and soil conservation performance of several cassava-based cropping systems.

Research was carried out at two sites in the Cauca department in the southwest of Colombia. The first was near Santander de Quilichao, located at 3^{o} 6' N, 76 ^{o} 31' W, at an altitude of 990 m a.m.s.l., with an annual precipitation of 1,789 mm and an average temperature of 23.7 ^{o} C. The second site was near Mondomo, which lies 2^{o} 53' N, 76 ^{o} 35' W at an altitude of 1,450 m a.m.s.l., has an annual precipitation of 2,133 mm and an average temperature of 18.2 ^{o} C. The soil at Quilichao was classified as an amorphous, isohyperthermic Oxic Dystropept, whilst that at Mondomo was categorized as a kaolinitic-amorphous, isohyperthermic Oxic Humitropept. Both belong to the inceptisols, which form about 77% of the soils of the Cauca departments.

In 1987 erosion plots were established at both sites on slopes of between 7% and 20% consisting of eight treatments and three repetitions at Quilichao with two at Mondomo. During the final phase of the research presented in this study, the eight treatments comprised: 1) Continuous bare fallow, 2) Traditional cassava-based rotation, 3) Continuous sole cassava, 4) Cassava-based rotation with minimum tillage and mulch, 5) Cassava-based rotation with two previous years of bush fallow, 6) Cassava-based rotation with vetiver grass barriers, 7) Cassava-based rotation with legume strips, and 8) Cassava-based rotation with improved fallow element.

The bare fallow plots were 22 m long and 11 m wide whilst the cropped treatments measured 16 m by 8 m. Both soil erosion and runoff amounts were collected in Eternit channels at the lower end of the plots and measured with the aid of splitters and collecting barrels.

The soil and sediments from the plots were analyzed for nutrients and organic matter on an ongoing basis. To determine long-term rainfall erosivity values, rainfall intensities were measured with pluviographs (Hellman Modell 1509, Lamprecht, Göttingen, Germany) and, at Quilichao, a Joss-Waldvogel disdrometer (Distromet, Zürich, Switzerland) was also used to measure raindrop distributions during six rainy seasons in the years 1993-1994 and 1996-1998. Furthermore, over 140 years of rainfall intensity data from four meteorological stations belonging to the Colombian Coffee Growers’ Association (FEDECAFE) in the Cauca and Valle del Cauca departments were evaluated.

Rainfall erosivity

Drop size distribution measurements performed with a Joss-Waldvogel disdrometer over a three-year period showed that the USLE R factor is applicable for the research region as no significant differences were found between the measured kinetic energy of rainfall events and calculated values according to the USLE.

The climatic erosive potential can be considered to be very high. The average energy load of the total rainfall at both locations was 21.0 J m^{-2} mm^{-1}, whereas the average energy load of the erosive rainfall was 22.3 J m^{-2} mm^{-1} at Quilichao and 22.4 J m^{-2} mm^{-1} at Mondomo. The highest energy load values for single rainfall events reached 31.0 J m^{-2} mm^{-1}. This also confirmed the observations of other authors regarding the higher percentages of intensive rainfall in tropical areas compared to temperate regions. 37.6% and 36.3% of the total rainfall amount at Quilichao and Mondomo fell at intensities of higher than 25 mm h^{-1}. Approximately 20% of the rainfall amount fell at intensities of higher than 50 mm h^{-1}, whereas close to 6% fell at intensities of over 100 mm h^{-1}. The highest intensities reached were 540 mm h^{-1} at Mondomo and 468 mm h^{-1} at Quilichao.

The average annual r-factor values during the twelve year research period for Quilichao and Mondomo were 10,037 and 9,016 MJ ha^{-1} mm h^{-1} a^{-1} respectively. The differences between the years were considerable, with values ranging between 4,891 and 14,496 MJ ha^{-1} mm h^{-1} a^{-1}.

Long-term rainfall intensity data from four additional meteorological stations in the Cauca and Valle del Cauca departments were analyzed and average annual r-factor values calculated. A highly significant relationship was found between a modified Fournier index based upon average monthly rainfall amounts and the equivalent monthly r-factor values. Based on these findings, it is assumed that this relationship can be used to calculate reliable r-factor values for parts of the Andean region where no rainfall intensity data is available.

Evaluation of cassava-based cropping systems in respect of erosion and yield performance

Soil losses

Whilst the K-factor values measured of 0.017 t h MJ^{-1} mm^{-1} at Quilichao and 0.011 t h MJ^{-1} mm^{-1} at Mondomo may be regarded as being between medium and low, the soil losses on the bare fallow plots were very high due to the extreme erosivity of the climate. During the research period from June 1994 to June 1998 913 t ha^{-1} of topsoil were lost on the bare fallow plots in Quilichao with the total loss for the complete period from 1986 to June 1998 amounting to 1,840 t ha^{-1}. In Mondomo 873 t ha^{-1} were lost from June 1994 to June 1998 whilst the total loss from 1986 to 1998 was 2,380 t ha^{-1}.

Soil losses from the cropped treatments were generally much lower compared to the bare fallow treatment. During the period from June 1994 to July 1997, the seven cropped treatments in Quilichao showed susceptibility to erosion in the following order (from high to low):

Sole continuous cassava, bush fallow >> farmer rotation, legume strips > improved fallow > minimum tillage, grass barriers.

In Mondomo the susceptibility to erosion for the same period was (in descending order):

Sole continuous cassava >> legume strips >> bush fallow > improved fallow, farmer rotation > grass barriers, minimum tillage.

After the last cropping season in July 1997 an observation period was maintained until June 1998 during which time all treatments were kept under continuous bare fallow. The objective was to study the possible soil stability enhancing or decreasing effects of the different cropping systems. The eight treatments produced the following order in respect of soil loss amounts (from high to low): sole cassava, bush fallow > continuous bare fallow >> farmer rotation > legume strips >> minimum tillage >> improved fallow, grass barriers. The soil losses from the sole cassava and bush fallow treatments were above 140 t ha^{-1}, whereas the lowest soil losses were recorded from the grass barrier treatment at 0.332 t ha^{-1}.

Soil losses during the same period in Mondomo were considerably lower for all treatments, probably due to lower erosivity. The treatments produced the following order with regard to soil losses (from high to low): sole cassava > bush fallow > continuous bare fallow, legume strips > farmer rotation > minimum tillage > improved fallow > grass barriers. The greatest soil losses reached 20 t ha^{-1} from the sole cassava treatment and the grass barrier treatment produced no soil losses for this period.

When calculating soil losses from a representative plot with a length of 50 m and a slope of 25%, only the minimum tillage and grass barrier treatments reached levels below the tolerable average annual soil losses under both the Quilichao and Mondomo conditions. The others would be not sustainable over longer periods due to the low soil formation rates.

The erosivity and erodibility values for the whole 12-year duration of this project showed that there is a highly significant relationship between annual soil loss amounts and the R-factor of the USLE. For Quilichao a linear regression gave the following result: $A=0.0281\ R - 84.65$ ($r^2=0.85$); for Mondomo $A=0.0127\ R-21.85$ ($r^2 = 0.76$), where A is the annual soil loss in t ha^{-1} and R the R-Factor value in MJ ha^{-1} mm h^{-1}. When eliminating the outlier value for 1997 from Mondomo, where a very low soil loss level together with medium erosivity values were evidenced, r^2 improved to 0.89.

The continuous bare fallow plots in Mondomo showed a strong decline of organic matter, with 52% being lost in 12 years. In Quilichao the original bare fallow plots lost 40.5% of the organic matter from the topsoil during the period from 1986 to 1995 with most of the decline taking place during the first three years. Newly established plots in Quilichao lost 27.6% within 4 years. Most cropped treatments maintained relatively stable organic matter contents, with the exception of the continuous sole cassava treatment which lost 22.4% within eight years in Quilichao and 25.7% in Mondomo.

Productivity of seven cassava-based cropping systems

A very important factor in the adoption of soil conservation measures by the farmers is productivity. If a production system produces lower yields in the short term in comparison to traditional ones, acceptance will be very low. When comparing the two conservation treatments, minimum tillage and grass barriers, with the continuously sole cropped cassava treatment used by the majority of the small scale cassava farmers in the Cauca department, no significant differences concerning yield performance were detected for either trial site during most cropping periods. During one cassava cropping period the minimum tillage treatment reached a significantly greater yield at Quilichao, whereas the grass barrier treatment produced a much higher yield during a phaseolus bean cropping phase at Mon-

domo. The performance of the grass barrier treatment may be considered remarkable in view of the fact that the grass barrier treatments production area is 12.5% smaller compared to all the other treatments, with the exception of the legume strip treatment.

The highest yield levels of all the treatments were achieved by the farmer rotation treatment, however there were no significant differences between this treatment and the minimum tillage treatment at Mondomo and Quilichao. Whilst no major differences were ascertained between the yields obtained in the farmer rotation treatment and the grass barrier treatment at Mondomo, the grass barrier treatment showed significantly smaller yields during all but one cropping period at Quilichao.

Considering the reduced fallow duration periods in the Cauca department hillsides (Ashby, 1985) the improved fallow treatment proved to be a good alternative when taking fodder production and general crop yields into account. However, it should not be used on slopes with inclines of more than 25% as the soil losses would be too high to be sustainable over longer periods.

Conclusions

The results confirm the high erosivity of the climate and support the necessity of maintaining permanent soil cover. The proven applicability of the R-Factor of the USLE for the region and the long-term soil erodibility values determined should enable the potential erosion risk to be estimated and appropriate soil conservation measures offered. Of the cropping systems evaluated, both the minimum tillage and the vetiver grass barrier treatments proved to be interesting alternatives to the local cropping systems as they reduced soil erosion to a sustainable level and at the same time reached or even surpassed the yields of the traditional cassava monocropping. All the other systems would lead to degradation if long-term permanent cropping was practised.

Zusammenfassung

Bodenerosion in Andinen Anbausystemen: Die Auswirkung der Niederschlagserosivität

Hintergrund und Methoden

Die Andine Region Kolumbiens, die etwa ein Drittel des Landes bildet, ist Lebensraum von 15% der Gesamtbevölkerung und von 50% der Landbevölkerung. Bedingt durch die Nutzung der fruchtbarsten und ebenen Gebiete der Andinen Hochtäler zum Anbau von Zuckerrohr und anderen Plantagenkulturen, werden viele Nahrungspflanzen auf Hanglagen angebaut. Ca 85% der Bohnen-, 70% der Mais-, 80% der Weizen-, 80% der Maniok- und 90% der Kartoffelproduktion finden in dieser Region statt. Aufgrund der hohen Bedeutung der Andinen Hanglagen für die Landesnahrungsproduktion ist es alarmierend, dass 84% der Region von Wassererosion betroffen sind, wobei 40% als zwischen moderat und extrem eingeschätzt werden.

In Anbetracht dieser alarmierenden Situation hat die Universität Hohenheim 1986 zusammen mit dem Maniokprogramm des Centro International de Agricultura Tropical (CIAT) ein Erosionsforschungsprojekt begonnen. Zielsetzung war es, die Universal Soil Loss Equation (USLE) an die örtlichen Bedingungen anzupassen und anzuwenden, sowie mehrere Maniokanbausysteme hinsichtlich ihrer Effektivität im Bodenschutz und bezüglich der Einkommenserwirtschaftung zu bewerten. Außerdem sollten Bodenschutzmassnahmen bei den Maniokbauern eingeführt und diese mit verbessertem Pflanzmaterial versorgt werden.

Die Hauptziele der hier vorgestellten Arbeit waren:

a) Den Erosivitätsfaktor R der USLE, insbesonders dessen Energie-Intensitätsrelation, für tropisch-andine Bedingungen zu ermitteln. Langjährige Niederschlagsintensitätswerte für mehrere Wetterstationen in der Versuchsregion zu errechnen und darauf basierend eine Erosivitätskarte zu erstellen.
b) Langjährige Bodenerodierbarkeitswerte (K-Faktor) für zwei Bodentypen der Versuchsregion zu bestimmen.
c) Die Effizienz verschiedener Maniokanbausysteme im Hinblick auf Bodenschutz und Einkommenserwirtschaftung zu bewerten.

Die Versuche wurden an zwei Standorten im Cauca Department im Südwesten Kolumbiens durchgeführt. Der erste Standort ist Santander de Quilichao, bei 3° 6' N, 76° 31' W auf einer Höhe von 990 m über N.N. gelegen. Das langjährige Jahresniederschlagsmittel liegt bei 1,789 mm und die Durchschnittstemperatur bei 23.7 °C. Der zweite Standort, Mondomo, liegt bei 2°53' N, 76°35' W auf einer Höhe von 1,450 m über N.N., mit einer durchschnittlichen Niederschlagsmenge von 2,133 mm und einer Durchschnittstemperatur von 18.2 °C.

Der Boden in Quilichao wurde nach der Amerikanischen Nomenklatur als amorpher, isohyperthermischer Oxic Dystropept klassifiziert, während der Boden am Standort Mondomo als kaolinitisch-amorpher, isohyperthermischer Oxic Humitropept eingestuft wurde. Beide Böden gehören zu den Inceptisolen, die etwa 77% der Böden des Cauca Departments bilden.

An beiden Versuchstandorten wurden Erosionsparzellen auf Hängen mit Gefällen zwischen 7 und 20% eingerichtet. Es wurden acht verschiedene Behandlungen durchgeführt, angelegt mit drei Wiederholungen in Quilichao und zwei in Mondomo. Während der hier beschriebenen finalen Phase des Projektes von 1994 bis 1998 wurden die folgenden Behandlungen mit einander verglichen:

1) Langjährige Schwarzbrache (USLE Standardparzellen), 2) Traditionelle auf Maniok basierende Fruchtfolge, 3) Maniok im Daueranbau, 4) Auf Maniok basierende Fruchtfolge mit Minimalbodenbearbeitung und Mulch, 5) Auf Maniok basierende Fruchtfolge mit vorheriger Buschbrache, 6) Auf Maniok basierende Fruchtfolge mit Vetiver Grassbarrieren im Abstand von 8 m, 7) Auf Maniok basierende Fruchtfolge mit Leguminosenstreifen im Mischanbau, 8) Auf Maniok basierende Fruchtfolge mit verbesserter Brache als Fruchtfolgeelement.

Die USLE Standardparzellen unter Schwarzbrache waren 22.1 m lang und 11 m breit, während die Behandlungen mit Kulturpflanzen 16 m lang und 8 m breit waren. Mit Hilfe von Eternitkanälen am Fuße der Parzellen sowie Filtern und Auffangtonnen wurden nach jedem Niederschlagsereignis Bodenabtrags- und Oberflächenabflussmengen erfasst. Sowohl die Böden in den Parzellen als auch die erodierten Sedimente wurden regelmäßig auf Nährstoffe und Gehalt an Organischer Substanz untersucht. Um langjährige Niederschlagserosivitätswerte für die Standorte zu erhalten, wurden Niederschlagsintensitäten mit Plu-

viografen (Hellman Modell 1509, Lamprecht, Göttingen) erfasst. Außerdem wurden am Standort Quilichao während sechs Regenzeiten in den Jahren 1993-94 sowie 1996-98 Regentropfengrößenverteilungen mit einem Joss-Waldvogel Disdrometer (Distromet, Zürich) erfasst. Zusätzlich wurden über 140 Jahre Intensitätsdaten von vier Wetterstationen der Kolumbianischen Kaffeeanbauerföderation (FEDECAFE) in den Cauca und Valle del Cauca Departments ausgewertet.

Niederschlagserosivität

Die mit dem Disdrometer gemessenen Tröpfchengrößenverteilungen zeigten, dass der R-Faktor der USLE im Einsatzgebiet anwendbar ist, da zwischen den gemessenen Kinetischen-Energiesummen von Niederschlagsereignissen und nach der USLE Methodologie errechneten keine signifikanten Unterschiede festgestellt wurden. Das erosive Potential des Klimas im Untersuchungsgebiet kann als sehr hoch eingeschätzt werden. Die durchschnittliche Energieladung des gesamten Niederschlags lag bei 21 J m^{-2} mm^{-1} an beiden Standorten, während die durchschnittliche Energieladung des erosiven Niederschlags bei 22.3 J m^{-2} mm^{-1} in Quilichao und bei 22.4 J m^{-2} mm^{-1} in Mondomo lag. Beobachtungen anderer Autoren bezüglich des hohen Anteils intensiver Niederschlagsereignisse in tropischen Regionen konnte bestätigt werden. 37.6% der Niederschlagsmenge in Quilichao bzw. 36.3% in Mondomo fielen mit Intensitäten über 25 mm h^{-1}. Ca 20% der Niederschlagsmenge fiel bei Intensitäten über 50 mm h^{-1}, während knapp 6% mit über 100 mm h^{-1} ermittelt wurden. Die höchsten gemessenen Niederschlagsintensitäten waren 540 mm h^{-1} in Mondomo und 468 mm h^{-1} in Quilichao. Die durchschnittlichen jährlichen R-Faktorwerte während der gesamten zwölfjährigen Untersuchungsperiode lagen bei 10,037 and 9,016 MJ ha^{-1} mm h^{-1} jeweils für Quilichao und Mondomo. Die Schwankungen der einzelnen Jahre waren beträchtlich,, mit Werten zwischen 4,891 und 14,496 MJ ha^{-1} mm h^{-1} a^{-1}. Die Auswertung von langjährigen Intensitätsdaten der vier zusätzlichen Wetterstationen zeigte, dass ein hoch signifikanter Zusammenhang zwischen monatlichen R-Faktorwerten und einem modifizierten Fournier-Index besteht. Dieser Zusammenhang ist für die Berechnung von R-Faktorwerten für Regionen in denen keine Intensitätsdaten vorliegen von großer Bedeutung.

Beurteilung der Maniok Anbausysteme im Hinblick auf Bodenschutz- und Ertragsleistungen

Bodenverluste

Während die ermittelten K-Faktorwerte von 0.017 t h MJ^{-1} mm^{-1} für Quilichao und 0.011 t h MJ^{-1} mm^{-1} für Mondomo als mittel bis niedrig gelten können, waren die Bodenverluste auf den Schwarzbracheparzellen, bedingt durch die hohe Erosivität der Niederschläge, sehr hoch. Während der Forschungsphase von Juni 1994 bis Juni 1998 wurden in Quilichao 913 t ha^{-1} Oberboden abgetragen, der Bodenverlust während des gesamten Projektlaufzeit von 1987 bis Juni 1998 betrug 1,840 t ha^{-1}. In Mondomo betrug der Verlust von Juni 1994 bis Juni 1998 873 t ha^{-1}, der Gesamtverlust lag bei 2,380 t ha^{-1}. Da die Dichte des Oberbodens in beiden Standorten bei eins liegt, würde dies einem Verlust von ca. 18 cm Oberboden in Quilichao und ca. 23 cm in Mondomo bedeuten, was in beiden Fällen dem Verlust beinahe des gesamten Oberbodens entspricht.

Bodenverluste auf den bepflanzten Behandlungen waren im allgemeinen viel niedriger verglichen mit der Schwarzbrache. Während der Versuchsphase von Juni 1994 bis Juli 1997 zeigten die sieben bepflanzten Behandlungen in Quilichao folgende Abfolge hinsichtlich der Empfindlichkeit gegenüber Erosion: Maniok im Daueranbau, Buschbrache >> traditionelle Fruchtfolge, Leguminosenstreifen > verbesserte Brache > Minimalbodenbearbeitung mit Mulch, Vetiver Grassbarrieren. In Mondomo wurde folgende Empfindlichkeitsrangfolge festgestellt: Maniok im Daueranbau >> Leguminosenstreifen >> Buschbrache > verbesserte Brache, traditionelle Fruchtfolge > Vetiver Grassbarrieren, Minimalbodenbearbeitung mit Mulch.

Bei Anwendung der ermittelten Bodenabtragswerte aus Quilichao und Mondomo auf ein Standardfeld, dass mit einer Hanglänge von 50 m und einem Gefälle von 25% die allgemein extremeren Bedingungen im Cauca Departement repräsentieren soll, zeigte sich, dass bis auf die Minimalbodenbearbeitungs- und Vetiver Grassbarrierenbehandlungen alle übrigen als nicht nachhaltig gelten können. Dies ist in erster Linie durch die sehr niedrigen Bodenbildungsraten bedingt, die zwischen 1 bis 4 t ha^{-1} und Jahr geschätzt wurden.

Bei Betrachtung der Erosivitäts- und Erodibilitätsdaten der gesamten Projektlaufzeit von 1986 bis 1998 zeigte sich, dass ein hochsignifikanter linearer Zusammenhang zwischen jährlichen Bodenabtragsmengen und dem R-Faktor der USLE besteht. Für Quilichao ergab die lineare Regression die Gleichung: $A = 0.0281 R - 84.65$ (Determinationskoeffizient $r^2=0.85$); für Mondomo $A = 0.0127 R-21.85$ ($r^2 = 0.76$), wobei A der jährliche Bodenabtrag in t ha^{-1} und R der R-Faktorwert in MJ ha^{-1} mm h^{-1} sind. Bei Eliminierung des Ausreißerjahres 1997, wo bei mittlerer Erosivität nur sehr geringe Bodenabtragswerte gemessen wurden, verbesserte sich das Bestimmtheitsmaß in Mondomo auf $r^2=0.89$.

Bodenerosion wirkt sich vor allem durch den Rückgang an Bodenfruchtbarkeit, durch Verlust von Nährstoffen und organischer Substanz negativ aus. Auf den langjährigen Schwarzbracheparzellen in Mondomo ging die organische Substanz in 12 Jahren um 52% zurück. In Quilichao verloren diese Parzellen im Zeitraum von 1987 bis 1995 40.5% der organischen Substanz. Nachdem diese Parzellen wegen beinahe kompletten Verlustes des Oberbodens ersetzt werden mussten, verloren die neu etablierten Parzellen in vier Jahren 27.6%. In den bepflanzten Parzellen blieb die organische Substanz relativ stabil, mit Ausnahme der Maniok im Daueranbaubehandlung, wo die organische Substanz in acht Jahren in Quilichao um 22.4% und in Mondomo um 25.7% zurückging.

Produktivität von sieben auf Maniok basierenden Anbausystemen

Hinsichtlich der Produktivität der untersuchten Anbausysteme zeigte sich, dass in Quilichao die traditionelle Fruchtfolge über vier Jahre die höchsten biologischen Erträge erbrachte, gefolgt von der Fruchtfolge mit verbessertem Brache Element, sowie der Fruchtfolge mit Minimalbodenbearbeitung und Mulch. Am schlechtesten schnitten die Maniok im Daueranbau und die Vetiver Grasbarrieren Behandlung ab, wobei die reduzierte Anbaufläche bei letzterer berücksichtigt werden muss. In Mondomo erbrachte ebenfalls die traditionelle Fruchtfolge die höchsten Erträge während des kompletten Untersuchungszeitraumes, während einzelner Anbauperioden jedoch lagen die Erträge der Minimal Bodenbearbeitung, Buschbrache sowie Verbesserten Brache Behandlungen deutlich über denen der traditionellen Fruchtfolge.

Die am häufigsten von den Landwirten der Region verwendete Anbauform ist Maniok im Daueranbau nach Buschbrache, da die Böden oft bereits so stark degradiert sind, dass finanziell interessantere Kulturen wie Bohnen und Mais nicht mehr anbaubar sind. Während der drei Maniokanbauperioden von 1994 bis 1997 lagen in Quilichao mit Ausnahme der

Grassbarrieren- und Leguminosenstreifenbehandlungen die Erträge der übrigen Behandlungen deutlich über demjenigen, der auf der Fläche mit Maniok im Daueranbau realisiert wurde. Dabei erreichte die Grasbarrieren-Behandlung trotz um 12.5% reduzierter Maniokanbaufläche nahezu das gleiche Ertragsniveau. In Mondomo lagen die Erträge von Maniok im Daueranbau auf gleichem Niveau verglichen mit Minimal Bodenbearbeitung und Buschbrache. Sowohl die traditionelle Fruchtfolge als auch die Grasbarrieren Behandlung erzielten zwischen 25% und 20% höhere Erträge, trotz der reduzierten Maniokanbaufläche bei letzterer.

Schlussfolgerungen

Die Ergebnisse belegen die hohe Erosivität des Klimas in der Versuchsregion und unterstreichen die Notwendigkeit, den Boden das ganze Jahr über zu schützen. Durch die Bestätigung der Verwendbarkeit des R-Faktors der USLE für die Region sowie der erfassten langjährigen Mittelwerte der Erodibilität des Bodens sollte es möglich sein, für weitere Bereiche der Andinen Region Kolumbiens und darüber hinaus das Erosionsrisiko unter Anwendung der USLE abzuschätzen und dementsprechend Bodenschutzmaßnahmen zu empfehlen. Unter den evaluierten Anbausystemen erwiesen sich sowohl die Minimalbodenbearbeitung als auch der Einsatz von Vetiver Grasbarrieren als interessante Alternative zu den lokalen Anbausystemen, da beide die Erosion auf ein sehr niedriges, nachhaltiges Niveau reduzierten und gleichzeitig das Ertragsniveau der herkömmlichen Anbaumethode erreichten bzw. übertrafen. Alle anderen Systeme würden auf längere Sicht zur Degradation und letztlich Verlust der Anbauflächen führen.

Resumen

Erosion de suelos hydrica en systemas de produccion Andinos: el impacto de la erosividad del clima

Objetivos y metodos

La region Andina de Colombia, cubriendo aprox. una tercera parte del pais, es hogar para alrededor de 15% de la populacion total y del 50% de la populacion rural. Debido al uso de la mayor parte de las tierras fertiles y planas para la produccion de azucar y otras plantas de plantaciones, alimentos son producidos netamente en las laderas Andinas. Alrededor el 85% del frijol, 70% del maiz duro, 80% del trigo, 80% de la yuca y 90% de la papa nacional son producidas en esta area. Considerando la alta importancia de las laderas Andinas para la nutricion nacional es alarmante que el 84% de la region Andina esta affectada por erosion hydrica, con casi el 40% considerado entre moderada y extrema.

Considerando esta situacion alarmante la universidad de Hohenheim junto con el programma de yucca del Centro de Internacional de Agricultura Tropical (CIAT) inicio un proyecto de conservacion de suelos en 1987 con el proposito de adaptar y aplicar la ecuacion universal de perdida de suelo (USLE) a las condiciones locales, estudiar la efficacia de varios systemas de produccion de yucca considerando efficacia contra erosion y generacion de ingresos, propagar medidas de conservacion de suelos y proveer la comunidad local campesina con asistencia tecnica y germoplasma mejorado. Los objetivos del trabajo presentado aqui eran:

a) determinar la aplicabilidad del factor de erosividad de lluvias de la USLE para el area de investigacion, con emphasis en la relacion de energia-intensidad, el uso de cual ha sido criticado en climas tropicales. Calcular valores de larga duracion para varias estaciones meteorologicas en el area de investigacion ampliado y crear un mapa de erosividad para el area.

b) establecer valores de erodibilidad de largo plazo para dos tipos de suelos en el area de investigacion.

c) Evaluar el valor de conservacion de suelos y productividad de varios systemas de produccion de yucca

La investigacion se realizo en dos sitios en el departamento del Cauca en el suroeste de Colombia. El primero fue Santander de Quilichao, localisado en 3°6'N, 76°35'W, a una altura de 990 m s.n.d.m., con una cantidad promedia de lluvia anual de 1,789 mm y una temperatura promedia de 23.7°C. El segundo estuvo cerca de Mondomo, en 2 °53'N, 76°35' W a una altura de 1,450 m s.n.d.m. Una precipitacion anual de 2,133 mm y una temperatura de 18.2°C. El suelo en Quilichao se classifico como un Oxic Dystropept amorpho, isohyperthermico, mientras que el de Mondomo se considera un caolinitico-amorpho, isohypertermic Oxic Humitropept. Ambos son inceptisoles, que forman alrededor del 77% de los suelos del departamento del Cauca.

En ambos sitios se establecieron parcelas de escorrentia en 1987 en pendientes entre 7 y 20% con ocho tratamientos y tres repeticiones en Quilichao y dos en Mondomo. Durante la face final del projecto los tratamientos fueron:

1) Barbecho desnudo continuo, 2) Rotacion tradicional basada en yuca, 3) Yuca continua, 4) Rotacion basada en Yuca con labranza minima y mulch, 5) Rotacion basada en yucca con dos años anteriores de barbecho natural, 6) Rotacion basada en yucca con barreras de pasto vetiver, 7) Rotacion basada en yucca con leguminosas intercaladas, 8) Rotacion basada en yucca con elemento de forraje mejorado.

Las parcelas de barbecho desnudo tenian las dimensiones de 22 m de largo y 11 m de ancho, mientras que los tratamientos con cultivos eran de 16 m por 8 m. Se colectaron suelo erodado y escorentia mediante canales de eternit en la parte baja de las parcelas y medidos mediante divisores y barriles de recoleccion. Suelo y sedimentos de las parcelas fueron analizados continuamente por contenido de nutrientes y materia organica. Para determinar valores de erosividad de lluvias de larga duracion se usaron pluviografos (Hellman Modell 1509, Lamprecht, Göttingen, Alemania). Adicionalmente se uso un pluviometro Joss-Waldvogel RD-69 (Distromet, Zürich, Suiza) en Quilichao para medir distribuciones de gotas durante seis epocas lluviosas en los años 1993 to 1994 and 1996 to 1998. Se evaluaron 140 años de datos de intensidad de lluvias de quatro estaciones

meteorologicas de la Federacion de productores de cafe (FEDECAFE, CENICAFE) en los departamentos del Cauca y Valle del Cauca.

Erosividad de lluvias

Distribuciones de tamaños de gotas medidas durante tres años con un distrometro mostraron que el factor R de la USLE es valido para el area de investigacion, ya que no se encontraron diferencias significantes entre energia cinetica de lluvias medida y valores calculados mediante la USLE. El potencial erosivo del clima se puede considerar como muy alto. La carga energetica promedia de la precipitacion total en ambas locaciones era 21.0 J m^{-2} mm^{-1}, mientras que la carga energetica promedio de la lluvia erosiva era 22.3 J m^{-2} mm^{-1} en Quilichao y 22.4 J m^{-2} mm^{-1} en Mondomo.

Los valores mas altos de carga energetica para un solo evento de lluvia alcanzaron 31.0 J m^{-2} mm^{-1}. Observaciones de otros autores se confirmaron considerando porcentajes mas altos de precipitaciones intensas en areas tropicales comparado con areas de clima templado. 37.6% y 36.3% de las lluvias totales en Quilichao and Mondomo calleron con intensidades mas altas que 25 mm h^{-1}. Aproximadamente 20% de la lluvia total cayo con intensidades mas altas que 50 mm h^{-1}, mientras cerca del 6% cayo con intensidades mayores de 100 mm h^{-1}. Las intensidades mas altas alcansadas fueron 540 mm h^{-1} en Mondomo y 468 mm h^{-1} en Quilichao.

Los valores promedio del factor R en los doce años de investigacion para Quilichao y Mondomo fueron 10,037 y 9,016 MJ ha^{-1} mm h^{-1} a^{-1}, respectivamente. Diefrecnias entre los años fueron considerables, con valores oscilando entre 4,891 y 14,496 MJ ha^{-1} mm h^{-1} a^{-1}.

Se analizaron adicionalmente datos de intensidad de lluvias de largo plazo de cuatro estaciones metereologicas en los departamentos del Cauca y Valle del Cauca y se calcularon valores annuales promedios del factor R. Una relacion altamente significante se encontro entre un indice modificado Fournier basado en cantidades promedias de lluvia mensuales y los valroes equivalentes de valores mensuales del Factor R. Con base en estos resultados, se puede assumir que esta relacion puede ser usada para calcular valores confiables del factor R para areas de la region Andina donde no hay datos de intensidad de lluvias.

Evaluacion de systemas de produccion basadas en Yuca considerando erosion y rendimientos

Perdidas de suelo

Mientras que los valores del factor K de 0.017 t h MJ^{-1} mm^{-1} y 0.011 t h MJ^{-1} mm^{-1} medidos en Quilichao y Mondomo respectivamente se pueden considerar de estar entre niveles medianos y bajos, las perdidas de suelo en las parcelas de barbecho desnudo fueron muy altas, debido a la erosividad extrema del clima. Durante el periodo de investigacion entre Junio 1994 y Junio 1998 la perdida total de suelo fue 913 t ha^{-1} en las parcelas de barbecho desnudo la perdida total para el periodo completo desde 1986 hasta Junio 1998 fue de 1,840 t ha^{-1}. En Mondomo la perdida entre Junio 1994 y Junio 1998 fue de 873 t ha^{-1}, mientras que la perdida total desde 1986 hasta 1998 fue de 2,380 t ha^{-1}.

Perdidas de suelo de los tratamientos bajo cultivos fueron generalmente mucho mas bajas comparadas con el barbecho desnudo. Durante el periodo de Junio 1994 hasta Julio 1997 los siete tratamientos en cultivo mostraron su susceptibilidad a la erosion en el siguiente orden (de alto a bajo): Yuca continua, barbecho natural >> rotacion tradicional, leguminosas intercalas > barbecho mejorado > labranza minima, barreras de vetiver.

En Mondomo la susceptibilad para el mismo periodo fue en orden descendiente:

Yuca continua>> leguminosas intercaladas >> barbecho natural > barbcho mejorado, rotacion tradicional > barreras de vetiver, labranza minima.

Despues de la ultima temporada bajo cultivo en Julio 1997 se mantuvo un periodo de observacion hasta Junio 1998, durante este periodo todos los tratamientos se mantuvieron bajo barbecho desnudo. El objetivo era de estudiar possibles effectos aumentando o diminuyendo la estabilidad del suelo de los tratamientos. Los ocho tratamientos mostraron el siguiente orden descendiente considerando perdidas de suelos: yuca continua, barbecho natural > barbecho desnudo >> rotacion tradicional > leguminosas intercaladas >> labranza minima >> barbecho mejorado, barreras de vetiver. Las perdidas de suelo de los tratamientos yuca continua y barbecho natural estuvieron mas altos de 140 t ha^{-1}, mientras que las perdidas mas bajas se medieron en el tratamiento de barreras de vetiver con 0.332 t ha^{-1}.

Perdidas de suelo durante el mismo periodo en Mondomo fueron considerablemente mas bajas considerando todos los tratamientos, probablemente debido a la erosividad mas baja. Los tratamientos mostraron perdidas de suelo en el siguiente orden descendiente: yuca continua > barbecho natural > barbecho desnudo, leguminosas intercaladas > rotacion tradicional > labranza minima > barbecho mejorado > barreras de vetiver. Las perdidas mas altas alcanzaron 20 t ha^{-1} en el tratamiento de yuca continua, mientras que el tratamiento de barreras de vetiver mostro ninguna erosion. Calculando perdidas de suelo para un lote representativo de una longitud de 50 m y una pendiente de 25% solamente los tratamientos de labranza minima y barreras de vetiver alcanzaron niveles debajo del promedio annual tolerable bajo condiciones de Quilichao y Mondomo. Todos los demas tratamientos no serian sostenibles en periodos de tiempo mas largos debido a las tasas bajas de formacion de suelos.
Considerando los valores de erosividad y erodibilidad para el periodo completo de 12 años se mostro que existe una relacion altamente significante entre perdida de suelo annual y el factor R de la USLE. En Quilichao la regression linear dio el resultado siguiente: A=0.0281 R –84.65 (r^2=0.85); en Mondomo fue A=0.0127 R-21.85 (r^2 = 0.76), donde A es la perdida de suelo annual en t ha^{-1} y R el valor del factor R en MJ ha^{-1} mm h^{-1}. Si se elimina el valor extraordinario para 1997 en Mondomo, donde se dieron un nivel muy bajo de perdida de suelos junto con valores medianos de erosividad, el r^2 mejora a 0.89.

Las parcelas de barbecho desnudo en Mondomo mostraron un descenso muy fuerte de la materia organica, perdiendo el 52% en años years. En Quilichao las parcelas originales de barbecho desnudo perdieron el 40.5% de la materia organica del horizonte A durante el periodo de 1986 hasta 1995, la major parte de las perdidas siendo durante los primeros tres años. Parcelas nuevas establecidas en Quilichao perdieron 27.6% en 4 años. La mayoria de los tratamientos en cultivo mantuvieron relativamente estables niveles de materia organica con escepcion del tratamiento de yuca continua que perdio 22.4% en 8 años y 25.7% en Mondomo.

Productividad de los siete systemas de cultivo basados en yuca

Un factor muy importante para la adopcion de medidas de conservacion de suelos por los campesinos es la productividad. Si un systema de produccion produce rendimientos mas bajos en corto plazo comparado con los systemas tradicionales la acceptancia sera muy baja. Comparando los dos tratamientos de conservacion labranza minima y barreras de vetiver, con la yuca continua, el systema mas practicado por los campesinos de escala pequeña en el departamento del Cauca, no se encontraron diferencias significantes considerando rendimientos en ambos sitios para casi todas las temporadas de cultivo. Durante una temporada de cultivo de yuca el tratamiento de labranza minima alcanzo rendimientos significantemente mas altos en Quilichao, mientras que el tratamiento de barreras de vetiver produjo un rendimiento mas alto durante un periodo de cultivo de frijol phaseolus en Mondomo. El rendimiento en el tratamiento de barreras de vetiver es notable ya que el area de cultivo es 12.5% menos comparado con todos los tratamientos menos el de leguminosas intercaladas. Los rendimientos mas altos se produjeron en el tratameinto de rotacion tradicional, pero no hubo diferencias significantes entre este tratamiento y el de labranza minima en Quilichao y Mondomo. Mientras que no se dieron diferencias signifcantes entre los rendimientos cosechados en la rotacion tradicional y el tratamiento de barreras de vetiver en Mondomo, el tratamiento de barreras de vetiver mostro rendimientos significantemente mas bajos durante todos periodos de cultivo menos uno en Quilichao.

Considerando el decremento de la duracion del tiempo de barbecho en las laderas del departamento del Cauca (Ashby, 1985) el tratamiento de barbecho mejorado mostro ser una buena alternativa considerando produccion de forajes y rendimiento general de cultivos. De toda manera no deberia ser usado en pendientes mas de 25%, ya que las perdidas de suelo serian demasiado altas para ser sostenibles para periodos mas largos de tiempo.

Concluciones

Los resultados confirman la alta erosividad del clima y apoyan la necesidad de mantener cobertura del suelo permanente. La confirmacion de la aplicabilidad del factor R de la USLE para la region y los valores de largo plazo de erodibilidad del suelo determinados deberian permitir estimar el riesgo potencial de erosion y ofrecer medidas respectivas de conservacion. Entre los tratamientos evaluados ambos el systema de labranza minima y las barreras de vetiver mostraron ser una alternativa interesante a los systemas usados locales, ya que redujieron la erosion de suelos a un nivel sostenible y al mismo tiempo alcanzaron o sobrepasaron los rendimeintos de la yuca continua. Todos los otros systemas evaluados llevarian a degradacion si se usaran en largo plazo.

1 General introduction

1.1 Erosion: worldwide situation

The further population increases anticipated during the coming decades mean that, for the most part, the areas that are currently being cultivated will have to feed more and more people. By 2020 the world population is expected to be close to 8 billion, with food grain and livestock production in developing countries expected to increase at lower rates than in previous decades (Scherr, 1999). As the increased use of land suitable for cultivation faces numerous constraints - such as the low availability of water for irrigation or the high cost of drainage systems, as well as ecological conflicts when considering the conversion of rainforests and other ecosystems into cultivated land - the primary solution to the problem of feeding more people would be to increase yields in presently cultivated areas (El-Swaify, 1991; Hudson, 1995). The requirements and investments necessary for this are often hindered by deficiencies in infrastructure and access to funding. Therefore, conserving the productivity of the current cultivated land and preventing further soil degradation is of the utmost importance.

According to El-Swaify (1991) about 10 ha of arable land are lost every minute with 50% being caused by soil erosion. Lal (1994) estimated that 915 million ha in the tropics have been degraded by water erosion. Worldwide costs incurred by erosion are estimated at 400 billion USD (Jones et al., 1997) and Pimentel et al. (1995) estimated the total annual cost of erosion at 44 billion USD solely for the USA.

Assuming that the land irretrievably lost due to soil degradation is put at the lowest figure, 5 million ha a^{-1}, Scherr (1999) estimates that between 1990 and 2020 about 150 million ha would be lost to production, which is the equivalent to almost 1.7% of the total agricultural land. The worst-case scenario of an annual loss of 12 million ha would lead to a 4.1% loss of agricultural land by 2020. However, about half of the worldwide soil degradation is caused by erosion, hence the high priority to conserve land currently under cultivation and implement sustainable cropping systems.

In addition to the direct impact on farms, soil erosion causes considerable off-site problems. It reduces the useful life span of reservoirs and hydro-electric power plants, causes eutrophication and pollution of streams and wetlands through the translocation of nutrients and pesticides washed out from upper areas of the watershed, has a negative impact upon environmental quality through the loss of landscape traits, threatens biodiversity in relation to both flora and fauna and possibly even impacts upon the global climate due to the reduced carbon sequestration of agricultural land (Brown and Wolf, 1984; Napier, 1991; Morgan, 1995; Scherr, 1999; Lal 1999).

1.2 Erosion: situation in Colombia

The soil erosion problems in Colombia were already recognized as a serious threat in around 1950. Basic research done by the Coffee Growers' Association (FEDECAFE) shows soil loss amounts of up to 200 t ha^{-1} a^{-1} from bare fallow plots. FEDECAFE and other institutions commenced various research and technical assistance programs that are still ongoing today (Lal R., 1977B; Lecarpentier et al., 1980; Gomez A., 1981; Rivera J.H., 1998). The Cassava Programme of the Centro International de Agricultura Tropical (CIAT) started researching erosion-related problems in the Andean hillsides in the early 1980s, and as part of this project Howeler (1984) performed erosion trials in the Cauca department in Colombia on slopes with a gradient of 27%, reporting soil losses of between 18 and 106 t ha^{-1} for several cassava cropping systems.

The erosion and therefore sediment load of Colombian rivers has increased dramatically during the last decade. The Instituto de Hidrología, Meteorología y Adecuación de Tierras (HIMAT) (1984) reported an annual sediment amount of 158 t km^{-2} a^{-1} for the high Cauca region and in 1997, the Corporacion Regional Valle del Cauca (CVC) estimated an annual sediment amount of 646 t km^{-2} a^{-1} for the same watershed (CVC, 1997). According to Brown and Wolf (1984) the Anchicaya reservoir, constructed in Colombia near Cali, lost 25% of its storage capacity during the first two years following completion due to siltation brought about by severe erosion in the feeding watershed.

As many fertile flat areas in the inter-Andean valleys are owned by a few, often corporate entities and are generally used to produce plantation crops such as sugarcane, the pressure upon marginal hillside areas is also increasing. Poor farmers in particular are often forced to move to such areas as they are unable to compete for the more fertile and accessible lands. This movement towards areas where the steepness of the terrain and the high erosivity of the climate facilitate soil erosion is further accelerated by migration movements caused by political instability and civil war (Fidar, 1999). Often, these displaced people migrating from very dissimilar ecological and topographical environments do not have the appropriate knowledge or proper technologies to implement sustainable cropping systems, thus further increasing erosion risks. In addition, marginal lands already prone to erosion and degradation are primarily cultivated by poor farmers who do not possess the economic means to restore or even maintain soil productivity (Jackson and Scherr, 1995).

According to the Instituto Geografico Agustin Codazzi (IGAC) (1988), the annual area lost in Colombia due to land degradation ranges between 170,000 to 200,000 ha. Table 1 shows that almost 50% of the total Colombian territory is affected, at least to some degree, by soil erosion.

Table 1. Areas in Colombia as affected by erosion

Degree of erosion	Area (ha)	% of total area
Extreme	829,575	0.7
High	8,875,575	7.8
Moderate	14,703,750	12.9
Light	32,134,896	28.2
Not eroded	55,371,995	48.5
Other	2,259,049	2.0
Total	114,174,800	100.0

Source: IGAC (1988), modified

Recent analyses of satellite imagery and field surveys performed during 1999-2000 showed that 80% of the Colombian territory is regarded as being affected by erosion to some degree (Ministerio del Medio Ambiente, 2000).

The Andean region of Colombia, covering about one third of the country, is home to about 15% of the total population and 50% of the rural population. As most of the fertile and flat areas are utilized for the production of sugar and other plantation crops destined for industrial use or exportation, food crops are generally grown on the hillsides. About 85% of bean, 70% of hard maize, 80% of wheat, 80% of cassava and 90% of potato production takes place in this region (Howeler, 1984). Considering the extreme importance of the Andean hillsides for the national food production, it is alarming that some 84% of the area is affected by erosion as shown in Table 2.

Table 2. Areas of the Andean region of Colombia as affected by erosion

Severity	Area (ha)	% of total area
Extreme	204,000	0.6
High	3,206,000	9.3
Moderate	10,433,000	30.1
Light	14,019,000	40.5
Very Light	1,209,000	3.5
Total	29,071,000	84.0

Source: IGAC (1988), modified

In response to this alarming situation, the University of Hohenheim, together with CIAT's cassava program, started an erosion research project with a view to adapting and applying the Universal Soil Loss Equation (USLE) to the local situation. It also aimed to study various cassava-based cropping systems in relation to their effectiveness and potential to control erosion and generate income, propagate conservation measures and provide the local farming communities with technical advice as well as improved germplasm. The present study portrays the final phase of the project, from 1994 to 1998, with specific emphasis on the rainfall erosivity factor of the USLE.

2 Materials and Methods

2.1 USLE

The USLE equation was developed by Wischmeier and Smith (1978) to provide farmers and conservation planners with a tool enabling them to consider the necessary measures for erosion prevention under specific circumstances at a given location. Long-term average soil losses can be estimated by means of the USLE which consists of six factors, of which only R and K have units and the others are dimensionless:

(1) $$A = R\,K\,L\,S\,C\,P$$

where A is the soil loss amount in t ha^{-1} for a given time period, commonly a year or a cropping season. R is the climate factor, K expresses the soil erodibility, L and S are the slope length and slope angle factors, C the crop factor and P includes the protection measures.

2.1.1 R-Factor

R expresses the rainfall erosivity in the unit MJ ha^{-1} mm h^{-1}. Wischmeier and Smith (1978) considered all rainfall events over 12.7 mm or with more than 6.4 mm falling within 15 minutes as erosive. Two events falling within less than 6 hours are treated as one event. After examining more than 10,000 plot years of erosion-related data they found that the erosivity index best related to soil loss was the EI_{30}. It is calculated by multiplying the sum of the energy of all increments of a given storm with the maximum average intensity sustained for 30 minutes. The R-Factor is calculated as the sum of all EI_{30} values from events considered as erosive for a particular period of time. The rainfall data in this study was recorded by raingauges (see below) working with a monthly sheet. Every erosive rainstorm on the sheet is evaluated in segments according to the breakpoint technique, recording time and cumulative rainfall amount for each segment representing a period of constant intensity (Armstrong, 1990). The kinetic energy of each segment is then calculated according to the formula:

(2) $$E_S = 0.119 + 0.0873 \log_{10}(I_S)\, A_S$$

where E_S is the kinetic energy in MJ ha^{-1}, I_S is the intensity of a segment in mm h^{-1} and A_S is the rainfall amount of the segment in mm. As, due to physical drop size limitations, the energy of rainfall is not supposed to increase further above an intensity level of 76 mm h^{-1}, a constant is used:

(3) $$E_S = 0.283\ A_S$$

EI_{30} is computed according to the following equation with EI_{30} in MJ ha^{-1}mm h^{-1}, I_{30max} in mm h^{-1} and E_S the energy of a storm increment:

(4) $$EI_{30} = I_{30max} \sum_{S=1}^{n} E_s$$

2.1.2 K-Factor

K expresses the erodibility or vulnerability of the soil in relation to erosion and is defined as soil loss rate per erosion index unit expressed in t h MJ^{-1} mm^{-1}. K can either be obtained from measurements on a standard unit plot (see equation 5) with a length of 22.1 m, an uniform slope of 9%, which has to be maintained in continuous bare fallow, or by using a nomograph representing a wide number of soil types in the US (Equation 6) (Wischmeier and Smith, 1978).

Equation 5 shows K as calculated from field measurements, where K is t h MJ^{-1} mm^{-1}, A the soil loss in t ha^{-1} representing a specified period and EI_{30} the R-Factor in MJ ha^{-1}mm h^{-1} for that period.

(5) $$K = \frac{\sum_{j=1}^{n} (A)}{\sum_{j=1} (EI_{30})_j}$$

Equation 6 shows K calculated according to Wischmeier and Smith (1978) and converted into SI units by Foster et al. (1981), where M is the sum of the percentages of silt and very fine sand (0.1 – 2.0 mm) multiplied with the sum of percentages of silt and sand; OM is the per

centage of organic matter, s an aggregate class and p the soil-permeability class.

(6) $$K = 0.277\ (10^{-6})\ M^{1.14}\ (12 - OM) + 0.0043\ (s - 2) + 0.0033\ (p - 3)$$

2.1.3 L- and S-Factors

As most plots used differ from the USLE standard plots in terms of the angle of the slope and the length, the soil loss values obtained from these plots have to be corrected. The equation used for this correction is:

(7) $$LS = \left(\frac{x}{22.13}\right)^n \left(0.0065 + 0.045s + 0.0065s^2\right)$$

where x is the slope length in meters and s is the slope gradient in %. The exponent n varies according to the angle of the slope, being 0.5 for slopes 5% as found at the two research sites. This relationship has been validated with slope gradients of up to 45% in Guatemala (Akeson and Singer, 1984) and has been adapted for slopes up to 70% (Bergsma, 1996).

2.1.4 C-Factor

The C-Factor is the crop management factor, characterizing the relative amount of soil loss under a specific cropping system compared to the soil loss from permanent bare fallow. Soil loss from permanent bare fallow is generally much higher than that from cropping systems. The vulnerability of a cropping system in relation to erosion hazards comprises the effects and interactions of soil cover, the crops used and general management practices. The values used are generally average annual values consisting of different crop growth phases. For annual crops, the following phases are used (according to Wischmeier and Smith, 1978):

Period F	Rough fallow	inversion ploughing to seed-bed establishment
Period SB	Seed bed	seed bed tillage to 10% crop cover
Period 1	Establishment	10 to 50% crop cover
Period 2	Development	50 to 75% crop cover
Period 3	Maturity	75% crop cover to harvest
Period 4	Residue	Harvest to new ploughing or seeding

As the soil preparation in this study was done in a single step, the first two phases were treated as one. The annual averages are calculated by adding the individual C-Factor values for the phases, which are weighted according to the corresponding percentage of the annual R-Factor. There is a large database of C-Factor values for cropping systems in the US, as well as for several tropical regions. In our study, soil cover was estimated by the use of a quadrat sighting frame.

2.1.5 P-Factor

All erosion control measures such as contour cropping, terracing, grass strips and all other measures whose main purpose is to reduce slope length and thus runoff water velocity and sediment transport are included in the USLE in the form of the P-Factor. It is defined as the ratio of soil loss from plots where erosion control measures are applied to that from plots with up and down slope cultivation.

2.2 Alternative erosivity indices

As the USLE was derived from data originating entirely from temperate regions, various researchers in tropical areas found that the R-Factor in particular did not adequately describe tropical rainfall effects. They developed and tested alternatives, the best known among these being the KE>25 mm h^{-1} by Hudson (1995), the AI_{max} by Lal (1976) and the EIA by Foster (1982). Table 3 shows single erosivity indices as well as their combinations as evaluated in this study. The squares of some indices such as I_{30}^2 and $E(I_{30})^2$ were also evaluated together with an index taking account of the antecedent rainfall. The formula to calculate kinetic energy used by Hudson (1995) was:

(8) $$KE = \sum_{s=1}^{n} 30 - \frac{125}{I} A_S ,$$

where KE is the sum of the kinetic energy in J m^{-2} of all storm increments falling at intensities of higher than 25 mm h^{-1} , I is the intensity in mm h^{-1} and A_S the rainfall amount of the storm increment in mm.

These indices are not an alternative to the R-Factor when applying the USLE but have proved to be more precise in describing the relationship between the climate’s erosivity and soil losses under tropical conditions where R proved to be inadequate. As doubts about the USLE’s applicability to the local climate have been raised in earlier research activities, these indices were also evaluated (Ruppenthal, 1995; Felske, 2000).

Table 3. Several erosivity indices evaluated

Erosivity index	Description	Unit
A	Rainfall amount	Mm
R	Runoff amount	Mm
E	Kinetic energy	MJ ha^{-1}
I_{30}	Maximum intensity during 30 minutes	mm h^{-1}
EI_{30} (R-Factor)	Kinetic Energy times I_{30}	MJ ha^{-1} mm h^{-1}
AI_{30}	Rainfall amount times I_{30}	mm^2 h^{-1}
AEI_{30}	Rainfall amount times kinetic energy times I_{30}	MJ ha^{-1} mm h^{-1}
KE>25	Kinetic energy of all increments that fell at $I \geq 25$ mm h^{-1}	J m^{-2}
EIA	Product of (Runoff volume)$^{-0.5}$ and I_{30}	mm mm h^{-1}
AI_{max}	Product of rainfall amount and $I_{7.5}$	mm mm h^{-1}
$(A+A_n/n)\ I_{30}$	Influence of rainfall prior to the erosive event (n = 3-5 days)	mm mm h^{-1}

2.3 Trial Locations and Methodology

The main part of the erosion trials was conducted at the Centro International de Agricultura Tropical (CIAT) experimental station at Santander de Quilichao, Cauca Department in the Southwest of Colombia, located at 3^{o}6' N, 76^{o}31' W. This site is located at the southern part of the Cauca River valley at an altitude of 990 m a.m.s.l. between the Western and the Central Cordillera. The landscape is characterized by small hills. The experiment was started in 1986 on moderate slopes with gradients of between 7 and 13%.

The trial site in Mondomo, Cauca was established on a field of a smallholder farmer in 1987. It is located 20 km to the south of Quilichao at 2^{o}53' N, 76^{o}35' W in the Central Cordillera at an altitude of 1,450 m a.m.s.l., with slope gradients ranging from 12 to 20%.

Additionally, long-term rainfall intensity data from four meteorological stations were analyzed and included in the study. These stations were operated by the Colombian Coffee Producers' research center (CENICAFE), two of them being located in the Cauca and two in the Valle del Cauca Department. These additional data sets from the southern parts of the Cauca department allowed a more detailed analysis of the region's climate erosivity. 43 years of rainfall intensity data were analyzed for the El Tambo station (2^{o}25'N 76^{o}45'W; 1,700 m a.m.s.l.) and 32 years for the La Florida station (2^{o}27'N 76^{o}35W; 1,800 m a.m.s.l.). El Tambo is located 75 km southwest from Quilichao whilst La Florida lies 64 km to the southwest, close to the department's capital Popayan. The El Tambo rainfall records comprised the period from 1956 to 1998 and these were analyzed according to the USLE criteria. The EI_{30} values for 1,800 erosive rainfall events were calculated. The La Florida station contributed 32 years of rainfall recordings and a total of 1,485 erosive rainfall events. Furthermore, data from the two nearest stations of CENICAFE in the Valle del Cauca department were examined. The results from the Trujillo station 130 km northwest of Quilichao in the Western Cordillera (4^{o}10'N 76^{o}21'W; 1,380 m a.m.s.l.) were based on 25 years of rainfall. The Restrepo station (3^{o}49' N 76^{o}31'W; 1,360 m a.m.s.l.) located 100 km northwest of Quilichao in the Western Cordillera showed very low R-Factor values and had the lowest average annual rainfall amount of 1,100 mm. 39 years of rainfall data were analyzed.

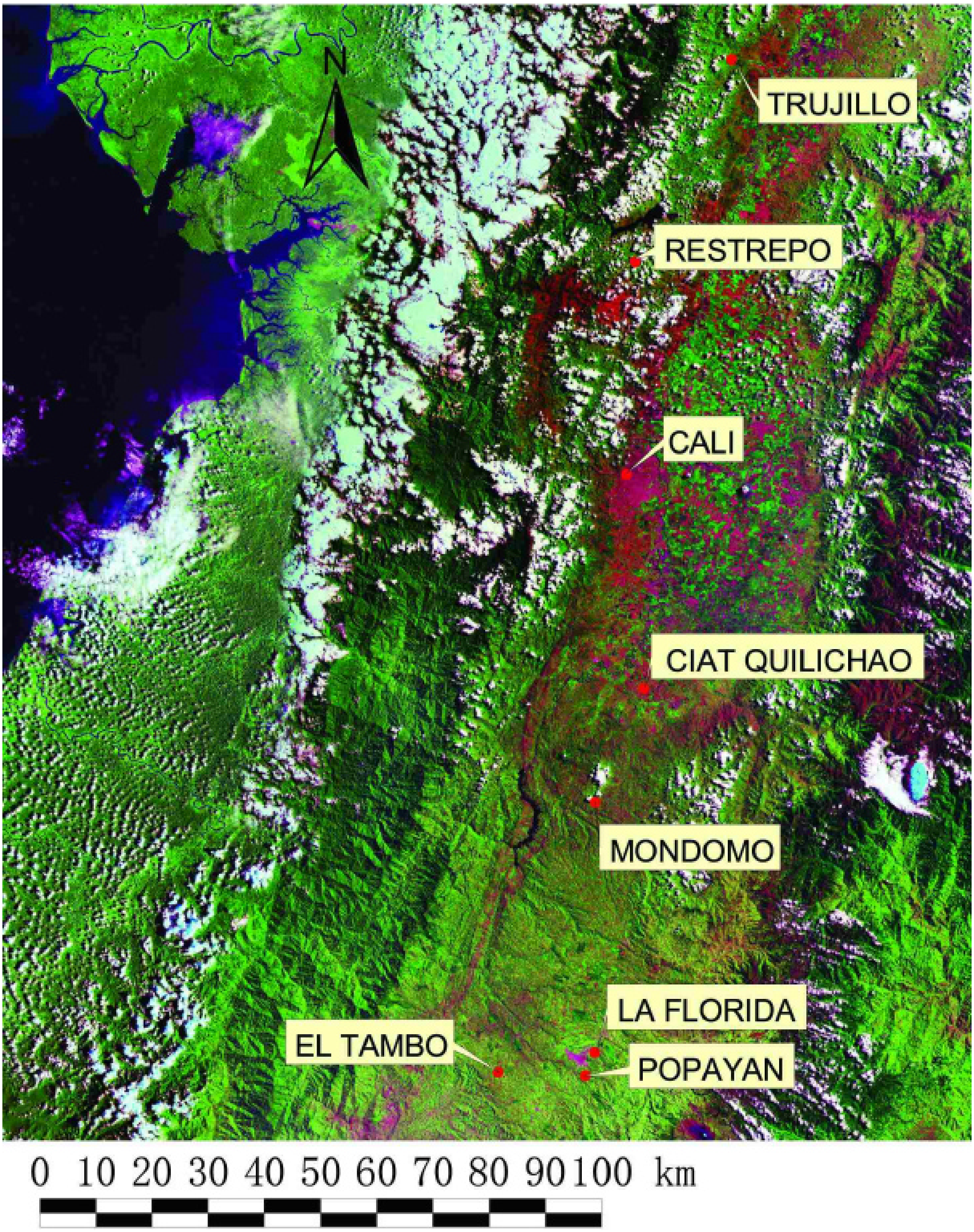


Figure 1. Landsat mosaic image (N-18-00) of the project area with the two main trial sites and the four CENICAFE climate stations. Changed from Global Landcover Facility.

2.3.1 Climate

The climate at both experimental sites is characterized by bimodally distributed rainfall with maxima in April/May and October/November. Dry seasons lasting from June to August and December to February may occur. The mean annual rainfall (30 years) is 1,789 mm for Quilichao and 2,133 mm (25 year average) for Mondomo. The average temperature is 23.7^{o}C at Quilichao and 21.5^{o}C at Mondomo.

2.3.2 Soils

The soils at both trial locations are Inceptisols, representative of about 77% of the soils found in the Cauca department. They comprise mainly young and poorly developed soils. The soil at Quilichao was classified as an amorphous, isohyperthermic Oxic Dystropept with high infiltrability, a low pH and generally low fertility. The soil at Mondomo was categorized as a kaolinitic amorphous, isohyperthermic oxic Humitropept, with physical and chemical soil parameters very similar to those of Quilichao.

2.3.3 Rainfall measurements

To establish the R-Factor for the trial region, rainfall intensity was recorded continuously by means of raingauges (Hellmann, Model 1509-20, Lamprecht, Göttingen, Germany). The resulting monthly sheets were analyzed manually in part, the 1993-1994 period was digitally analyzed by the Meteorology Department of the University of Stuttgart and the years from 1995-1997 were analyzed by the Meteorology Department of the University of Hannover. In addition a Distromet disdrometer (Distromet, Zürich, Switzerland) was used to measure raindrop size distributions (see chapter 3.2).

2.3.4 Collection of eroded soil and runoff water

To measure the K-factor, USLE standard plots were installed according to Wischmeier and Smith (1976). They were maintained in permanent bare fallow and were 22.1 m long and 11 m wide. The plots for the rest of the treatments were 16 m long and 8 m wide. To avoid the entrance of runoff-water from areas outside the plots, 30 cm high zinc plates were installed both on the upper and lateral sides and fortified by small dams. Both water runoff and eroded soil were collected in small Eternit® channels positioned at the lower part of the plots. The channels were installed at a slight angle so that the runoff-water flowed through a filter and was separated from the heavier sediments. Floating sediments were further processed in three sedimentation chambers connected to a splitter with 15 outlets. These were installed to avoid runoff loss during prolonged or very heavy rainfall when the runoff amount could exceed the storage capacity of the collection drums. The greater size of the standard plots necessitated the installation of bigger splitters with 25 outlets. Runoff water was measured whenever it occurred, whereas eroded soil was recorded after each erosive event for the standard plots. For the rest of the treatments eroded soil was only collected after severe erosive events as the amounts were generally quite small (below 1 kg) and in most cases only a monthly collection was necessary.

2.3.5 Treatments

Of the originally eight treatments established at Quilichao and Mondomo in 1987 (Reining, 1992), seven were changed several times during the project duration as some had proved to be unsustainable in terms of erosion or not economically interesting to the farmers and were therefore abandoned. Also, new research topics were introduced. The only treatment that remained unchanged for the whole duration was the bare fallow. The treatments listed below were managed in the form described during the period June 1994 to June 1998 (Table 4).

Treatment 1: USLE standard plots maintained in continuous bare fallow

Treatment 2: Cassava-based conventional crop rotation with organic fertilizer (chicken manure)

Treatment 3: Sole cassava (first established in 1990), consisted of continuously sole cropped cassava from 1990 to 1997, only during the last cropping period (97A see Table 6) cassava was replaced by *Vigna unguiculata* L. Walp. in Quilichao and P*haseolus vulgaris* L. in Mondomo

Treatment 4: Cassava-based rotation with minimum tillage and mulch application

Treatment 5: Cassava-based rotation with bush fallow

Treatment 6: Cassava-based rotation with vetiver grass barriers (*Vetiveria zizanioides* (L.) Nash.) and organic fertilizer (chicken manure)

Treatment 7: Cassava-based rotation with legume strips (*Vigna unguiculata* L. Walp. in Quilichao and *Phaseolus vulgaris* L. in Mondomo)

Treatment 8: Cassava-based rotation with improved fallow (*Brachiaria decumbens* Stapf and *Centrosema macrocarpum* Benth)

Table 4. Description of the different cassava-based cropping systems for Quilichao and Mondomo

Time period Duration	94B* 6.94-4.95	95A 5.95-9.95	95B 10.95-3.96	96A 4.96-3.97	96B 4.96-7.96	97A 4.97-7.97	OP 9.97-5.98
Treatment 1	Bare Fallow	Bare Fallow	Bare Fallow	Bare Fallow	Bare Fallow	Bare Fallow	Bare Fallow
Treatment 2	Cassava	Maize	Maize	Cassava	Cassava	Cowpea[2]	Bare Fallow
Treatment 3	Cassava	Cassava	Cassava	Cassava	Cassava	Cowpea[2]	Bare Fallow
Treatment 4	Cassava	Maize	Maize	Cassava	Cassava	Cowpea[2]	Bare Fallow
Treatment 5	Cassava	Maize	Maize	Cassava	Cassava	Cowpea[2]	Bare Fallow
Treatment 6	Cassava	Maize	Maize	Cassava	Cassava	Cowpea[2]	Bare Fallow
Treatment 7	Cassava + Legumes[1]	Maize + Cowpea[2]	Maize + Cowpea[2]	Cassava	Cassava Cowpea[2]	Cowpea[2]	Bare Fallow
Treatment 8	Cassava	Maize	Maize	Improved fallow[3]	Improved fallow[3]	Improved fallow[3]	Bare Fallow

1 *Centrosema macrocarpum* Benth, *Chamaechrista rotundifolia* (Persoon) (CIAT No. 8990) Greene, *Galactia striata* (Jacq.)
2 in Mondomo Cowpea was replaced by *Phaseolus vulgaris* L.
3 *Brachiaria decumbens* Stapf together with *Centrosema macrocarpum* Benth.
* A and B refer to the respective first and second cropping seasons realized during the specific year

The last period was used as an observation period to establish the effects of the cropping systems on soil aggregate stability and other K-factor related parameters not included in the present study. From September 1997 to June 1998, all the plots were left in continuous bare fallow after uniform soil preparation in all treatments with a rotary tiller. Plots were kept clean of weeds with hand hoes and shovels. The plots were raked to establish homogenous conditions after all rainfall events causing the formation of rills.

2.3.6 Antecedent history

During the two years preceding the research period presented in this study, i.e. September 1992 to June 1994, Treatment 2 (Farmer rotation) at Quilichao went through two crop cycles of cowpea with chicken manure (phaseolus beans in Mondomo). Treatment 3 (Sole cassava) was already maintained as cassava sole crop at both sites, whereas Treatment 4 (Minimum tillage) was under an improved fallow with *Brachiaria decumbens* Stapf and *Pueraria phaseoloides* (Roxb.) Benth. established with minimum tillage. Treatment 5 (Bush fallow) was kept under bush fallow without any external input. The vetiver barriers in Treatment 6 (Grass barriers) had already been established in 1990 both in Quilichao and Mondomo and the previous two crops planted between the vetiver barriers were cowpea in Quilichao and phaseolus beans in Mondomo. In Treatment 7 (Legume strips) the two previous crop cycles were cassava with strips of *Centrosema acutifolium* Benth and *Centrosema macrocarpum* Benth. in the first cycle and cassava with strips of *Centrosema macrocarpum* Benth, *Galactia striata* (Jacq.) Urb. and *Chamaecrista rotundifolia* (Peerson) Greene (CIAT No. 8990). Treatment 8 (Improved fallow) had been fallowed with *Brachiaria* *decumbens* Stapf and *Centrosema macrocarpum* Benth. with conventional tillage when established in 1992. Table 5 shows the history from 1987 onwards.

Table 5. Description of the different cassava-based cropping systems for Quilichao and Mondomo

Time period	87-88	88-89	89-90	90-91	91-92	92-93	93-94
Treatment 1	Bare Fallow	Bare Fallow	Bare Fallow	Bare Fallow	Bare Fallow	Bare Fallow	Bare Fallow
Treatment 2	Cassava flat	Cassava flat	Cassava monoculture	Cassava contour ridges	Cassava contour ridges	Cowpea	Cowpea
Treatment 3	Cassava contour ridges	Cassava contour ridges	Mulch, Pasture	Cassava monoculture	Cassava monoculture	Cassava monoculture	Cassava monoculture
Treatment 4	Cassava Ridges down slope	Cassava Ridges down slope	Cassava, Pennisetum	Cassava, Kudzu, MT	Cassava, Kudzu, MT	Cassava, Kudzu, MT	Cassava, Kudzu, MT
Treatment 5	Cassava intercropped cowpea contour rows	Cassava intercropped cowpea contour rows	Maize, Mulch	Cassava, Zornia	Cassava, Zornia	Fallow	Fallow
Treatment 6	-	-	-	Cassava, Vetiver barriers	Cassava, Vetiver barriers	Cowpea, Vetiver barriers	Cowpea, Vetiver barriers
Treatment 7	Cassava grass contour strips	Cassava grass contour strips	Cassava, Peanut	Cassava, Centrosema acutifolium	Cassava, Centrosema acutifolium	Cassava, Centrosema acutifolium	Cassava, Centrosema acutifolium
Treatment 8	Cassava minimum tillage	Cassava minimum tillage	Cassava contour ridges	Cassava, Pennisetum purpureum	Cassava, Pennisetum purpureum	Kudzu, Brachiaria decumbens	Kudzu, Brachiaria decumbens

2.3.7 Soil preparation and planting

The soil was prepared with a rotary tiller except in the case of the minimum tillage treatment (T4) where hand hoes were used to prepare the planting holes. Hoes, shovels and rakes were used to prepare the seed bed in all other treatments. Weeding was either performed with a machete or hand hoe. In the minimum tillage treatment mulch suppressed weed growth most of the time and where necessary, weeds were cut with a machete. The USLE standard plots (T1) were tilled up and down slope with a rotary tiller twice a year and raked and leveled with hand hoes whenever rills occurred after heavy rainfall events. Weeds were also removed manually.

Cassava grown as the sole crop was planted at 1.0 m by 0.8 m in a triangular pattern (12,500 plants ha^{-1}). Cowpea and phaseolus beans were seeded at 0.1 m by 0.6 m (approx. 160,000 plants ha^{-1}), when grown as sole crops. The vetiver grass barriers (T6) were planted every eight meters as a double row with one plant every 0.3 m by 0.3 m, occupying 12.5% of the plot area. In the legume strip treatment (T7) rows of cowpea or Phaseolus beans were planted at a plant distance of 0.1 m between the cassava or maize rows. During the first cassava period from June 1994 to April 1995 this treatment consisted of cassava planted in three rows of 0.8 m by 0.6 m alternating with three strips of *Centrosema macrocarpum* Benth., *Galactia striata* (Jacq.) Urb. and *Chamaecrista rotundifolia* (Peerson) Greene. planted at 0.5 m by 0.1 m.

2.3.8 Fertilization

During the 94B period the farmer rotation and grass barrier treatments received 2 t ha^{-1} of chicken manure which resulted in a fertilization equivalent of 90 kg N ha^{-1}, 17 kg P ha^{-1} and 55 kg K ha^{-1} (Felske, 2000). The sole cassava, minimum tillage, bush fallow, legume strips and improved fallow treatments received 30 kg ha^{-1} N, 60 kg ha^{-1} P and 60 kg ha^{-1} K applied as a compound fertilizer (10-20-20).

The farmer rotation and grass barrier treatments received 2 t ha^{-1} of chicken manure during the two maize periods 95A and 95B. 400 kg ha^{-1} of dolomitic lime were applied in the sole cassava treatment by broadcast manual application prior to soil preparation. In addition, 300 kg of 10-20-20 were applied 45 days after planting. 7.8 t ha^{-1} of *Brachiaria decumbens* Stapf (approximately 2 t ha^{-1} of dry matter) were used as mulch in the minimum tillage treatment. The minimum tillage, bush fallow, legume strips and improved fallow treatments received 200 kg ha^{-1} of triple super phosphate, 100 kg ha^{-1} of urea and 50 kg ha^{-1} of KCl.

During the second cassava period from June 1996 to March 1997 the traditional rotation and grass barrier treatments received 2 t ha^{-1} of chicken manure, whereas the sole cassava, minimum tillage, bush fallow and legume strips treatments received 300 kg ha^{-1} of 10-20-20.

Chicken manure was selected as it is the main organic fertilizer source for the farmers in the region due to its availability and relatively low price.

2.3.9 Varieties

During the first cassava cropping cycle the variety used was CM 2136-2 and during the second it was CM 523-7. The cowpea variety used in Quilichao was Verde Brasil whilst the local phaseolus variety ICA-Caucaya was cultivated in Mondomo.

2.4 Chemical soil analysis

The soil organic matter was analyzed by wet ashing with a $K_2Cr_2O_7$-H_2SO_4 solution and subsequent photometric measurement of the Cr^{3+} content according to Walkley and Black (from Salinas and Garcia, 1985). The total N in soil and sediments was analyzed according to Kjeldahl (Bremner and Mulvaney, 1982) and the available P fraction was determined with the Bray II method (Salinas and Garcia, 1985). The total phosphorous was determined colorimetrically after fusion with Na_2CO_3 from the water soluble extract (Olson and Sommers, 1982). The extraction of available Potassium was performed with a solution of NH_4Cl and determined with AAS (Salinas and Garcia, 1985)

2.5 Statistical analysis

All statistical analyses were performed using the SAS program version 6.12 (SAS, 1996). Linear regressions were executed with PROC REG and PROC NLIN and variance analysis was completed with the general linear model procedure. The Shapiro-Wilk-test was applied to check the variables for normality in distribution for p   0.05. The mean soil losses from the treatments were compared with the Ryan-Einot-Gabriel-Welsh multiple range test at á = 0.05 and mean comparisons between two groups were carried out with Students t-test. A one-way ANOVA with a subsequent Tukey-test was used to test for differences between treatments whilst a one-way ANOVA with a subsequent Dunnet was used to test for differences between the treatments and a reference.

3 Rainfall erosivity in the Cauca valley and hillsides in the Colombian highlands

3.1 Introduction

The further population increases anticipated during the coming decades mean that food for more people will have to be produced, for the most part, from the same areas that are currently under cultivation. As the increased use of land suitable for cultivation faces numerous constraints, such as the low availability of water for irrigation or high cost of drainage systems as well as ecological conflicts when considering the conversion of rainforests and other ecosystems into cultivated land, the main solution to the problem of feeding more people would be to increase yields on presently cultivated areas (El Swaify, 1991; Hudson, 1995). The investments necessary are often hindered by deficiencies in infrastructure and access to funding. Conserving the productivity of the land used at present and preventing further soil degradation is therefore of the utmost importance. In this context decision-makers and extension services alike need tools that allow them to estimate the potential soil erosion of cropping systems in order to apply soil conservation methods where necessary.

The USLE has been used successfully to predict soil erosion for several decades and, although new approaches to soil erosion modeling have been implemented, it remains the most widely-used and best-documented model (Armstrong, 1990; Lal, 1994). As the USLE was created in the US, based upon climate and soil data from temperate regions, its use under tropical conditions has often been questioned (Palacios and Alfaro, 1994; Morgan, 1995). The energy-intensity term of the USLE’s R factor was derived from drop size measurements by Wischmeier and Smith (1958), founded upon basic research on drop fall velocities by Laws and Parsons (1943) and Gunn and Kinzer (1949). Very little information exists as to whether this energy-intensity term is valid for use under tropical rainfall conditions as the relationship varies between locations in different world regions (Hudson, 1995). Drop size distributions from a wide, representative number of rainfall events must be recorded in order to calculate a region’s energy-intensity relationship. Due to the high cost of essential equipment and the time-consuming procedures (flour pellet method) necessary to establish these rainfall parameters, research has been limited. Hudson (1995) found the widely used formula for tropical rainfall conditions in Zimbabwe:

(9) $KE = 29.8 - \frac{127.5}{I}$

where KE is kinetic energy in J m^{-2}, and I is the rainfall intensity in mm h^{-1}. Other relationships were established under tropical or subtropical conditions for India, Trinidad, Venezuela and Australia.

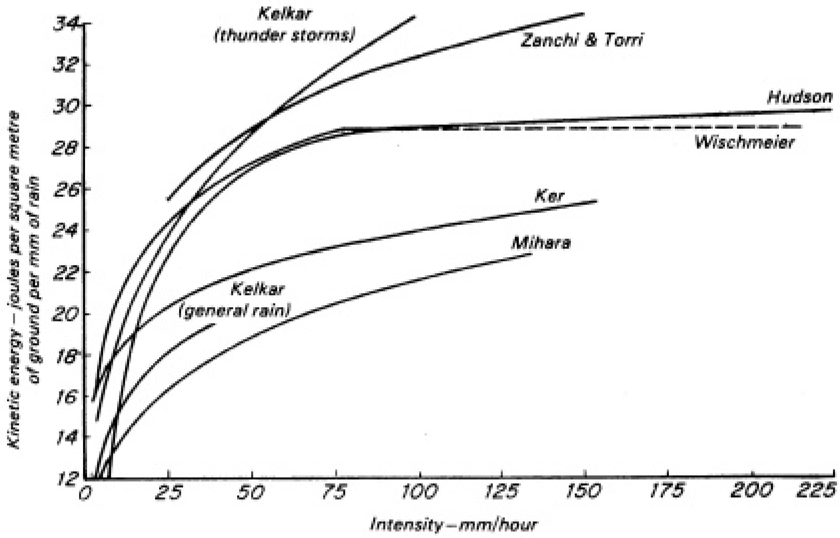


Figure 2. Different energy-intensity relationships (from Hudson, 1995)

Figure 2 shows the different relationships between rainfall intensity and energy including the base of the USLE energy term by *Wischmeier* and *Hudson's* curve from Zimbabwe. The two relationships denominated *Kelkar* were established in India, *Ker* was derived from measurements performed in Trinidad, whereas *Zanchi & Torri* developed the energy-intensity relationship shown in the Figure in Italy and *Mihara* in Japan. Kinetic energy measurements in Venezuela produced the formula:

(10) $KE = 2.9582 + 0.6418 \cdot I - 0.0025 \cdot I^2$

where KE is kinetic energy in J m^{-2} mm^{-1} and I is intensity expressed in mm h^{-1}, indicating that tropical rainfall may reach much higher kinetic energy values compared to temperate rainfall (Capriles, 1980). Nyssen et al. (2003) found high kinetic energy values and D_{50} values in the northern Highlands of Ethiopia and established an energy-intensity relationship formula for the region.

The energy load of tropical rainfall is reported to be considerably higher than in temperate regions, due either to a higher number of large raindrops or more raindrops falling per unit time. This reduces the applicability of the EI_{30} used in the USLE (Bomah, 1988; Jackson, 1989; Lal, 1998). Erosive rainfall measured in Nigeria showed average values for an energy load of 38.0 J m^{-2} mm^{-1}, whereas non-erosive rainfall had an average energy load of 25.9 J m^{-2} mm^{-1}. Raindrop size distributions determined by the same authors showed a high percentage of large drops, with a mean drop diameter of 3.42 mm. The total kinetic energy and average energy load for all rainfall measured were far higher in Nigeria (33 J m^{-2} mm^{-1}) than comparable measurements performed in Zimbabwe (19 J m^{-2} mm^{-1}) (Kowal and Kassam, 1976). Maene and Chong (1978) performed drop size measurements in Malaysia and found a high median drop diameter (D_{50}) of 3.1 mm at intensities of 160 mm h^{-1}. In Colombia, Vis (1986) evaluated rainfall events from the Central Cordillera and found a D_{50} value of 2.0 mm whilst the average energy load of the rain was 18.9 J m^{-2} mm^{-1}.

Reining (1992), Ruppenthal (1995) and Felske (2000) had calculated R-Factor values for the period 1987 to 1994 at the Quilichao and Mondomo research sites used in the present work. Their results when relating annual soil loss amounts to R-factor values had been ambiguous, showing high correlations in some years and low ones in others. Felske (2000) stipulated that it was possibly the inadequate energy-intensity relationship, developed for temperate rainfall, that was responsible for the discrepancies.

The main objective of the present study was therefore to establish the energy-intensity relationship for the south-western mountainous region of Colombia with a view to improving the applicability of the USLE.

3.2 Materials and Methods

A disdrometer (Joss-Waldvogel Model RD69, Distromet Ltd., Zürich, Switzerland) was used from December 1993 to March 1994 and from September 1996 to June 1998 to measure raindrop distributions in order to establish the energy-intensity relationship for the south-western Andean region of Colombia.

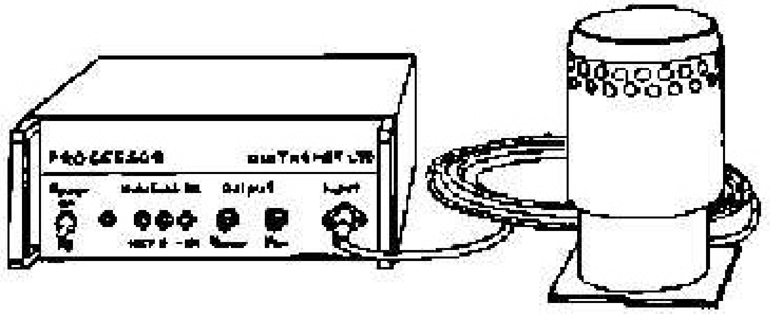


Figure 3. Distromet unit, to the left the analyzing unit and to the right the transducer with Styrofoam cone

The Disdrometer consists of a Styrofoam transducer with a measuring surface of 50 cm^2, which is exposed to the rainfall, and an analyzing unit (Figure 3). The latter is connected to a computer which serves as a storage device.

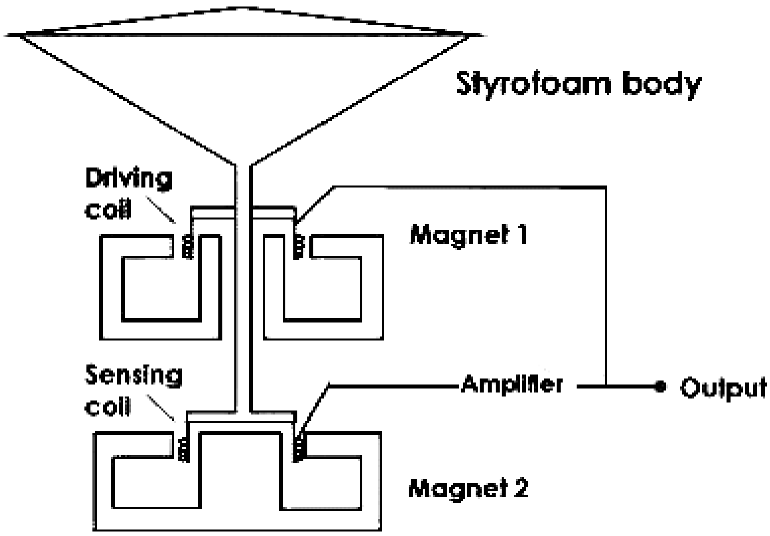


Figure 4. Blue print of Distromet disdrometer measuring unit

The Styrofoam cone is connected to two moving coils, a sensing coil and a driving coil (Figure 4). When a raindrop hits the Styrofoam body, the downward movement induces an electric pulse in the sensing coil. The pulse is amplified and sent to the processing unit and at the same time redirected to the driving coil, which moves the Styrofoam body into measuring position again with a minimal time loss. In this way, the dead time that may occur after the impact of one drop is minimized. The amplitude of the pulse is a function of the drop diameter. In the analyzing unit, the size of the different impacting raindrops is established via a pulse height analysis and the raindrops are divided into 20 different drop size classes. Different parameters such as rainfall amount, kinetic energy, drop size distributions and liquid water content can be established.

3.2.1 Calculation of raindrop sizes

Table 6 shows the values provided by the manufacturer of the disdrometer; the device was calibrated for these drop diameters. The terminal velocities are based on measurements performed by Gunn and Kinzer (1949). These measurements included only drop diameters up to 6 mm as larger drops are generally considered to be unstable and tend to split up. The velocities for such drops were extrapolated as little is known about drop size distributions of tropical rainfall. Whilst real falling raindrops have an oblate shape, a perfect sphere shape (equivalent spherical diameter) is assumed to facilitate calculations.

Table 6. Physical properties of the disdrometer raindrop classes

Raindrop size class	Drop diameter range (mm)	Mean drop diameter (mm)	Drop Volume (ml)	Mean terminal velocity (m s^{-1})	Kinetic Energy (J m^{-2})
1	0.468-0.630	0.5	8.7E-05	2.3	4.4E-05
2	0.630-0.796	0.7	1.9E-04	2.9	1.6E-04
3	0.796-0.959	0.9	3.5E-04	3.6	4.5E-04
4	0.959-1.163	1.1	6.3E-04	4.2	1.1E-03
5	1.163-1.348	1.3	1.0E-03	4.8	2.4E-03
6	1.348-1.663	1.5	1.8E-03	5.4	5.3E-03
7	1.663-2.085	1.9	3.4E-03	6.2	1.3E-02
8	2.085-2.455	2.3	6.1E-03	7.0	3.0E-02
9	2.455-2.742	2.6	9.2E-03	7.6	5.3E-02
10	2.742-3.061	2.9	1.3E-02	7.9	8.1E-02
11	3.061-3.728	3.4	2.0E-02	8.4	0.1
12	3.728-4.494	4.1	3.6E-02	8.9	0.3
13	4.494-5.116	4.8	5.8E-02	9.1	0.5
14	5.116-5.865	5.5	8.7E-02	9.1	0.7
15	5.865-6.822	6.3	1.3E-01	9.2	1.1
16	6.822-7.662	7.2	2.0E-01	9.2	1.7
17	7.662-8.771	8.2	2.9E-01	9.3	2.5
18	8.771-9.903	9.3	4.3E-01	9.3	3.7
19	9.903-11.472	10.7	6.4E-01	9.4	5.7
20	>11.472	11.5	7.9E-01	9.5	9.0

The rainfall amount for each interval was calculated by means of the equation :

$$(11) \quad \text{Rainfall amount} = \sum_{c=1}^{20} \left(\frac{4}{3} r_c^3 \, \Pi \, n_c \right)$$

where r is the radius of the assumed sphere, c the disdrometer raindrop size class and n the amount of drops falling in the corresponding size class. The rainfall data measured were stored in ASCII format and imported into Microsoft-Excel® for further processing and calculation. The disdrometer stores all raindrop impacts in 1-minute intervals.

The disdrometer was used exclusively on the field station at Quilichao from December 1993 to March 1994 and then from May 1996 to June 1998. A total of 18000 1-minute increments were recorded including 140 rainfall events. Of these events 45 were considered to be erosive in accordance with the criteria of Wischmeier and Smith (1978) and Hudson (1995) (rainfall amount of over 12.7 mm or more than 6.4 mm falling in 15 minutes or containing increments with intensities of higher than 25 mm h^{-1}) and were analyzed more closely. The remaining events mainly comprised drizzle with very low median drop diameters. Data from the latter events were included in the calculations relating to the energy-intensity relationship.

3.3 Results

3.3.1 Drop size distributions and D_{50}

The kinetic energy of rainfall depends on the raindrop amount per unit time and the size distribution of raindrops. In order to characterize a region's physical rainfall parameters, it is important to measure a wide spectrum of rainfall events. The D_{50} is the most suitable index to characterize drop size distributions as it describes the median volume drop diameter. Half of the precipitation volume falls in drop sizes below the D_{50} and half above (Hudson, 1995).

The evaluation of 45 erosive rainfall events from Quilichao showed that two types of raindrop distributions prevail in both rainy and dry seasons. The first type represents so-called advective rainfall events of lower intensities, which are characterized by a D_{50} of below 2.0 mm, a predominant raindrop class at 1.9 mm diameter and a secondary peak raindrop class of between 3.5 and 4 mm diameter. Drop sizes seldom exceed 5 mm diameter. This distribution type is represented in the figure by the distributions from the <1 mm h^{-1} to 25-35 mm h^{-1} intensity classes.

The second type is representative for convective rain with sustained intensities of higher than 35 mm h^{-1}, with a maximum raindrop class of 4 mm diameter, a secondary peak of between 2.0 and 2.5 mm and a mean D_{50} of 2.4 mm. Drop sizes very often exceed 5 mm and can reach values of up to 8 mm. As shown in Figure 5 the frequencies of larger raindrops increase with intensity as do the D_{50} values.

Figure 6 shows the drop size distributions of four rainstorms representing rainfall characteristics for the research area. The first event produced a total amount of 60.4 mm and was characterized by a long duration (more than 12 h) at mostly low intensities; 92% of the time rainfall intensity was below 10 mm h^{-1} with a short period of heavy rainfall near the end. The mean energy load was 18.7 J m^{-2} mm^{-1} and the D_{50} was 1.6 mm. It produced a soil loss of 8.4 t ha^{-1} on the bare fallow plots. The second rainfall event was a short, intense storm with peak intensities of up to 70 mm h^{-1} and a rainfall amount of 34.5 mm. The median drop diameter was 2.65 mm with a mean energy load of 28.3 J m^{-2} mm^{-1}. Together with a second event the amount of eroded soil was 12.8 t ha^{-1}. The third event was a short cloudburst with a D_{50} of 2.75 mm and a mean energy load of 30.1 J m^{-2} mm^{-1}, the highest measured during the entire project period. The induced soil loss on the USLE standard plots was 8.3 t ha^{-1}. The last rainfall event considered here comprised light rain with several drizzle phases with the lowest D_{50} measured at 1.2 mm, a mean energy load of 14.2 J m^{-2} mm^{-1} and a soil loss of 3.2 t ha^{-1}.

The median drop diameters were evaluated separately for the early and late rainy seasons for the period from December 1993 to March 1994 and June 1996 to June 1998 (Figure 7). In the early rainy season from March to May, D_{50} values ranged from between 1.2 to 2.65 mm. The second rainy season lasting from September to December showed median drop diameters of between 1.35 and 2.66 mm. Only rains considered erosive in accordance with the definitions of either Wischmeier and Smith (1978) or Hudson (1995) were analyzed (see Material and Methods). All the other rainfalls measured were primarily drizzle with high numbers of small drops and correspondingly low D_{50}s and rainfall amounts. They were considered to have no erosive impact. The means for both seasons were identical at 1.85 mm.

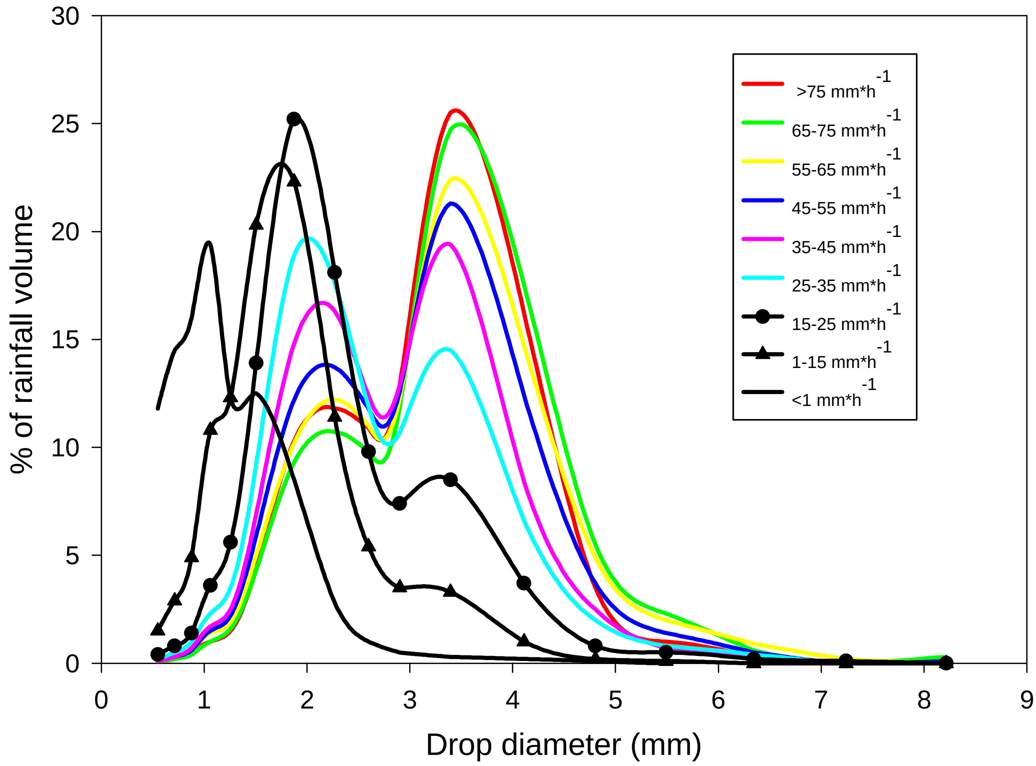


Figure 5. Changes in drop size distributions with increasing intensity

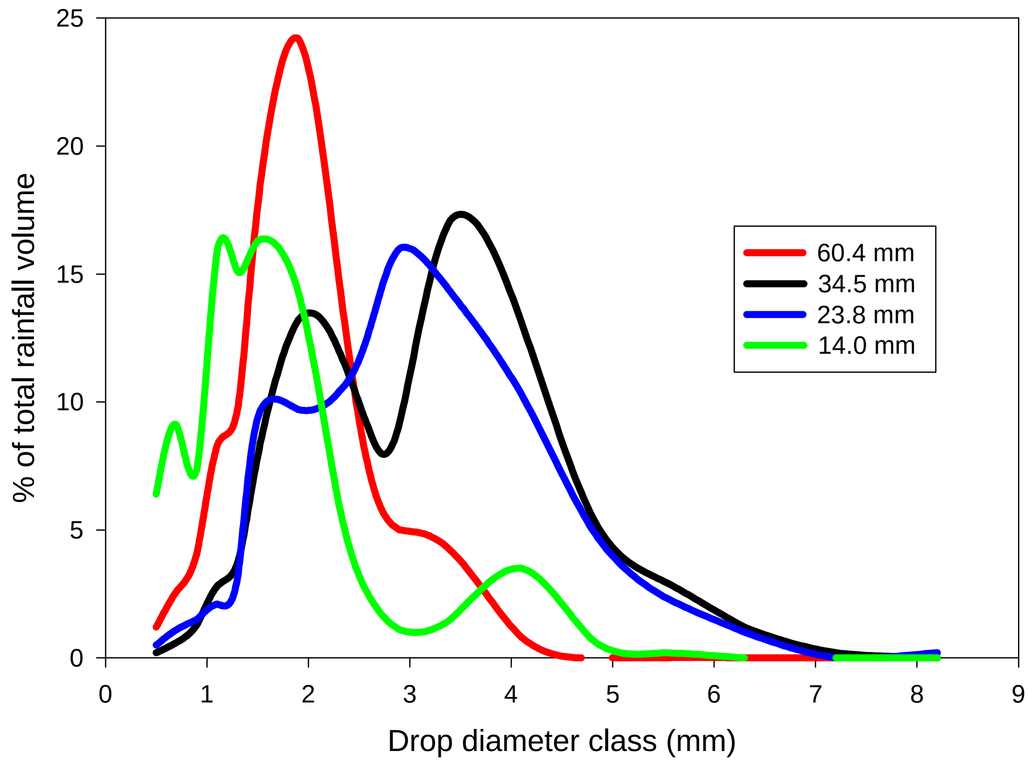


Figure 6. Drop size distributions of four typical rainfall events

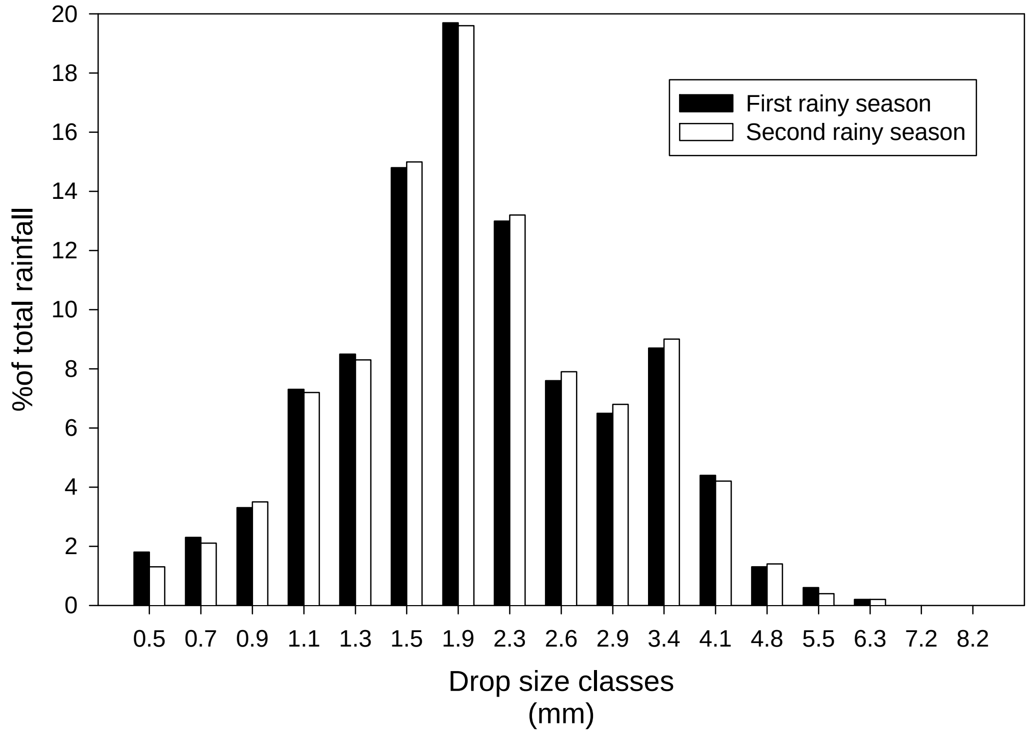


Figure 7. Drop size distributions for the first and second rainy seasons for the periods from December 1993 to March 1994 and June 1996 to June 1998.

A Students t-test showed no significant differences between the drop size frequencies of the early and the late rainy seasons. D_{50} values of individual rainfall events did not correlate with amount, intensity or kinetic energy of rainfall for any season.

When all 1-minute increments were classified and analyzed, a high correlation between intensity and D_{50} was found. The relationship was best described by the power function:

12) $$D_{50} = 0.9174 I^{0.2641}$$

where I is rainfall intensity in mm h^{-1} ($r^2 = 0.97$). This relationship however, is only valid for intensities of up to approximately 75 mm h^{-1}, as drop sizes no longer increase after reaching a threshold value where the drops become unstable (Hudson, 1995). Figure 5 shows that at intensities of over 75 mm h^{-1}, the proportion of drops with a diameter > 5 mm is lower than at intensities of between 65 and 75 mm h^{-1} and between 55 and 65 mm h^{-1}. Consequently, the lower D_{50} value at intensities over 75 mm h^{-1} demonstrates a decreasing tendency at higher intensities, indicating that the peak of the function for the research region lies between 75 mm h^{-1} and 80 mm h^{-1} (Figure 8).

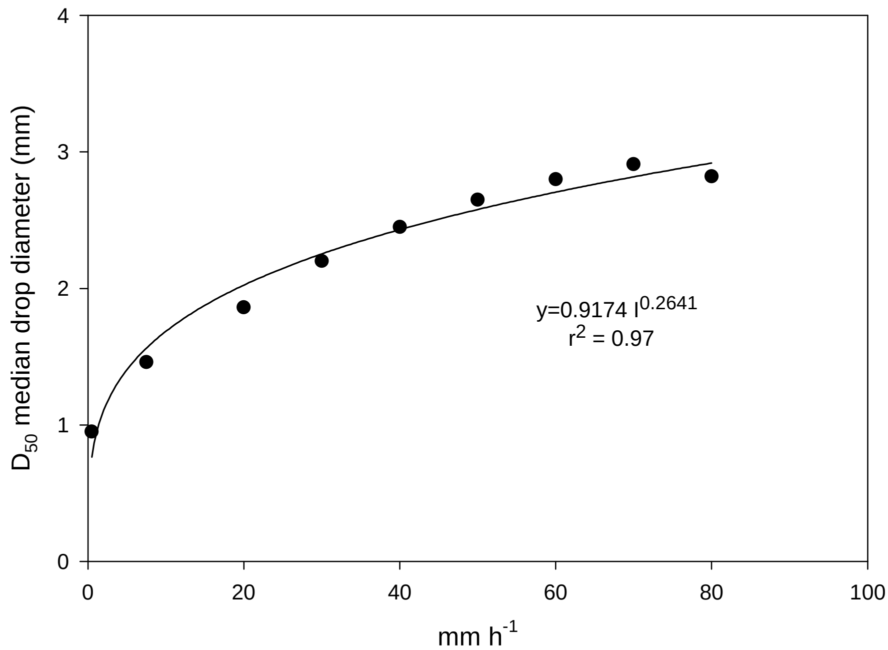


Figure 8. D_{50} rainfall intensity relation curve for a site in Southwest Colombia. The equation is based on 18000 1-minute increments, recorded at CIAT, Quilichao station, during December 1993 to March 1994 and June 1996 to June 1998

3.3.2 Energy Intensity Relationship

During a 2-year period from 1996 to 1998 and also a previous shorter period in 1993/94, over 18000 1-minute increments were recorded. As especially lower intensities occurred with high frequency, means were calculated. Fig. 9 shows the relationship between rainfall intensity and energy load for the complete data set. Like the rainfall measurements done by Kinnell (1987) in Australia, the data show a strong bias towards low intensities. During 45 % of all 1-minute increments the rainfall intensities were less than 1 mm h^{-1} and during 90% of the entire measurement period rainfall fell at intensities of below 10 mm h^{-1}. Regression analyses were therefore performed both for unweighted and weighted means, the latter being weighted by the frequencies of the measurements at equal intensities. Several types of equations were evaluated and the best descriptions were achieved with the equations of the types:

13) $E_L = a + (b\, c^{-I})$ and $E_L = a + (b\ \log(I))$

where E_L is energy load in J m^{-2} mm^{-1}, a, b and c are empirical constants and I is rainfall intensity in mm h^{-1}.

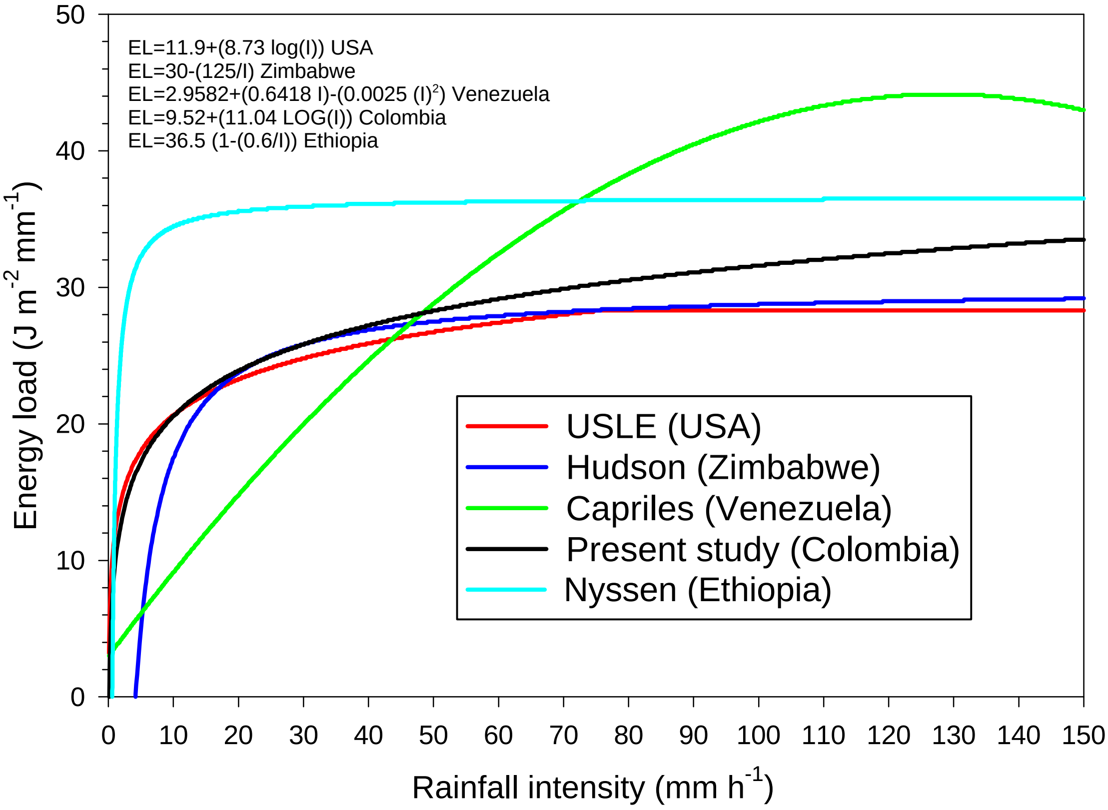


Figure 9. Energy intensity relationships established by different authors, the USLE by Wischmeier and Smith (1978), the relationship for Zimbabwe by Hudson (1995), the one in Venezuela by Capriles (1980) and the relationship for the Ethiopian Highlands by Nyssen (2003)

Whilst the weighted means showed better estimates at low intensities, they severely underestimated E_L at intensities of higher than 40 mm h^{-1}. Therefore, the equation obtained by the regression analysis of the unweighted means

14) $E_L = 9.52 + (11.04 \log(I))$

was selected, which showed the best correlation (r^2= 0.96). The result is presented in Figure 9 together with other studies.

It is often quite difficult to obtain reliable and continuous rainfall intensity measurements in many regions and in these cases relationships between rainfall amount and the parameters defining erosivity can be used to calculate approximations (Morgan, 1995).

The disdrometer measurements from the study area indicated a linear relationship between rainfall amount and kinetic energy:

15) $K_I = (20.89\, R_a) + 8.47$ (r^2=0.90)

where R_a is the rainfall amount in mm and K_I kinetic energy in J m^{-2}.

3.3.3 Energy load

3.3.3.1 Total rainfall

The erosive potential or the ability of rainfall to detach soil particles is partly expressed by the energy load term. The higher the energy load of rainfall expressed in J m^{-2} mm^{-1}, the higher the erosive potential.

Individual values from the 1-minute measurement intervals reached energy load values as low as 2.6 J m^{-2} mm^{-1} and as high as 40.3 J m^{-2} mm^{-1}. The range of mean energy loads from the 45 rainfall events measured with the disdrometer was between 14.2 J m^{-2} mm^{-1} and 30.1 J m^{-2} mm^{-1} and the average energy load of these events was 21.3 J m^{-2} mm^{-1}. There were no significant differences between the energy load values measured with the disdrometer and those calculated using the USLE intensity equation, both showing an average of 21.1 J m^{-2} mm^{-1}). All the further energy values presented were therefore calculated according to the USLE to facilitate comparisons with the earlier project phases of this long-term project. When analyzing raindrop distributions in Panama, McIsaac (1990) found that local kinetic energy values of rainfall were within 10% of the values calculated in accordance with the USLE.

Reining (1992), Ruppenthal (1995) and Felske (2000) reported nearly constant average energy load values for all rainfall in the period from 1987 to 1992 at both Quilichao and Mondomo. This tendency was confirmed as they changed little over the remainder of the research period from 1993 to 1998 (Table 7).

Table 7. Energy loads of total and erosive rainfall for the entire project period at Quilichao and Mondomo.

Year	Quilichao ($J\ m^{-2}\ mm^{-1}$)	Mondomo ($J\ m^{-2}\ mm^{-1}$)	Quilichao ($J\ m^{-2}\ mm^{-1}$)	Mondomo ($J\ m^{-2}\ mm^{-1}$)
	total rainfall		erosive rainfall	
1987[1]	21.7	21.3	22.8	22.2
1988[1]	21.6	20.9	22.8	22.4
1989[1]	19.9	20.8	20.8	21.9
1990[2]	21.1	21.4	22.7	23.4
1991[2]	21.1	20.0	22.7	22.1
1992[2]	21.9	21.6	22.5	24.7
1993[3]	20.1	21.4	21.5	22.6
1994[3]	21.2	20.3	21.8	21.6
1995	20.6	21.8	22.3	22.8
1996	21.3	20.9	23.1	21.9
1997	21.3	20.6	22.4	22.0
1998	19.8	21.1	21.6	21.1
Means	**21.0**	**21.0**	**22.3**	**22.4**

1, 2 and 3 data recorded by Reining (1992), Ruppenthal (1995), Castillo (1994) and Felske (2000), respectively

3.3.3.2 Erosive rainfall

All the events considered as erosive in accordance with the USLE criteria were analyzed for energy load. Again, tendencies shown by Reining (1992) and Ruppenthal (1995) from earlier project phases were validated (Table 7). The average energy loads for both Quilichao and Mondomo were nearly identical at 22.3 $J\ m^{-2}\ mm^{-1}$ and 22.4 $J\ m^{-2}\ mm^{-1}$, and a t-test showed no significant difference between both sites. Individual erosive rainfall events in Quilichao showed energy loads ranging between 14.0 $J\ m^{-2}\ mm^{-1}$ and 31.0 $J\ m^{-2}\ mm^{-1}$ and the values recorded at Mondomo varied between 12.6 $J\ m^{-2}\ mm^{-1}$ and 27.4 $J\ m^{-2}\ mm^{-1}$.

The erosive rainfall events were divided in the following energy classes: <500 $J\ m^{-2}$, 500-1000 $J\ m^{-2}$, 1000-1500 $J\ m^{-2}$, 1500-2000 $J\ m^{-2}$, 2000-2500 $J\ m^{-2}$ and also >2500 $J\ m^{-2}$ which were proposed by Lal (1998). Rainfall events of below 1000 $J\ m^{-2}$ are deemed to possess low kinetic energy, whilst medium energy events are in the range between 1000-2000 $J\ m^{-2}$ and all events above 2000 $J\ m^{-2}$ have high kinetic energy.

Figure 10 shows the frequencies of kinetic energy classes for 472 rainfall events recorded at Quilichao and 459 at Mondomo in the period from 1987 to 1998. Both sites show very similar energy distributions, with more than 82.8% of the events falling in the energy class of below 1000 $J\ m^{-2}$ in Quilichao and 88.2% in Mondomo. 16.9% of events in Quilichao and 11.3% in Mondomo fell into the medium energy range and there were two erosive events with more than 2000 J m^{-2} during the entire 12 year period in Mondomo with one in Quilichao. The differences between the two rainy seasons were not pronounced for either site. The more prominent second dry season from June to September showed less medium and low energy rainfall than the first one.

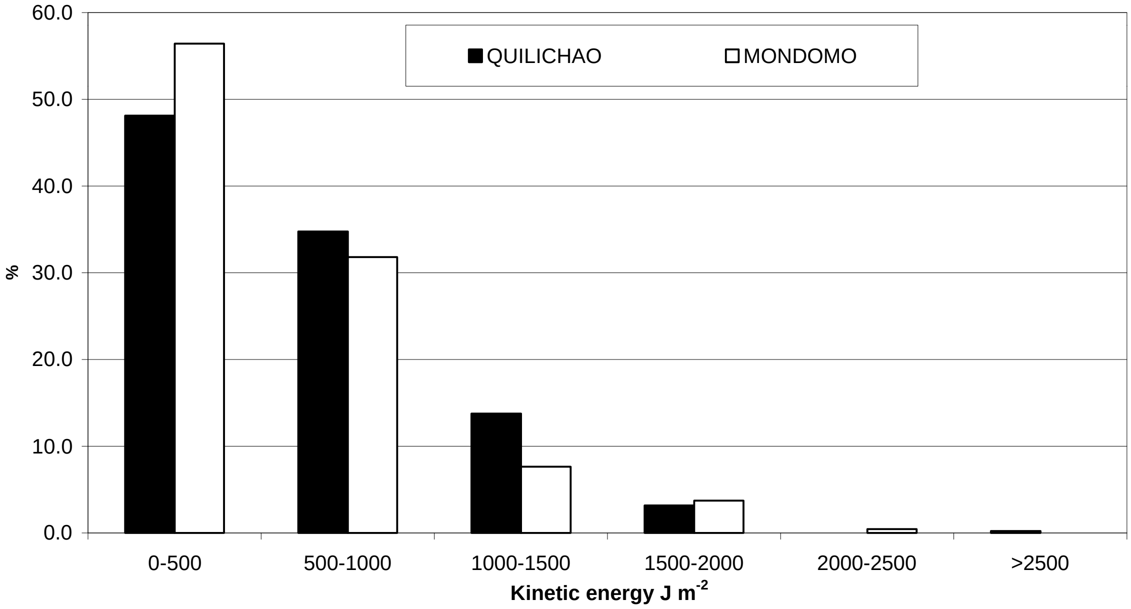


Figure 10. Frequencies of rainfall kinetic energy classes for Quilichao and Mondomo. Data represent 472 erosive rainfall events at Quilichao and 459 at Mondomo and were recorded during 1987 to 1998,

3.4 Rainfall characteristics for Santander de Quilichao, Mondomo, El Tambo, La Florida, Restrepo and Trujillo

Tropical rainfall is generally characterized by higher rainfall amounts and higher intensities as compared to temperate climates. Continuing a tendency already reported by Reining (1992), Ruppenthal (1995) and Felske (2000), most annual rainfall amounts were below the long-term average. In Quilichao, annual rainfall was as low as 66% of the average, reaching its minimum in the El Niño year of 1992. Rainfall was above average in only three years. In Mondomo, annual rainfall was even lower in relation to the long-term average, reaching only 55% of the average in 1992. Over all the fully accounted project years, rainfall was 13% below average in Quilichao and 26% in Mondomo (see Tables 14 and 18 in chapter 4.1).

According to Wischmeier and Smith (1978), rains with a rainfall amount of above 12.7 mm or with more than 6.5 mm falling in less than 15 minutes are considered erosive. 77.3% of the total rainfall amount in Quilichao fell in rainfall events of more than 12.7 mm and in Mondomo the figure was 74.0% (during a 12-year period). 51.1% in Quilichao and 42.0% in Mondomo fell in events with more than 25 mm, whereas events with more than 50 mm accounted for 17.9% and 14.8% respectively of the total rainfall amount in Quilichao and Mondomo. Rainfall events of over 70 mm produced 1.6% of the total rainfall amount in Quilichao, reaching 6.5% in Mondomo. Additionally 1.3% in Quilichao and 3.8% in Mondomo of the total rainfall amount were produced by events with less than 12.7 mm but reaching more than 6.5 mm within 15 minutes, thus fulfilling the second criterion of Wischmeier and Smith.

3.4.1 Intensities at Quilichao and Mondomo

In general, a higher percentage of rainfall falls at intensities that are considered erosive in the tropics and much higher intensities are reached more frequently in comparison to temperate regions. Intensity frequency distributions for both trial sites were very similar (Figure 11). During the 12-year experiment 37.6% of the total rainfall at Quilichao fell with an intensity of more than 25 mm h^{-1} and in Mondomo it was 36.3%. 19.1% of the rainfall fell at intensities of more than 50 mm h^{-1} in Quilichao and 19.6% in Mondomo. The values for intensities higher than 75 mm h^{-1} were 10.6% and 9.6% respectively for Quilichao and Mondomo. Still 5.9% and 5.6% of the rainfall fell at very high intensity levels of more than 100 mm h^{-1}. The highest intensities reached at both sites were 540 mm h^{-1} in Mondomo, where 9.0 mm fell in one minute, and 468 mm h^{-1} in Quilichao, where 7.8 mm of rainfall fell in 1 minute.

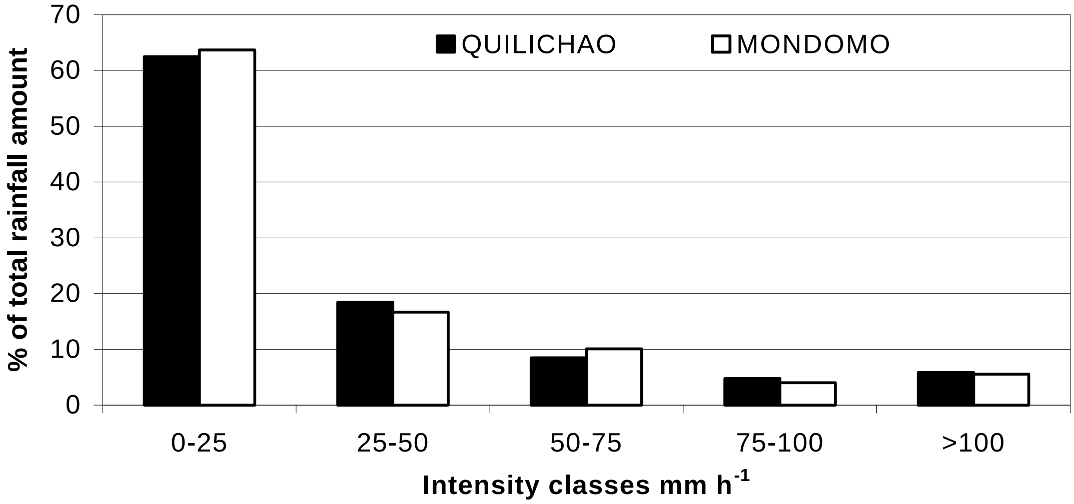


Figure 11. Rainfall intensity frequencies of Quilichao and Mondomo. Data are based upon rainfall recordings from April 1987 to June 1998, excluding the period from March 1989 to March 1990 when no measurements took place

3.4.2 I_{30} Quilichao and Mondomo

The climate erosivity factor of the USLE (R) is defined as the sum of all energy increments of a rainfall event multiplied by the maximum intensity sustained during 30 minutes (I_{30}) (Wischmeier and Smith, 1978). The importance of the I_{30} is based upon the observation that short rainfall events with a relatively low rainfall amount but falling at high intensities have a much higher erosive potential than long events with low intensities which may possess the same or even a higher kinetic energy. The I_{30} values for 472 erosive events in Quilichao and 459 in Mondomo over the entire project duration (1987-1998) were calculated and analyzed. The highest I_{30} in Mondomo was 106.4 mm h^{-1}, whereas only 87.0 mm h^{-1} was reached in Quilichao. The mean I_{30} of all erosive rainfall events in Mondomo was 25.5 mm h^{-1} with Quilichao showing a slightly higher mean of 26.8 mm h^{-1}. In Mondomo 40.5% of the erosive events showed an I_{30} above 25 mm h^{-1}, 8.7% were above 50 mm h^{-1} and in 0.7% of the events the maximum 30-minute intensity was above 75 mm h^{-1}. The values obtained in Quilichao were similar with 44.5% of the I_{30} values above 25 mm h^{-1}, 8.1 higher than 50 mm h^{-1} and 1.7% above 75 mm h^{-1} (Figure 12).

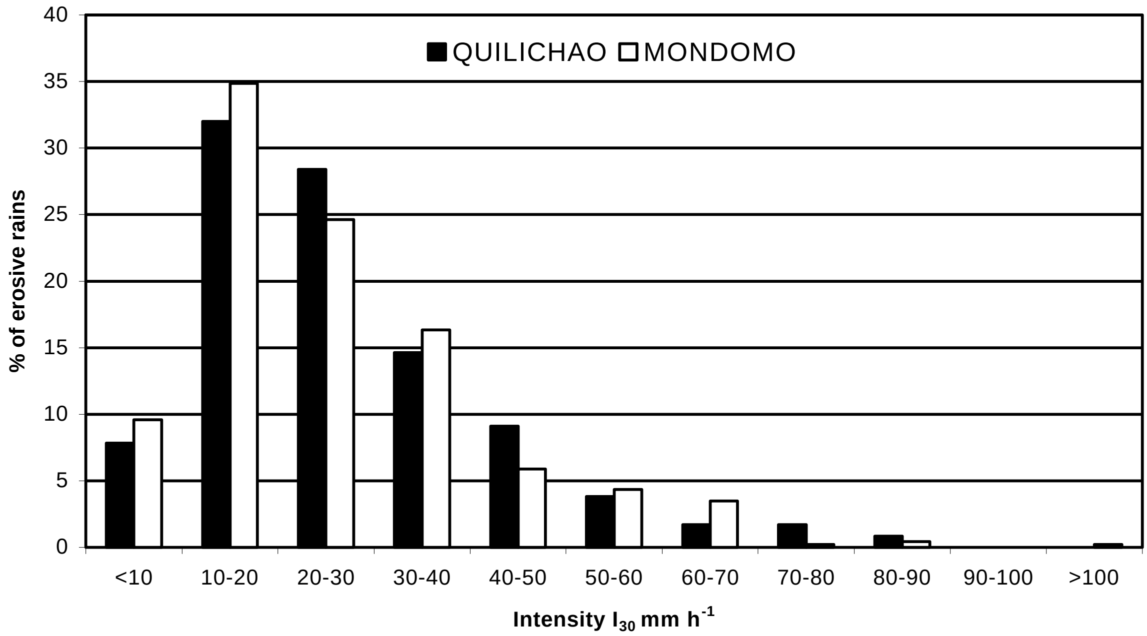


Figure 12. Intensity class frequencies of erosive rainfall events measured at Quilichao and Mondomo. Data represent 472 erosive events from Quilichao and 459 from Mondomo during the period from 1987 to 1998

3.4.3 I_{15} and $I_{7.5}$ Quilichao and Mondomo

Part of the criticism of the USLE R-Factor has focused on the I_{30} component. Better correlations have been achieved by using I_{15}, the maximum rainfall intensity during 15 minutes, and the AI_{max} index, which includes the maximum intensity during 7.5 minutes (Lal, 1977A; Morgan, 1995). The I_{15} and $I_{7.5}$ values were calculated for 108 events from Quilichao and 84 from Mondomo that produced erosion in the period from 1995-1998. The mean I_{15} was 43.7 mm h^{-1} for Quilichao and 43.2 mm h^{-1} for Mondomo and the highest values reached were 111.2 mm h^{-1} for Quilichao and 103.6 mm h^{-1} for Mondomo. The average $I_{7.5}$ was 57 mm h^{-1} for Quilichao and 56.6 mm h^{-1} for Mondomo with the highest intensity sustained during 7.5 minutes being 124.8 mm h^{-1} in Quilichao and 156.0 mm h^{-1} for Mondomo.

3.4.4 EI_{30} Quilichao and Mondomo

To apply the USLE in a certain region requires specific knowledge of the R- and K-Factors as well the topography (Roose, 1977). This is especially important for the climate factor that may vary greatly between locations in one country due to differences in the topographic and geographic position. Long-term rainfall data are necessary to obtain reliable average values for the R-Factor. According to Wischmeier and Smith (1978), at least 20 years of records are necessary to account for possible fluctuations at a specific location. 12 years of rainfall recordings are available for both project sites. In addition data from 4 weather stations maintained by the Colombian coffee growers' research center (CENICAFE) were analyzed, covering a total of 144 years with all single datasets including more than 20 years.

The average annual R-Factor in Quilichao for the period from 1987 to 1998 was 10,037 MJ ha^{-1} mm h^{-1} a^{-1} with a standard deviation of 2,479 MJ ha^{-1} mm h^{-1} a^{-1} (Table 9). The highest annual value of 14,496 MJ ha^{-1} mm h^{-1} a^{-1} was recorded in 1988 when the annual rainfall amount was well above average. The lowest R-Factor was measured in 1993, reaching 6,730 MJ ha^{-1} mm h^{-1} a^{-1}. The months of highest erosivity were March and April in the early rainy season, and October and November in the late rainy season, with November being the most erosive month with a mean R-Factor of 1,633 MJ ha^{-1} mm h^{-1} a^{-1}. The variations during the entire research period were extreme as expressed by the high standard deviations for all the months (Table 9).

Table 9. Annual Rainfall and R-Factors of Quilichao and Mondomo in the period from 1987 to 1998

	Quilichao		Mondomo	
Years	Rainfall amount (mm)	R-Factor (MJ ha^{-1} mm h^{-1} a^{-1})	Rainfall amount (mm)	R-Factor (MJ ha^{-1} mm h^{-1} a^{-1})
1987	*1,227*[4]	*8,876*	*1,285*	*7,424*
1988	207[1]	14,496	1,926	12,861
1989	*481*[3]	*1,673*	*544*	*3,068*
1990	*1,219*[2]	*7,166*	*670*	*3,759*
1991	1,436	8,610	1,240	4,891
1992	1,191	7,566	1,171	7,820
1993	1,435	6,730	1,930	12,413
1994	2,477	13,217	1,422	7,138
1995	1,593	9,960	1,852	12,727
1996	1,804	10,276	1,552	6,751
1997	1,616	9,438	1,410	7,529
1998	*770*[1]	*3,808*	*578*	*2,211*

Values in italics indicate measurement periods of less than 12 months. 1 January to June; 2 April to December; 3 January to March; 4 April to December

The dry months of January, June, July and August oscillated between having no erosive rainfall at all and R-Factor values of up to more than 465% of the average. Even the predominant rainy season months of March, April, October and November had R-Factors as low as 1% and as high as 337% of the 12-year average.

Mondomo showed a slightly lower mean annual R-Factor than Quilichao at 9,016 MJ ha^{-1} mm h^{-1} a^{-1} and with a standard deviation of 4,208 MJ ha^{-1} mm h^{-1} a^{-1}. The year with the lowest R-Factor was 1991 at 4,891 MJ ha^{-1} mm h^{-1} a^{-1}, where only one rainfall event of more than 40 mm was recorded and the total annual rainfall was 600 mm below the long-term average. In three years, the R-Factor was above 12,000, 1995 being the most erosive year with 12,727 MJ ha^{-1} mm h^{-1} a^{-1} (Table 8).

In Mondomo, the monthly repartition of climate erosivity was very similar in comparison to Quilichao with only February and May showing higher monthly R-Factors (Table 10).

Table10. Average monthly R-Factor values and oscillations for Quilichao and Mondomo for the entire research period from 1987-1998

	Quilichao				**Mondomo**			
	Mean R-Factor	SD	Max. in % of mean	Min. in % of mean	Mean R-Factor	SD	Max. in % of mean	Min. in % of mean
Month	MJ ha^{-1} mm h^{-1}		%		MJ ha^{-1} mm h^{-1}		%	
January	615	763	345	0	668	616	274	5
February	596	539	323	10	811	692	224	0
March	1,163	1,143	337	5	906	634	224	9
April	1,538	693	182	12	1,178	844	234	13
May	923	380	289	7	546	467	412	7
June	547	619	291	0	502	771	449	0
July	205	261	339	0	377	390	299	0
August	154	280	465	0	295	60	847	0
September	692	323	149	18	552	375	243	0
October	1,071	558	184	1	1,059	597	173	32
November	1,633	1,325	264	9	1,532	851	256	2
December	745	586	240	9	870	475	226	20

November had the highest average R-Factor at 1,411 MJ ha^{-1} mm h^{-1} a^{-1}, with October being the second highest in the late rainy season at 958 MJ ha^{-1} mm h^{-1} a^{-1} and March and April showing the highest R-Factors in the early rainy season at 838 MJ ha^{-1} mm h^{-1} a^{-1} and 1,102 MJ ha^{-1} mm h^{-1} a^{-1} respectively. Again, oscillations of the values were extreme between the years. February, June, July, August and September had years where no erosive rain fell at all or showed high values of up to 847% of the average. Even the dominant months of the rainy seasons presented values as low as 2% and as high as 412% of the average monthly R-Factor during the 12-year period. As in Quilichao, the standard deviations for all months were high.

3.4.5 Kinetic energy and energy loads of erosive rainfall events at El Tambo and La Florida

The energy class frequency distributions of erosive rainfall events were very similar to those from Quilichao and Mondomo. 89.0% of the events in El Tambo and 91.5% in La Florida were below 1,000 J m^{-2} and 8.1% of the events in El Tambo were medium energy events with 10.2%. in La Florida. As in Quilichao frequencies of high-energy rainfall events were low, although there were 15 events of over 2,000 J m^{-2} in El Tambo and 6 in La Florida. These events can be considered as extraordinary events that generally cause the highest soil losses and have disastrous effects when occurring early in the crop cycles when the soil is bare (Hudson, 1995). The 15 events measured at El Tambo had a mean I_{30} of 61.2 mm h^{-1}, the average energy amount was 2,434 J m^{-2} with a mean R-Factor of 1,505 MJ ha^{-1} mm h^{-1} and a mean rainfall amount of 98.3 mm. For La Florida, the mean values of the 6 extraordinary events were: an I_{30} of 74.2 mm h^{-1}, a kinetic energy amount of 2,255 J m^{-2}, an R-Factor of 1,686 MJ ha^{-1} mm h^{-1} and a rainfall amount of 88.6 mm. Both Reining (1992) and Ruppenthal (1995) reported extraordinary events at Quilichao and Mondomo that caused up to 90% of the annual soil loss amount, these events being of a lesser erosivity as compared to the ones reported from El Tambo and La Florida.

The energy loads of the erosive rainfall were very close to those of Quilichao and Mondomo, demonstrating the similarities of the rainfall parameters in the region. The average energy load values were 23.0 J m^{-2} in La Florida and 22.6 J m^{-2} in El Tambo with the range lying between 14.7 and 28.1 J m^{-2} for the La Florida data set and 15.2 and 28.2 J m^{-2} at El Tambo. As only the rainfall events considered erosive were analyzed, no information about the kinetic energy of the total rainfall were calculated for either station.

3.4.6 Intensities El Tambo and La Florida

Due to the large amount of data, only erosive rainfall events were evaluated to ascertain the distribution of intensities. 43.4% of the erosive rainfall at El Tambo fell at intensities of over 25 mm h^{-1}, with 19.7% above 50 mm h^{-1}, 7.6% above 75 mm h^{-1} and 3.3% above 100 mm h^{-1} (see Figure 13). Erosive rainfall at La Florida fell at slightly higher intensities than in El Tambo. Almost half of the erosive rainfall amount, 47.7%, was above 25 mm h^{-1}, with 25.2% above 50 mm h^{-1}, 12.2% at more than 75 mm h^{-1} and a remarkable 6.6% at more than 100 mm h^{-1}.

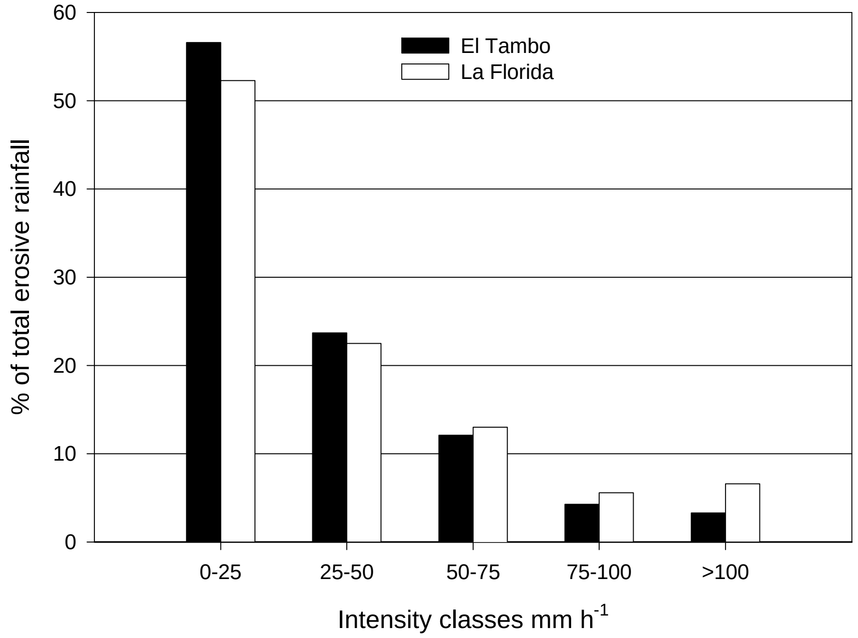


Figure 13. Intensity classes and their frequencies from 1,800 erosive events measured at El Tambo and 1485 erosive events from La Florida

3.4.7 I_{30}

The I_{30} values for both stations were in the same range as those at Quilichao and Mondomo. The average I_{30} for La Florida was 27.1 mm h^{-1} and the highest intensity reached was 101 mm h^{-1}. 45.1% of all erosive events had I_{30} values of above 25 mm h^{-1}, 8.1% above 50 mm h^{-1} and 1.2% above 75 mm h^{-1}. There was only one event with an I_{30} of more than 100 mm h^{-1}. The average I_{30} at the El Tambo station was 26.4 mm h^{-1} with a maximum value of 118.2 mm h^{-1}. 43.7% of the evaluated events had an I_{30} of above 25 mm h^{-1}, 7.4% above 50 mm h^{-1} and 0.7% above 75 mm h^{-1}. As in La Florida there was only one event above 100 mm h^{-1}.

3.4.8 EI_{30}

The mean annual R-Factor of the 42 year period for El Tambo was 8,018 MJ ha^{-1} mm h^{-1} a^{-1} (Figure 14). The high standard deviation of 2,597 MJ ha^{-1} mm h^{-1} a^{-1} emphasizes the extreme variations during the 4 decades. The highest annual erosivity was 15,471 MJ ha^{-1} mm h^{-1} a^{-1}, whilst the minimum annual R-Factor of 3,465 MJ ha^{-1} mm h^{-1} a^{-1} was measured in 1983, one of the strongest El Niño years recorded. March and April were the predominant months of the early rainy season, but were not as pronounced as in Quilichao and Mondomo. October, November and December were the months with the highest erosivity. The differences between the years were extreme and taking account of the entire period analyzed, April was the only month that showed erosive rainfall events in every year. Dry season months such as June and July oscillated widely, with July reaching a maximum value of 1,290% of the average, whilst February and April had monthly values amounting to half of the annual average R-Factor (Table 11).

Table 11. Average monthly R-Factor values for El Tambo and La Florida. The data presented here represent 42 years of rainfall records for El Tambo and 33 years for La Florida

	El Tambo				La Florida			
	Mean R-Factor	SD	Max. in % of mean	Min. in % of mean	Mean R-Factor	SD	Max. in % of mean	Min. in % of mean
	MJ ha^{-1} mm h^{-1}			%	MJ ha^{-1} mm h^{-1}			%
January	561	546	428	0	654	625	390	0
February	524	753	889	0	684	537	301	0
March	684	785	472	0	727	641	356	0
April	846	775	483	4	803	571	241	6
May	532	421	335	0	631	445	292	0
June	153	230	779	0	374	343	305	0
July	183	411	1,290	0	197	420	967	0
August	253	414	861	0	146	209	522	0
September	499	482	426	0	503	470	337	0
October	1,471	1,240	476	0	1,249	795	234	18
November	1,378	796	242	0	1,273	749	259	7
December	950	697	260	0	1,187	885	355	0
Annual	8,018	2,597	193	43	8,580	1,846	167	63

The most extreme monthly R-Factor was recorded during October 1966 at 7,010 MJ ha^{-1} mm h^{-1}, reaching 45% of the annual R-Factor and 87% of the mean annual R-Factor. October is a critical month for soil erosion in the region as the soil is freshly tilled after preparation for planting. Due to a slow initial growth, the soil cover provided by cassava plants is very poor which also contributes to the risk of soil erosion (Howeler 1980; Reining, 1992; Leihner et al, 1996).

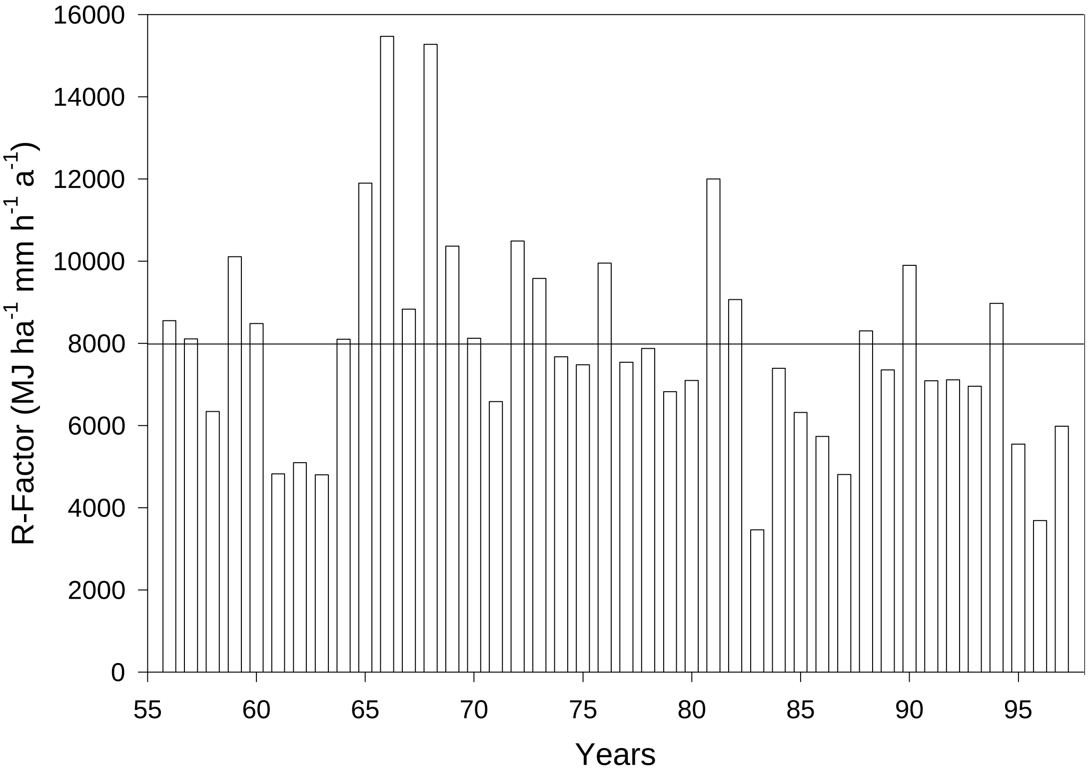


Figure 14. R-Factor values for the period 1956 to 1998 from El Tambo. The horizontal line represents the 42 year average

La Florida presented a mean annual R-Factor of 8,580 MJ ha^{-1} mm h^{-1} a^{-1}, with a maximum value of 14,327 MJ ha^{-1} mm h^{-1} a^{-1} and a minimum of 5,393 MJ ha^{-1} mm h^{-1} a^{-1} (Figure 15). The standard deviation was 1,846 MJ ha^{-1} mm h^{-1} a^{-1}. The months of highest erosivity during the first rainy season were March and April, whereas during the second they were October, November and December. The second rainy season was more pronounced than the first and oscillations were again high, especially in the dry seasons. Only April, October and November showed erosive rainfall during every year. Compared to El Tambo, the maxima and minima were less extreme.

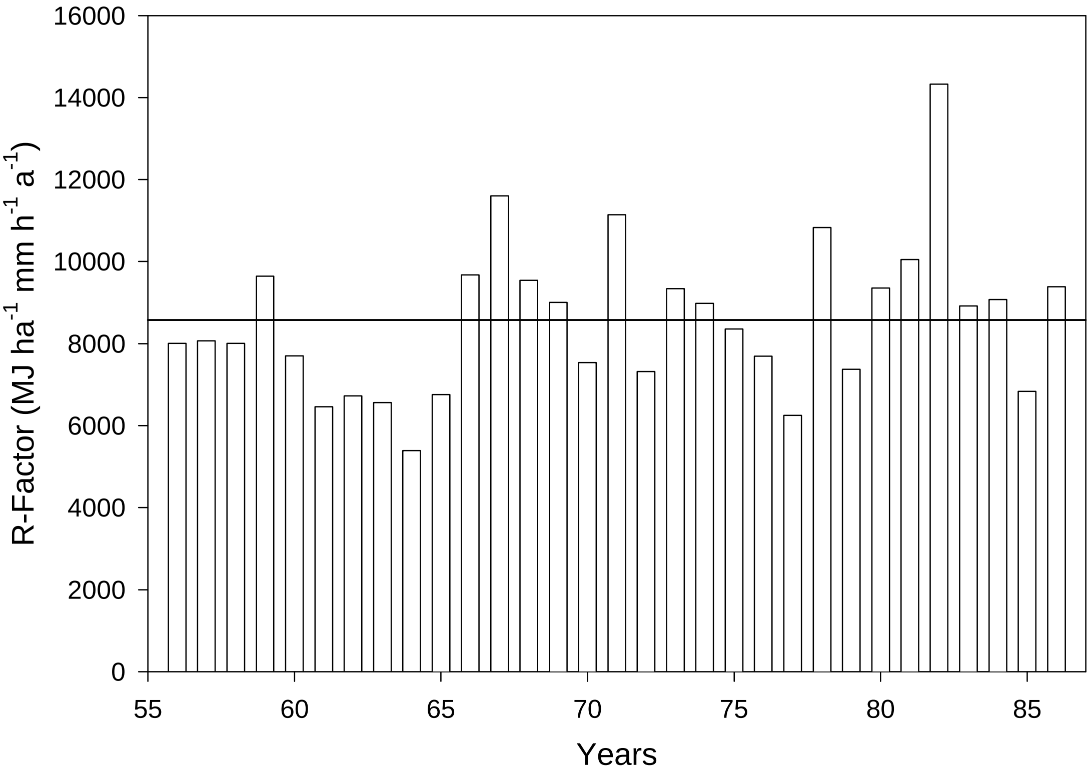


Figure 15. R-Factor values for the period 1956 to 1986 from La Florida. The horizontal line represents the 33 year average

3.4.9 Kinetic energy and energy loads of erosive rainfall events at Restrepo and Trujillo

The two nearest meteorological stations belonging to CENICAFE outside the Cauca department were Restrepo and Trujillo, located in the neighboring department of Valle del Cauca on the Western Cordillera. They were included in the analysis to expand the applicability of the results and obtain data under different agroclimatic conditions such as those in Restrepo.

While the energy class frequency distributions of erosive rainfall events from Trujillo were similar to those already reported from the four stations in the Cauca department, the Restrepo station differed due to the generally lower rainfall amounts and lower erosivity. 88.5% of the events at Trujillo were in the energy class of below 1,000 J m^{-2}, whereas in Restrepo it was 95.6%. 11.1% of the rainfall events in Trujillo and 4.3% in Restrepo fell into the range between 1,000 and 2,000 J m^{-2}. Events with high-energy class were few and far between at both sites with a total of 4 (0.4%) in Trujillo (25 years) and 1 (0.1%) measured at Restrepo (39 years) (Figure 16).

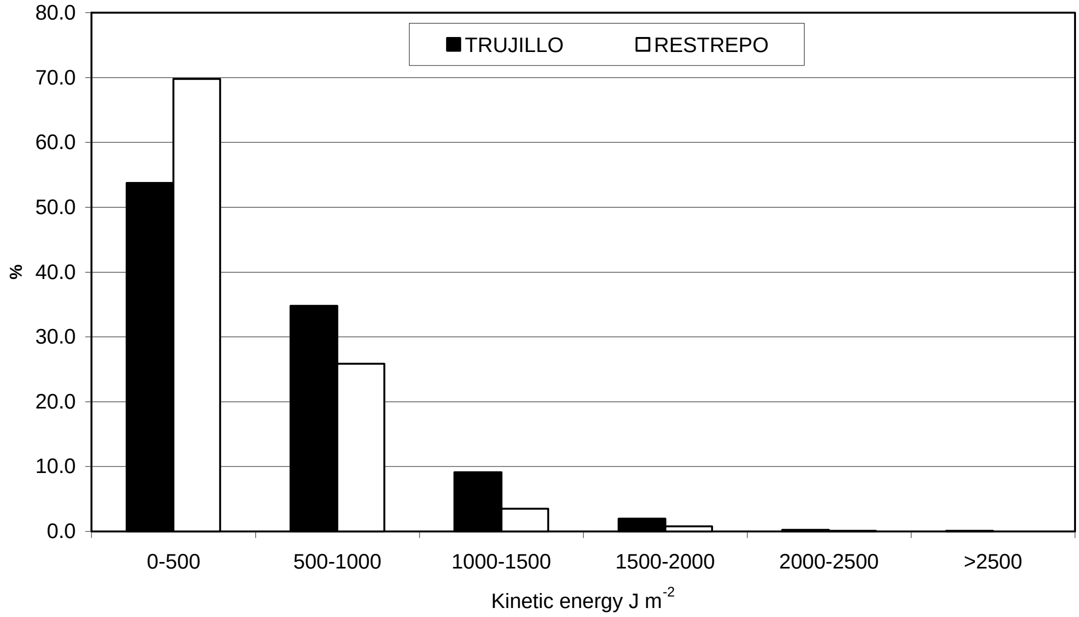


Figure 16. Frequencies of rainfall kinetic energy classes for Restrepo and Trujillo. Data represent 774 erosive events measured at Restrepo (25 years) and 1070 erosive events from Trujillo (39 years)

During the 25 years analyzed there were four extraordinary events at Trujillo, which had a mean I_{30} of 35.1 mm h^{-1}; the average energy amount was 2,296 J m^{-2} with a mean R-Factor of 1,618 MJ ha^{-1} mm h^{-1} and a mean rainfall amount of 92.5 mm. The one extraordinary event measured at Restrepo in 39 years had an I_{30} of 29.0 mm h^{-1}, an energy amount of 2,013 J m^{-2}, an R-Factor of 1,168 and a total rainfall amount of 79.5 mm.

The energy loads of the erosive rainfall showed average values of 22.7 J m^{-2} and 22.8 J m^{-2} for Restrepo and Trujillo respectively (Tables 11, 12). Again these values correspond well with those of the other four stations and emphasize the closeness of the rainfall parameters for the region, even under conditions with lower rainfall amounts such as in Restrepo.

Table 11. Attributes of 774 erosive rainfall events from the Restrepo station (39 years)

	Average	Min	Max
I_{30} (mm $h^{-1)}$	23.9	4.4	114
Kinetic energy (MJ ha^{-1})	4.626	1.655	20.137
Energy load (J m^{-2} mm^{-1})	22.7	14.3	27.9
R-Factor (MJ ha^{-1} mm h^{-1})	132	11	2,177
Rainfall amount (mm)	20.3	6.7	79.5
Annual R-Factor (MJ ha^{-1} mm $h^{-1)}$	2,787	686	5,704

The range in Restrepo lay between 16.8 and 27.9 J m^{-2} and between 14.9 and 27.2 J m^{-2} for Trujillo. Due to the large amount of analog data, non-erosive rainfall events were not evaluated or considered.

Table 12. Attributes of 1070 erosive rainfall events from the Trujillo station (25 years)

	Average	Min.	Max.
I_{30} (mm $h^{-1)}$	27.3	4.0	99.2
Kinetic energy (MJ ha^{-1})	5.783	1.649	26.325
Energy load (J m^{-2} mm^{-1})	22.8	14.9	29.5
R-Factor (MJ ha^{-1} mm h^{-1})	194	11.0	2,611
Rainfall amount (mm)	25.2	6.9	106
Annual R-Factor (MJ ha^{-1} mm $h^{-1)}$	8,094	3,947	15,415

3.4.10 Rainfall amounts and intensities Trujillo and Restrepo

As in El Tambo and La Florida, only erosive rainfall events were evaluated in terms of rainfall amount classes and distribution of intensities due to the large amount of analog data. At Restrepo more than three-quarters of all erosive events did not fulfill the first criterion of Wischmeier and Smith (1978) for erosive rainfall, showing a rainfall amount of below 12.7 mm, but reached more than 6.4 mm of rainfall in 15 minutes. 23.9% of the events had rainfall amounts of above 25 mm. Very few rainfall events with amounts over 50 mm and none over 100 mm were registered during the 39 years (Table 13).

Table 13. Rainfall amount classes for 774 erosive rainfall events from the Restrepo station (39 years)

Rainfall amount class Mm	Number of events	% of total
<12.7	589	76.1
>25	168	21.7
>50	16	2.1
>75	1	0.1
>100	0	0.0

At Trujillo, which has a more erosive climate and generally higher annual rainfall amounts, the percentage of erosive rainfall events with a total rainfall amount of less than 12.7 mm was 60.5%. 39.5% of the events had rainfall amounts of higher than 25 mm, whereas 6.4% were above 50 mm. There were only 7 events over 75 mm and one over 100 mm in 25 years (Table 14).

Table 14. Rainfall amount classes for 1070 erosive rainfall events from the Trujillo station (25 years)

Rainfall amount class mm	n	% of total
<12.7	648	60.5
>25	354	33.1
>50	60	5.6
>75	7	0.7
>100	1	0.1

44.7% of the erosive rainfall at Trujillo fell at intensities of over 25 mm h^{-1}, with 19.0% above 50 mm h^{-1}, 7.3% above 75 mm h^{-1} and 3.1% above 100 mm h^{-1} (see Figure 17). Erosive rainfall at Restrepo fell at very similar intensities. 46.4% of the erosive rainfall amount fell at intensities of above 25 mm h^{-1}, with 22.3% above 50 mm h^{-1}, 9.2% at more than 75 mm h^{-1} and 3.8% at more than 100 mm h^{-1}. Even though the rainfall amounts at Restrepo were generally lower, the frequencies of the intensity classes did not differ greatly from those at the other stations.

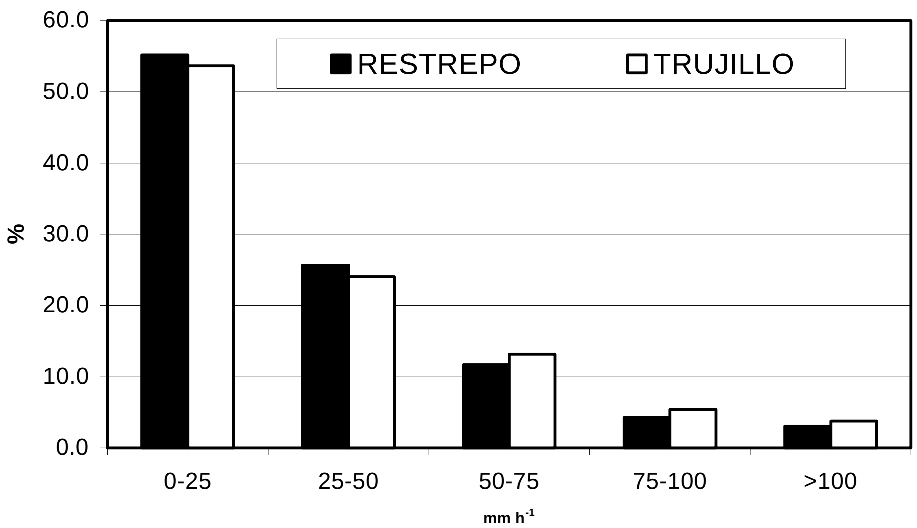


Figure 17. Intensity classes and their frequencies from 774 erosive events measured at Restrepo and 1070 erosive events from Trujillo

3.4.11 I_{30}

The I_{30} values for both stations were in the same range as those of the other stations. The average I_{30} for Restrepo was 23.9 mm h^{-1} and the highest intensity reached was 114 mm h^{-1}. 41.2% of all erosive events had I_{30} values of above 25 mm h^{-1}, 4.1% above 50 mm h^{-1} and 0.1% above 75 mm h^{-1}. There was only one event with an I_{30} of more than 100 mm h^{-1} (Table 15).

Table 15. I_{30} intensity classes for 774 erosive rainfall events from the Restrepo station (39 years)

I_{30} Mm h^{-1}	N	% of total
<10	53	6.8
>25	287	37.1
>50	29	3.7
>75	2	0.3
>100	1	0.1

The average I_{30} at the Trujillo station was 27.3 mm h^{-1}, with a maximum value of 99.2 mm h^{-1}. 56.4% of the evaluated events had an I_{30} of above 25 mm h^{-1}, 9.3% above 50 mm h^{-1} and 1.3% above 75 mm h^{-1}. No event with an I_{30} of more than 100 mm h^{-1} took place during the 25 years (see tables 12 and 16).

Table 16. I_{30} intensity classes for 1070 erosive rainfall events from the Trujillo station (25 years)

I_{30} mm h^{-1}	N	% of total
<10	67	6.3
>25	504	47.1
>50	86	8.0
>75	14	1.3
>100	0	0.0

3.4.12 EI_{30}

While several rainfall parameters for Restrepo were very similar to those of the other stations, the total rainfall amount and consequently the R-Factor values were much lower. The mean annual R-Factor of the 39-year period for Restrepo was 2,787 MJ ha^{-1} mm h^{-1} a^{-1} (Table 17, Figure 18).

Table 17. Annual R-Factor statistics for Trujillo and Restrepo stations

Station	Annual R-Factor			
	Average	Max.	Min.	SD
	MJ ha^{-1} mm h^{-1} a^{-1}			
Trujillo	8,094	15,415	3,947	3,151
Restrepo	2,787	5,704	686	1,176

The high standard deviation of 1,176 MJ ha^{-1} mm h^{-1} a^{-1} emphasizes the extreme variations during the period of almost 4 decades. The highest annual erosivity was 5,704 MJ ha^{-1} mm h^{-1} a^{-1}, still far lower than the average values at the other five sites, whereas the minimum annual R-Factor was 686 MJ ha^{-1} mm h^{-1} a^{-1}. The much lower annual erosivity as compared to the other five stations is evident when considering that even the maximum annual R-Factor is still much lower than the average values of Quilichao, Mondomo, El Tambo, La Florida and Trujillo. This maximum annual value was 1,300 MJ ha^{-1} mm h^{-1} a^{-1} lower than the maximum monthly value from El Tambo.

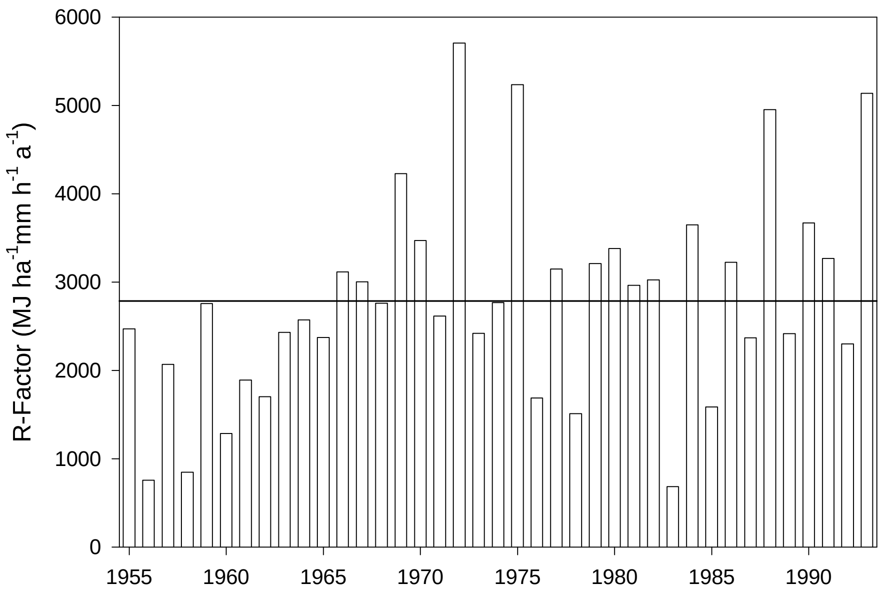


Figure 18. R-Factor values for the period 1955 to 1993 from Restrepo. The horizontal line represents the 39 year average

April and May were the predominant months of the early rainy season and this season is longer than at the other sites, extending up to June. Generally the bimodal rainfall distribution was not as pronounced as at the other sites. October was the month with the highest erosivity and the months with the lowest erosivity were January and December followed by August. The differences between the years were extreme and over the entire period analyzed, no month showed erosive rainfall events in every year (Table 18).

Table 18. Statistics of monthly rainfall erosivity for Restrepo (39 years)

Month	R-factor average	Max.	Min.	Min. above 0
		MJ ha^{-1} mm h^{-1}		
January	62	563	0	53
February	200	2,177	0	48
March	233	1,169	0	27
April	370	1,188	0	47
May	382	967	0	63
June	263	952	0	46
July	179	1,135	0	27
August	109	456	0	32
September	234	1,663	0	18
October	431	1,325	0	45
November	196	814	0	47
December	70	556	0	24

The station at Trujillo showed a mean annual R-Factor of 8,094 MJ ha^{-1} mm h^{-1} a^{-1}, with a maximum value of 15,415 MJ ha^{-1} mm h^{-1} a^{-1} and a minimum of 3,947 MJ ha^{-1} mm h^{-1} a^{-1} (Figure 19, Table 17).

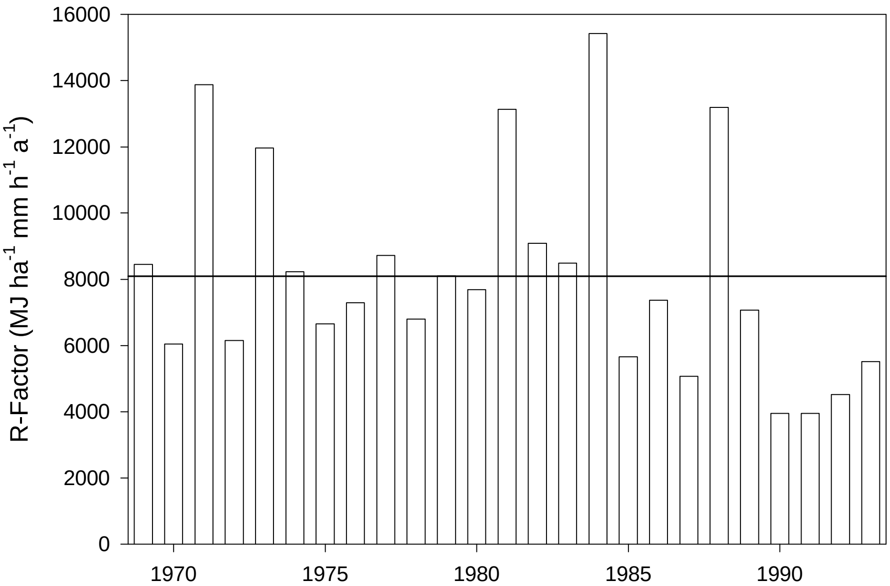


Figure 19. R-Factor values for the period 1969 to 1993 from Trujillo. The horizontal line represents the 25 year average

The standard deviation at Trujillo was 3,151 MJ ha^{-1} mm h^{-1} a^{-1}. The months with the highest erosivity during the first rainy season were April and May, whereas during the second, they were October and November. The second rainy season was more pronounced than the first and oscillations were again high, especially in the dry seasons. Only April, September and November showed erosive rainfall in every year (Table 19).

Table 19. Statistics of monthly rainfall erosivity for Trujillo (25 years)

Month	R-factor average	Max	Min	Min above 0
	MJ ha^{-1} mm h^{-1}			
January	411	1,652	0	30
February	346	3,342	0	28
March	670	2,727	0	41
April	999	3,630	45	45
May	945	2,828	0	188
June	667	4,262	0	27
July	351	2,160	0	23
August	362	1,431	0	23
September	680	1,937	28	28
October	1,091	3,874	0	140
November	1,001	3,210	32	32
December	571	1,707	0	21

3.5 Relationships between rainfall amount data and the R-Factor

Due to the enormous input required in terms of time and labor to gather and analyze information on a region's climate erosivity, efforts have been made to find relationships between simple parameters such as the rainfall amount and the R-Factor of the USLE. These relationships can be applied to data gathered from the region and give a more complete view of the region's erosivity (Bergsma, 1996). Two approaches were tried, the first examining the relationship between the annual amount of rainfall and the annual R-Factor, and the second using the relationship between average monthly R-Factor values and a modified Fournier index defined as:

16) $R_c = \frac{p^2}{p_i}$

where R_c is the rainfall coefficient for a given month, p the average monthly rainfall amount in mm and p_i the average annual precipitation in mm (Carvalho et al. 1991).

A highly significant (r^2=0.90) linear relationship between the annual rainfall amount and the annual R-Factor was found for the two stations of Quilichao and Mondomo:

17) $R = 6.537\, R_a - 932.9$

where R_a is the rainfall amount in mm a^{-1} and R the R-Factor in MJ ha^{-1} mm h^{-1} a^{-1} (Figure 20).

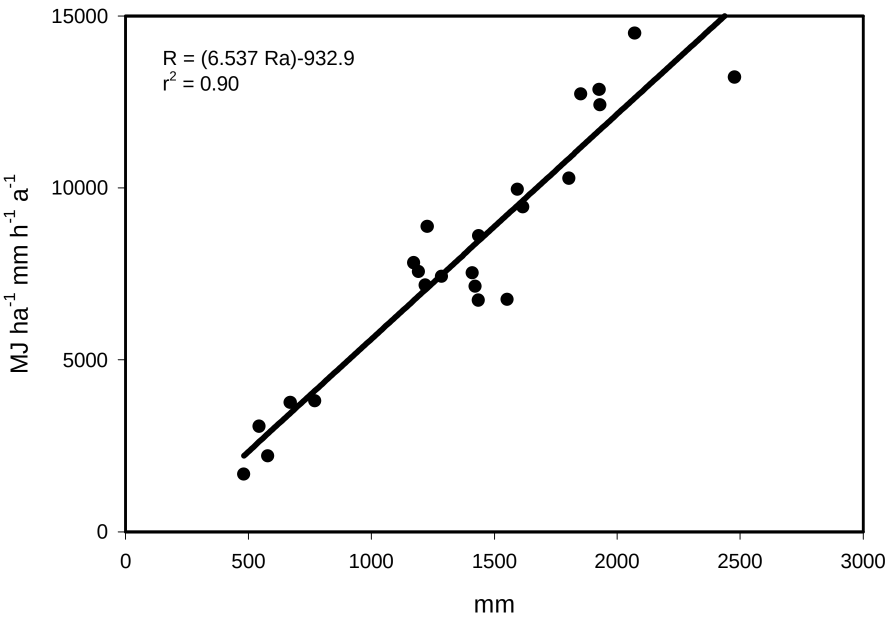


Figure 20. Relationship between annual rainfall amount and R-factor for Quilichao and Mondomo

This relationship produced no satisfactory results for the other four stations, except for Trujillo where a highly significant relationship (r^2 = 0.84) was found:

18) R = 7.5 Ra – 4,486

where R_a is the rainfall amount in mm a^{-1} and R the R-Factor in MJ ha^{-1} mm h^{-1} a^{-1}.

The approach using the modified Fournier index was more precise and the results were highly significant for all six stations. Two regression types were evaluated, linear and power. The power type was slightly superior for all the stations except Mondomo and Restrepo (Table 20). Restrepo showed the lowest regression coefficients. When November was eliminated from the regression, the r^2 improved to 0.84 (linear) and 0.85 (power). November had a very low R-Factor value compared to the average monthly rainfall amount and resulting p^2/p_i index.

Table 20. Results for the application of the modified Fournier index to calculate average monthly R-Factor values

Station	Linear regression	r^2	Power regression	r^2
Quilichao	$y=40.41\ (p^2/p_i)+291.4$	0.93	$y=201.93\ (p^2/p_i)^{0.5811}$	0.95
Mondomo	$y=49.62\ (p^2/p_i)+307.9$	0.92	$y=259.02\ (p^2/p_i)^{0.5174}$	0.88
El Tambo	$y=23.52\ (p^2/p_i)+236.8$	0.93	$y=126.16\ (p^2/p_i)^{0.6086}$	0.95
La Florida	$y=25.41\ (p^2/p_i)+264.1$	0.96	$y=161.0\ (p^2/p_i)^{0.5520}$	0.99
Trujillo	$y=41.11\ (p^2/p_i)+266.8$	0.94	$y=188.55\ (p^2/p_i)^{0.5784}$	0.96
Restrepo	$y=19.36\ (p^2/p_i)+70.99$	0.76	$y=58.38\ (p^2/p_i)^{0.6721}$	0.76

3.6 Application of rainfall erosivity data to create a R-factor map

In order to apply the results of the present work in relation to rainfall erosivity data and its practical application, a rainfall erosivity map, originally produced by Kingston (1997), was used. An Arc/Info GRID coverage, based upon the average monthly and annual precipitation rainfall data in Colombia from the Instituto Colombiano de Hidrologia, Meterologia y Adecuación de Tierras (HIMAT, 1989), was used to provide the rainfall data. Points from this coverage comprising the northern Cauca department were clipped into the GIS model and interpolated into a surface using the SPLINE function in Arc/INFO GRID. A mask was applied to produce a grid containing solely the data for the Cabuyal sub-watershed. The digital elevation model (DEM) used had a cell size of 20 m which is recommended for the most accurate modeling of hillsides.

The rainfall map used had an average of 20 years as a database; Kingston originally used only 3 years of data from the CIAT/University of Hohenheim to calculate R-Factor values based upon a linear relationship between the annual rainfall amount and R-Factor values. For the new version of the R-Factor map shown in Figure 21, the linear relationship $R = 6.537\,R_a - 932.9$ (r^2=90) (R = annual R-Factor value, R_a = annual rainfall amount) presented in chapter 3.5 was used to recalculate the R-Factor based upon 11 years of rainfall erosivity data.

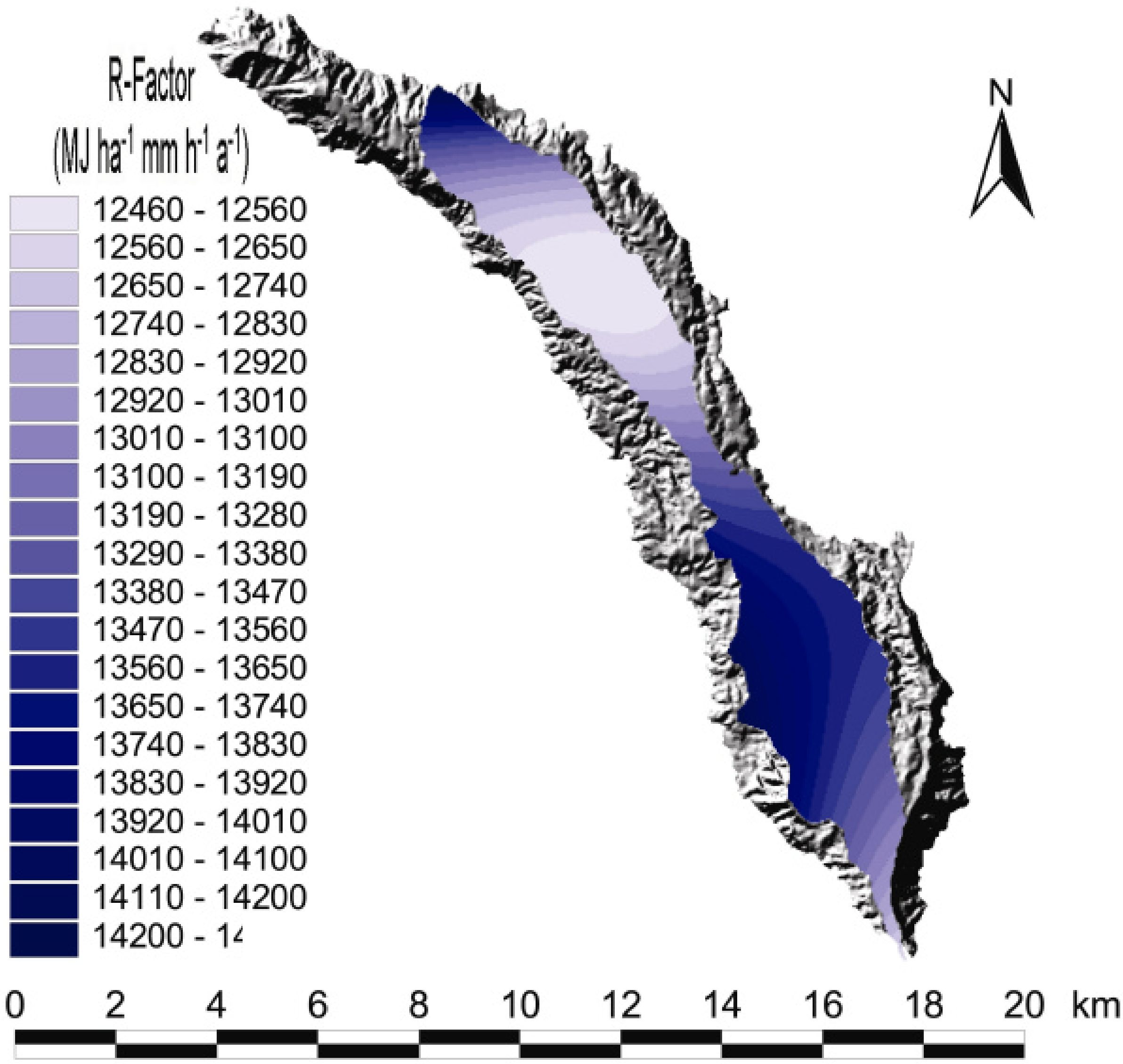


Figure 21. R-Factor map for the Cabuyal sub-watershed with hillshade layer underlayed

For areas, where rainfall erosivity data are unavailable, monthly rainfall amounts can be used to calculate R-factor values using the relationships developed in the present work (Table 20). An additional option especially in areas with low density of meteorological stations is the combination of these relations with climate estimators like LocClim 1.0 (FAO, 2002). This program estimates values for basic climate variables like temperature, montly precipitation, sunshine fraction, windspeed and others using the Inverse Distance Weighted Average (IDWA) approach based on data from the surrounding nearest stations from the database FaoClim 2.0 (FAO, 2001) of the Agrometeorology Group in the Environment and Natural Resources Service (SDRN) of FAO. Using this program a grid of montly rainfall values was estimated for the easternmost part of the Rio Ovejas watershed. Based on the linear relationship between R-Factor and Fournier index derived for Mondomo (Table 20), being the nearest station, the R-Factor values for this grid were calculated and are shown in Figure 22.

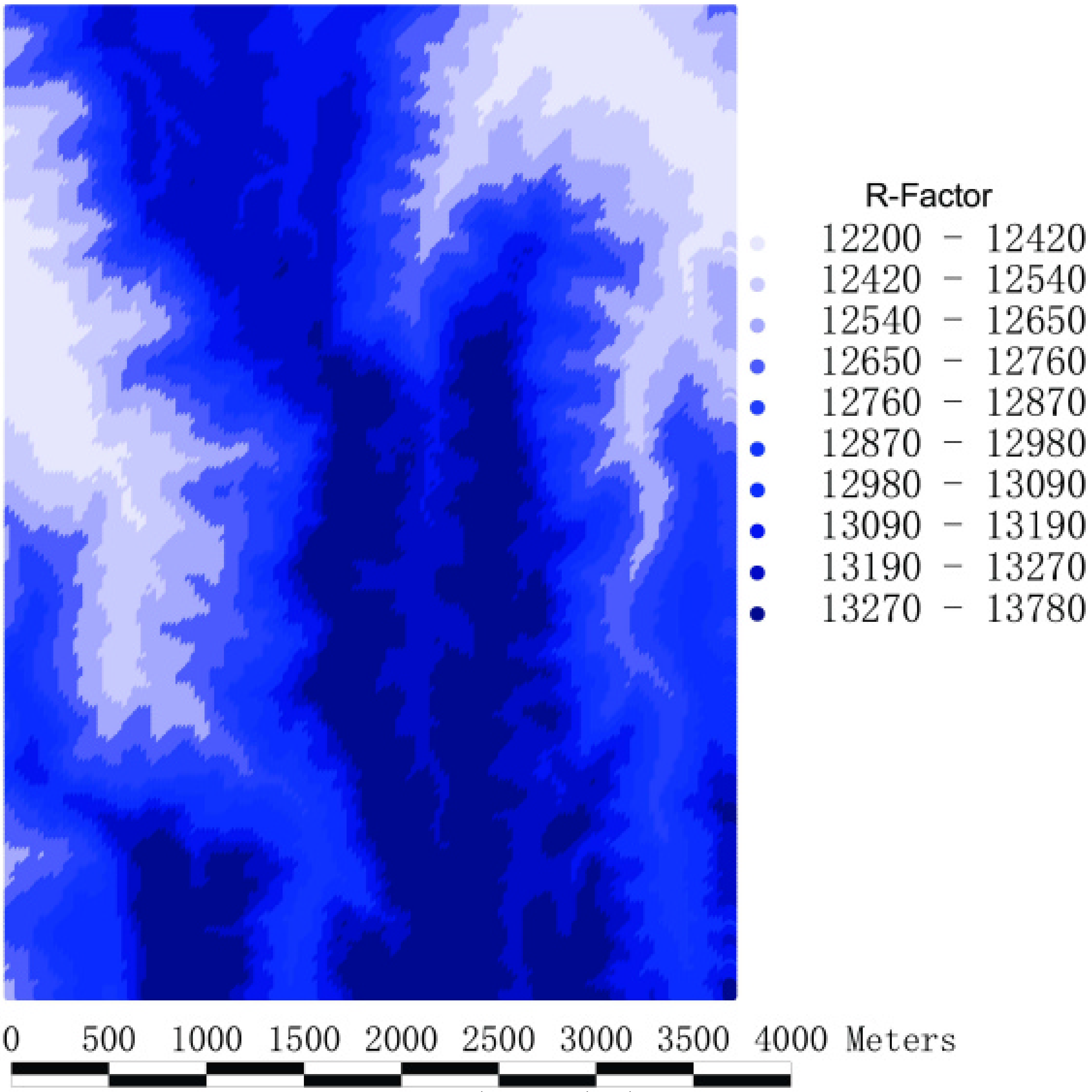


Figure 22. R-Factor map in MJ ha^{-1} mm h^{-1} a^{-1} for the easternmost part of the Rio Ovejas watershed based on LocClim 1.0 estimated values

3.7 Discussion

Analysis of the drop size measurements confirmed the validity of the relationship between rainfall intensity and the D_{50} for the research area, formerly established in other regions. The tendency of the curve to increase to an intensity level of between 80 mm h^{-1} and 100 mm h^{-1} and to drop off after reaching that level was observed. As the measurements did not cover any intensities of above 86 mm h^{-1}, no conclusions could be drawn about the curve beyond this point. The drop sizes measured lay within ranges reported formerly (Hudson, 1995) with low amounts of drops above 5 mm. The mean D_{50} values of 1.85 mm are very close to the measurements made by Vis (1986) in an area of the Central Cordillera about 200km to the north of the present research area.

Kowal and Kassam (1976) as well as Lal (1998) reported higher D_{50} values from Nigeria. As the intensities recorded were in a similar range, it can be assumed that the rains measured in Colombia reached these intensities due to a higher number of raindrops per unit area. The average drop number per cm^2 for a 20 mm rainfall in Nigeria was 96.3 while a similar rainstorm measured in Colombia reached 557 drops cm^2. The number of drops per cm^2 for all the rains measured ranged from 269 to 5,116. Direct comparison with the measurements of Kowal and Kassam is however restricted by the technical differences between the devices used, as the lowest drop diameter measurable with the device used in Nigeria was 2.34 mm, whereas the disdrometer records raindrops from a 0.5 mm diameter upwards. The D_{50} values reported by Lal (1998) were measured using a Distromet® device as in Colombia. Maene and Chong (1978) reported D_{50} values in the range between 1.2 and 3.1 mm measured in Malaysia. Nyssen et al. (2003) measured higher D_{50} values and a higher energy load in the northern Highlands in Tigray, Ethiopia.

The average energy loads were much lower than those measured by Kowal and Kassam (1976) in Nigeria, but higher than those reported by Hudson (1995) from Zimbabwe and Vis (1986) from Colombia.

The energy load values of all, the erosive rainfall from Quilichao and Mondomo and the energy load of erosive rainfall from the other five stations were all very close. The same applies to the frequencies of intensities and mean R-Factors apart from at the Restrepo station which was very close in respect of the physical parameters but showed a far lower mean R-factor due to lesser annual rainfall amounts. It can therefore be assumed that these energy loads, as well as the other physical parameters of the rainfall, are relatively constant and applicable to larger areas with comparable geographical attributes. Similar observations have been made in other regions of the world. Kinnel (1987) compared Distromet® disdrometer measurements from two stations in south-eastern Australia that were 480 km apart and found that the energy-intensity relationships and the maximum energy load values did not differ considerably.

This significantly improves and facilitates the use of models such as the USLE, as it enables rainfall erosivity data - which are limited in tropical areas (especially in developing countries) due to constraints concerning the available meteorological information and its analysis - from key sites to be used and extrapolated to a wider area. An interesting fact in this context is the highly significant linear relationship found between rainfall amount and total kinetic energy as it permits the use of rainfall amount data that are easy to obtain for a wide selection of stations and years, and allows further calculations to be performed that are essential to establishing a region's erosivity.

Doubts about the applicability of the USLE energy term under tropical rainfall conditions – in respect of its derivation from temperate rainfall data - raised in former project phases were dispelled, as the energy intensity term calculated on the basis of the disdrometer measurements did not differ significantly from the one used in the USLE. It should therefore be possible to apply the USLE energy term in the southern parts of the Colombian Andes. A similar observation was made in the neighboring country of Panama where measurements of raindrop distributions showed that regional values were within 10% of the values calculated in accordance with the USLE (McIsaac, 1990).

The erosive potential of the research region's climate can be regarded as very high. With regard to rainfall amount, three-quarters of the annual rainfall amount fell during rainfall events that are deemed to cause erosion. According to Hudson (1995), the rainfall distribution patterns of the tropics increase erosion risks as rainfall is concentrated into one or two periods in comparison with a more uniformly distribution throughout the year. This increase is brought about by the concentration of rainfall in certain periods and the loss of soil cover due to the drying and often burning of plants in the pronounced dry seasons. In the research region, these risks are further enhanced by the time of planting, as the most erosive months of the bimodal rainfall distribution coincide with the planting times of the cropping systems, i.e. March, April and September, October (Howeler, 1980; Reining, 1992). In addition, the slow initial growth and therefore poor soil cover of the main crop, cassava, increases the vulnerability of the soil (Cock, 1989; Leihner et al., 1996). Howeler (1984) reported from erosion trials carried out with cassava cropping systems near Mondomo that the highest soil losses occurred during the first two months after planting.

As regards intensity, the values obtained from the total project duration of 12 years matched well with those obtained from other tropical regions. Hudson (1995) stated that 5% of temperate rainfall falls at intensities of higher than 25 mm h^{-1} with values above 75 mm h^{-1} being seldom reached, whereas in the tropics approximately 40% of the rainfall is above 25 mm h^{-1} and high intensities are often reached. Jackson (1989) reports that 34.2% of all rainfall fell at intensities of above 25 mm h^{-1} for New Guinea, which is very close to the values measured in Quilichao and Mondomo.

As to I_{30} values, the range recorded showed that high intensities occurred frequently. The average I_{30} for all the stations in the Cauca or Valle del Cauca Departments except Restrepo was above 25 mm h^{-1} and each station frequently achieved high values of above 50 mm h^{-1}. Even the station with the lowest climate erosivity, Restrepo, showed an average I_{30} of 23.9 mm h^{-1}. The maximum values reached were well above 100 mm h^{-1}. Compared to measurements from temperate and some tropical regions, these values can be regarded as very high. Chow (1990) reported a maximum I_{30} of 20 mm h^{-1} for a two-year period from Canada, whereas 77% of the rainfall events had an I_{30} of below 10 mm h^{-1}. To compare, only between 3.6 and 9.6% ($\bar{x}$ = 6.5%) of the events from the six Colombian stations presented in this work had I_{30} values of below 10 mm h^{-1}. Other maximum I_{30} values were established in Kenya at 44 mm h^{-1} (Ulsaker and Onstad, 1984) and in New South Wales, Australia at 65 mm h^{-1} (Armstrong, 1990). 72% of the I_{30} values were above 25 mm h^{-1} in Nigeria, a higher value compared to the present study (Wilkinson, 1975). Bomah (1988) found a distribution of I_{30} values in Nigeria that can be deemed to be very close to the ones reported in this study. 41% of the I_{30} was below 25 mm h^{-1}, whereas 46% lay between 25 and 50 mm h^{-1}, 11% between 50 and 75 mm h^{-1} and 2% between 75 and 100 mm h^{-1}.

The average annual R-Factors from the four Cauca stations were high and, together with the range between 3,500 and 15,500 MJ ha^{-1} mm h^{-1} a^{-1}, correspond well with data from other tropical countries as presented in Table 21. A wide range of annual R-Factor values can be expected depending on a country's rainfall distributions. Additionally, factors such as the distribution of rainstorm sizes and intensities as well as topographic differences may cause differences between regions showing similar annual rainfall amounts. Areas within Colombia comparable with the research region in relation to physical rainfall attributes and topography, such as the coffee growing zone in the departments Antioquia, Quindio, Risaralda and Caldas, may have much higher annual rainfall amounts and consequently higher R-Factors can be expected (Jaramillo-Robledo and Kogson-Quintero, 1994).

Table 21. Annual R-Factor values from various tropical countries.

Country	R-Factor (MJ ha^{-1} mm h^{-1} a^{-1})	
	Lowest value	Highest value
Barbados [5]	2,500	9,000
Brasil [4]	5,700	15,000
Costa Rica [1]	1,700	15,000
Colombia [6]	700	15,000
Panama [7]	3,300	17,350
St. Lucia [5]	3,000	12,000
Burkina Faso	2,000	6,500
Cameroon	6,900	20,000
Chad	-	5,500
Guinea	-	20,000
Ivory Coast	5,000	14,000
Kenya [2]	-	1,700
Madagaskar	6,300	14,000
Zambia	2,600	12,000
India	1,200	30,000
Java	1,500	4,000
Taiwan	4,300	30,000
Australia [3]	1,400	2,500

1 Vahrson, 1990; 2 Ulsaker and Onstad 1984; 3 Armstrong 1990; 4 Carvalho 1991; 5 Madramootoo and Norville, 1990; 6 present study; 7 Oster 1980; All other values were taken from Bergsma, 1996 and converted to MJ ha^{-1} mm h^{-1}.

The high variability of monthly R-Factor values further emphasizes the necessity of keeping the soil covered during all times of the year. High values were frequently observed even during dry season months with generally very low rainfall amounts. Single events with an R-Factor of above 1,000 MJ ha^{-1} mm h^{-1} a^{-1}, and therefore up to 12% of the mean annual R-Factors, occurred frequently and these can be expected to occur once every year in Quilichao and Mondomo, once every 1.5 years in El Tambo and once every 1.6 years in La Florida. The most erosive event of 2,610 MJ ha^{-1} mm h^{-1} was 17% of the annual R-

Factor of that year and reached 32% of the 25-year annual average. As the records for Quilichao and Mondomo were limited in comparison to the other stations, it can be assumed that over a long-term period they would develop in a similar manner in terms of extreme values and averages. This would probably also be true in respect of the average R-Factor values which were lower in all 4 comparable stations when compared to the 12 year records from Quilichao and Mondomo.

4 Establishment of long term soil erodibility and evaluation of seven cassava-based cropping systems in respect of susceptibility to erosion and productivity

The K or erodibility Factor of the USLE characterizes the susceptibility of the soil to the erosive forces of the climate. Erodibility is primarily influenced by the physical parameters of the soil and secondarily by the topography of the location and the land management system (Morgan, 1995). The most significant physical parameters defining the erodibility of a given soil are texture, aggregate stability and sheer strength as well as infiltration capacity and organic and chemical composition. The USLE includes a nomograph to establish the K-Factor from selected physical and chemical properties which is applicable to the majority of soils in temperate regions. Research has shown that this nomograph is not adequate for use with most tropical soils (Vanelslande et al. 1984 cited in Hudson 1995). Former periods of this research project confirmed this statement. Reining (1992), Castillo (1994, 1995), Ruppenthal (1995) and Felske (2000) reported that the use of the nomograph clearly overestimated K-Factor values as compared to measured values. According to Lal (1994) and Hudson (1995) the only reliable way to establish K-Factors is to perform measurements using runoff plots under natural rainfall conditions in order to obtain local values. Wischmeier and Smith (1978) recommended at least five years of continuous measurements, commencing two years after establishment of the bare fallow plots. These measured values are generally assumed to be relatively constant in order to facilitate the use of the USLE or other models but seasonal influences and cropping system alterations may cause changes. The objectives of the current study were to define long-term K-Factor values for the two research sites and to use the long-term measurements to evaluate the potential of the USLE for estimating the erosion risk in the region. Additionally, seven cassava-based cropping systems were assessed as to their susceptibility to erosion and long-term nutrient losses.

4.1 Soil losses from bare fallow plots (USLE standard plots) at Quilichao

Soil losses from the bare fallow plots were evaluated from January 1994 to the end of the observation period in June of 1998. As in previous project years soil losses were high. At Quilichao. the total soil loss corrected in accordance with the LS-Factor of the USLE for the whole period shown in Table 22 was 868 t ha^{-1} and the measured soil loss was 913 t ha^{-1}. This would correspond to a loss of more than 9 cm of the topsoil assuming a 1.0 g cm^{-3} average bulk density of the topsoil layer.

Table 22. Soil loss from bare fallow plots in Quilichao in the period from January 1994 to June 1998

Year	Soil loss LS-corrected t ha^{-1}	Soil loss Not corrected t ha^{-1}	R-Factor MJ ha^{-1} mm h^{-1}	Rainfall mm
1994	274	296	13,217	2,477
1995	224	231	9,959	1,594
1996	191	197	10,276	1,804
1997	121	127	9,438	1,616
1998 [1]	58	62	3,805	770
long-term average	180 [2]	191 [2]	10,037 [3]	1,799 [4]

1 Data from 1998 only comprise the period January to June; 2 10-year average (first two years not included according to USLE methodology; 3 12-year average; 4 32-year average CIAT Quilichao station records

The annual rainfall amount was lower compared to the long-term average except in 1994 and 1996 whilst the annual R-Factor values were above the twelve-year average (data include the period from 1987 to 1998 gathered by: Reining 1992; Castillo, 1994; Ruppenthal 1995; and Felske, 2000). The soil loss distributions between the years evaluated showed large differences in respect of the amount, concentration in time and response to the respective erosivity and rainfall amount values. A total of 144 erosive events were registered and the distribution in soil loss classes is shown in Table 23.

Table 23. Distribution of soil loss events in Quilichao from January 1994 to June 1998

Soil loss class t ha^{-1}	n	% of events	Soil loss t ha^{-1}	% of total soil loss
< 1	43	29.9	15.0	1.6
1-5	45	31.3	106.9	11.7
5-10	29	20.1	201.1	22.0
10-20	19	13.2	254.7	27.9
20-30	3	2.1	81.4	8.9
>30	5	3.5	254.1	27.8

Soil losses were primarily concentrated in a few events producing a high amount of eroded soil. 81.3% of the events produced only 35.4% of the soil loss whereas 18.7% of the events generated 64.6% of the total soil loss amount. The five most erosive events (3.5% of the events), shown in Table 24, accounted for a soil loss amount of 254 t ha^{-1} (27.8% of total soil loss), the greatest soil loss of a single event being 73 t ha^{-1}. This event caused 24.7% of the total soil loss of the particular year and 8% of the total soil loss of the whole period presented. The importance of factors such as antecedent rainfall and soil moisture content are evident as the rainstorm that caused the highest soil loss reached only 50% of the erosivity compared to the following two most erosive events. A possible explanation for this disparity was an almost identical rainstorm in respect of erosivity, maximum I_{30} and rainfall amount that fell three days before. This only caused a soil loss of 11 t ha^{-1} but it saturated the soil thus making it more vulnerable to erosion. This phenomenon was observed frequently, especially at the end of the dry season when rainfall events with high erosivity caused only insignificant soil loss amounts, whereas events of only low erosivity - in some cases even not fulfilling the criteria for erosive rainfall established by Hudson (1995) or Wischmeier and Smith (1978) - falling shortly afterwards caused very high soil losses. According to Wischmeier and Smith (1978), below-average soil losses can be expected when a rainfall event takes place in dry, freshly tilled soil conditions due to a higher infiltration rate. Above-average soil losses may occur under differing conditions with rain falling upon presaturated soil. According to these authors, phenomena such as strong winds, that may increase the force of drop impact leading to higher erosion amounts, or high intensities at the beginning sealed the soil surface quickly and thus led to higher runoff rates and erosion during later low intensity phases of the rainfall event. These circumstances underline the necessity of performing erosion measurements over a longer period of time to ensure that a broad spectrum of different rainfall events is taken into account and reliable long-term average values are obtained.

Table 24. Characteristics of the five most erosive rainfall events at Quilichao recorded from January 1994 to June 1998

Soil loss t ha^{-1}	Peak intensity mm h^{-1}	I_{30} mm h^{-1}	Total energy MJ ha^{-1}	R MJ ha^{-1} mm h^{-1}	Rainfall amount mm	% of annual soil loss
35	234	57.0	9.9	566	38.0	17.8
37	378	74.2	13.5	1,002	55.0	15.8
45	142	83.7	15.4	1,287	60.8	15.3
64	228	65.0	19.4	1,264	80.4	27.8
73	113	52.3	12.7	666	50.4	24.7

The months with the highest soil losses were March and April followed by October and November (Table 25). Although, according to the twelve-year average of the project and also the long-term CIAT recordings (32 years), the second rainy season has to be seen as the more pronounced with a higher rainfall amount and higher erosivity, the first rainy season showed higher R-Factor values and higher soil losses during the later project phase. During the period from June 1994 to June 1998 the first rainy season produced 57.8% of the total soil loss amount whereas the second rainy season accounted for 27.6%. The first dry season produced 6.5% of the total soil loss amount and the second 8.1%.

Table 25. Monthly averages for R-Factors and soil loss from Quilichao. Data were recorded between January 1994 and June 1998

Month	R-Factor MJ ha^{-1} mm h^{-1}	Soil loss t ha^{-1}	SD Soil loss t ha^{-1}
JAN	721	8.1	15.4
FEB	511	18.1	37.8
MAR	1,873	34.3	25.7
APR	1,550	42.1	34.1
MAY	928	28.6	27.6
JUN	650	6.0	6.2
JUL	89	0.3	0.6
AUG	185	1.8	3.5
SEP	798	12.8	16.2
OCT	1,239	19.8	25.4
NOV	1,042	15.8	15.1
DEC	666	7.8	7.7

The monthly relationship between erosivity and soil loss in every year showed a concentration of soil losses in the early rainy season except in 1997 when erosive events were more evenly distributed (Figure 23). Reining (1992), Ruppenthal (1995) and Felske (2000) reported the opposite behavior at the trial location for the periods from 1987 to 1989, 1990 to 1992 and 1992 to 1994. The highest total annual soil loss amount recorded was in 1994 at 296 t ha^{-1}. This year also contained three of the months with the highest erosion rates recorded between 1994 and 1998. April produced almost 100 t ha^{-1}, followed by February and March with 86 and 57 t ha^{-1} respectively. The soil loss amount measured for the second dry season of 1994 was very low and July, August and September produced no soil losses at all. 1995 also showed the typical bimodal distribution although was slightly more balanced. The months with the highest soil losses were May and October with 72 t ha^{-1} and 56 t ha^{-1} respectively. March and April also produced high levels of soil loss, but four months did not show any soil losses at all and June recorded only 0.2 t ha^{-1}. In contrast, all the months in 1996 recorded soil losses, but only at low levels of between 1 and 2 t ha^{-1} in the dry season months and in November. March and September were the months with the highest erosion levels at 61 and 37 t ha^{-1} with March showing the highest monthly erosivity of all of the years at more than 3,900 MJ ha^{-1} mm h^{-1}.

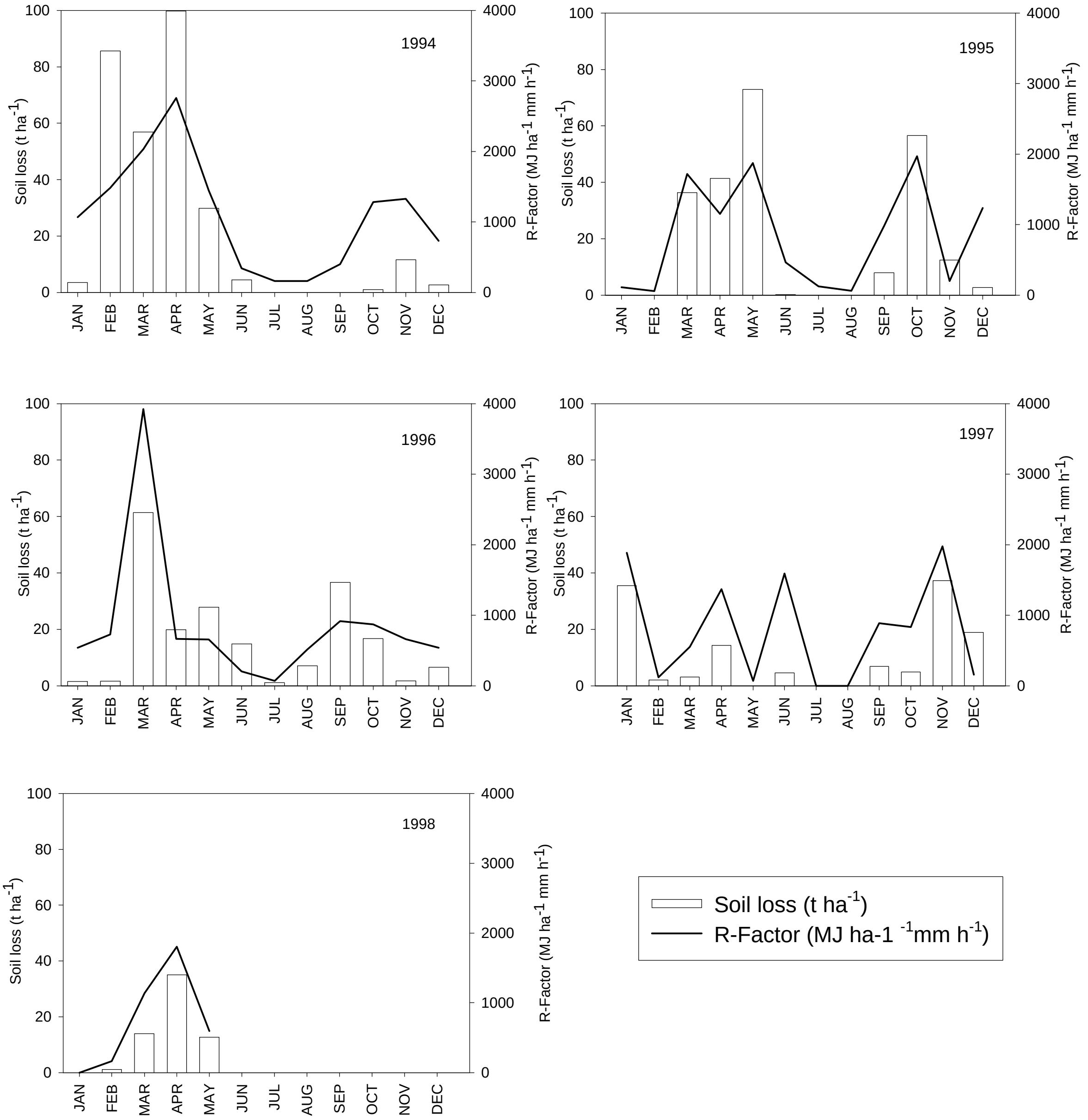


Figure 23. Monthly soil loss amounts in Quilichao from the bare fallow plots for the period from January 1994 to June 1998 with corresponding rainfall erosivity

A possible explanation for the continuous soil losses throughout the year could be the distribution of rainfall and erosivity, as only one month showed a rainfall amount of below 100 mm and most months had only short dry spells. The daily distribution of rainfall was very balanced, probably permanently maintaining the soil in a moist condition and thus decreasing infiltration capacity and increasing erosion.

1997 was a very balanced year with regard to soil losses with the highest amounts reached being 36 t ha^{-1} and 37 t ha^{-1} in January and November respectively. No soil loss occurred in July and August due to the second pronounced dry season. Between June 29th and September 22nd only 19 mm fell in four small events, with no rainfall in July and only 5 mm in August. Soil losses in all the other months were relatively low.

The first six months of 1998 followed the typical first rainy season pattern with January and February recording low levels of rainfall and soil erosion. April, being the month with the most erosive conditions, produced a sediment amount of 35 t ha^{-1}, whilst soil erosion amounts in both March and April came in at slightly below 20 t ha^{-1}.

4.2 Soil losses from bare fallow plots (USLE standard plots) at Mondomo

Due to the more pronounced slope gradients, the difference between the LS-corrected and measured soil loss amounts calculated at Mondomo were far higher than those obtained at Quilichao. The total LS-corrected soil loss for the period from January 1994 to June 1998 shown in Table 26 was 340 t ha^{-1}, whereas measured soil losses amounted to 873 t ha^{-1}, corresponding to a topsoil loss of almost 9 cm.

Table 26. Soil loss from bare fallow plots at Mondomo for the period January 1994 to June 1998

Year	Soil loss LS-corrected t ha^{-1}	Soil loss not corrected t ha^{-1}	R-Factor MJ ha^{-1} mm h^{-1}	Rainfall mm
1994	131	335	7,138	1,422
1995	115	297	12,727	1,852
1996	63	160	6,751	1,552
1997	22	57	7,529	1,410
1998 [1]	9	24	2,211	578
long-term average	88 [2]	238 [2]	9,016 [3]	2,133 [4]

1 Data from 1998 only comprise the period January to June; 2 10-year average (first two years not included according to USLE methodology; 3 12-year average; 4 25-year average Mondomo meteorological station records

The annual rainfall amounts in every year were below the long-term average (32 years) as were as the R-Factor values apart from in 1995. However, consideration must be given to the fact that the long-term average rainfall values come from the meteorological station located in the town of Mondomo, which lies a few kilometers to the north of the trial site. Due to the topography of the region values could differ even between close locations. Like the observations in Quilichao the differences between the years in respect of the soil loss amount, rainfall amount, corresponding erosivity and associated aspects were high. A total of 106 erosion-producing events were recorded and analyzed. Results were similar when compared to those from Quilichao with a high number of events producing low amounts of erosion, whilst a few extraordinary events caused the bulk of the erosion (Table 27). 72.6% of the events caused 20.1% of the total erosion amount, whereas 15.1% of the events accounted for 58.4% of soil loss. The six events with the highest soil losses (5.7% of all events) produced 32% of the total soil loss.

Table 27. Distribution of soil loss events at Mondomo from January 1994 to June 98

Soil loss class t ha^{-1}	n	% of events	Soil loss t ha^{-1}	% of total soil loss
< 1	40	37.7	18.6	2.1
1-5	24	22.6	60.8	7.0
5-10	13	12.3	96.2	11.0
10-20	13	12.3	188.1	21.5
20-30	10	9.4	231.0	26.4
>30	6	5.7	279.5	32.0

The highest soil loss recorded for a single rainfall event was 60 t ha^{-1}, causing 37.6% of the soil loss in 1996. As shown in Table 28, this event had an R-Factor of 440, reaching only a third of the corresponding value of the first event presented with a soil loss of 32 t ha^{-1}. It had been preceded by two smaller events (falling one and two days before), both considered to be erosive according to the USLE, but not causing evident soil loss. As already described above these events had probably saturated the soil and thus considerably increased its vulnerability to water-induced erosion.

Table 28. Characteristics of the six most erosive rainfall events recorded at Mondomo from January 1994 to June 1998

Soil loss t ha^{-1}	Peak intensity mm h^{-1}	I_{30} mm h^{-1}	Total energy MJ ha^{-1}	R MJ ha^{-1} mm h^{-1}	Rainfall amount mm	% of annual soil loss
32	182.4	73.8	18.0	1,187	78.4	9.2
41	234.6	81.6	13.4	1,091	53.1	15.4
42	259.2	50.2	10.3	516	41.4	12.6
52	84.3	37.0	12.6	467	54.6	15.4
54	504.0	65.4	10.5	687	41.7	18.0
60	348.0	51.4	8.6	440	33.8	37.6

Like the pattern observed at Quilichao, the first rainy season was more pronounced than the second one. The months with the highest average soil loss were, in order: March, January, November and April. The differences between the years were very high as evidenced by the high standard deviations in Table 29. Months normally considered to possess low erosive potential such as January and, even more so, July, recorded high amounts of soil loss in respect of both individual years and the 12-year average. The necessity to keep the soil covered during all times of the year is emphasized by this phenomenon, as already reported from earlier project phases (Felske, 2000).

Both dry seasons produced very similar soil loss amounts. For the period from June 1994 to June 1998, the first dry season produced 14.4% of the total soil loss amount and the second 13%. As reported for Quilichao, the first rainy season accounted for a higher level of soil loss than the second one. However the differences were not as pronounced as those observed at the Quilichao field station, with 40.2% of the total soil loss amount being produced during the first rainy season and 32.4% during the second.

Table 29. Monthly averages for R-Factors and soil loss in Mondomo between January 1994 and June 1998

Month	R-Factor MJ ha^{-1} mm h^{-1}	Soil loss t ha^{-1}	Standard deviation Soil loss t ha^{-1}
JAN	1,013	30.1	32.2
FEB	430	4.6	6.5
MAR	1,147	38.7	44.2
APR	1,174	24.2	32.0
MAY	330	14.6	21.6
JUN	818	5.7	11.4
JUL	276	15.2	30.4
AUG	33	0.2	0.4
SEP	458	5.1	6.0
OCT	954	19.0	28.3
NOV	808	24.7	21.5
DEC	627	8.4	11.4

Erosion amounts varied considerably between years and months. The highest annual soil loss was 335 t ha^{-1} in 1994 as compared to 57 t ha^{-1} in 1997. The annual R-Factor values for both years were very close, with 1994 showing a considerably higher number of high erosivity rains. The most erosive event in 1997, falling in October, had an R-Factor value of 1,222 MJ ha^{-1} mm h^{-1}, but this fell after a period of 7 days with no rainfall. This probably caused most of the rainfall to infiltrate, thus minimizing the erosive power of the runoff water and limiting erosion to splash effects only.

As shown in Figure 24, the soil losses and the development of the R-Factor coincided quite well during 1994 except in November. Rainfall events and soil losses were mainly concentrated in the first half of the year. The highest soil loss for a single month throughout the entire period was March 1994 at 111 t ha^{-1} with January 1994 coming in second at 80 t ha^{-1}. April, May and November had soil losses of between 39 t ha^{-1} and 48 t ha^{-1}. February, October and December produced soil losses of below 10 t ha^{-1} whilst the very pronounced second dry season from June to the end of September produced no soil loss at all. Five of the highest monthly soil loss amounts were recorded in 1995, a year that showed the region’s typical pronounced bimodal distribution of rainfall and associated soil loss.

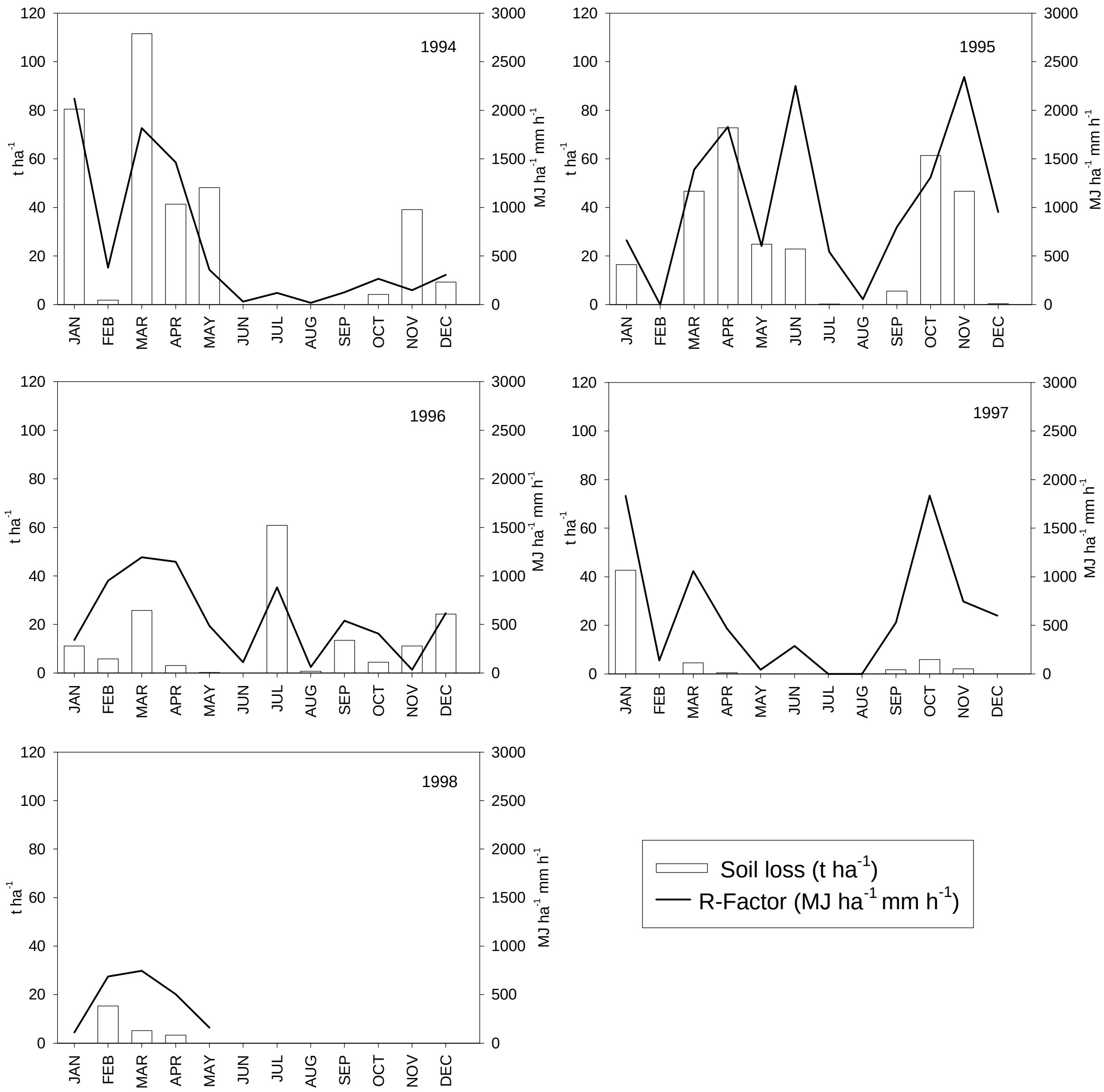


Figure 24. Monthly soil losses from bare fallow plots in Mondomo for the period from January 1994 to May 1998

April and October 1995 produced 73 t ha^{-1} and 61 t ha^{-1}, whereas soil losses in both March and November amounted to 47 t ha^{-1}. February, July, August and December produced very low to no soil losses. In 1996 soil losses over the whole year were more balanced and, with exception of July, did not reach very high levels. May, June and August showed soil losses of below 1 t ha^{-1} and the high soil loss in July was produced by only one rainfall event (see above).

Soil loss levels in 1997 were generally low compared to the other years with the exception of January, where only three events produced 87% of the total soil loss amount of 42 t ha^{-1}. The discrepancy between erosivity and soil loss for October has already been mentioned above, the monthly erosivity was almost identical to that in January but soil losses in January were more than seven times higher compared those in October. Again, this accentuates the necessity to establish long-term relationships between erosivity and soil loss for a wide number of antecedent soil moisture levels and climatic conditions. 1997 was the year with the highest number of months with no or very low levels of erosion. No evident soil loss was apparent during a period of six months and two more recorded very low amounts. In the period of 1998 covered in this study, January and May did not produce any soil loss and March and April only reached low levels. February was the month of highest soil losses at 15 t ha^{-1}.

4.3 Erodibility of several cassava-based cropping systems

4.3.1 Quilichao

Compared to the bare fallow plots, soil loss from the other treatments was relatively low during all the phases when crops were grown (Table 31). This changed only during the observation period in the final phase of the experiment. Table 30 shows the soil loss relationship for treatments 2 to 8 expressed as a percentage of the bare fallow treatment. The highest value reached was 18.3% for the cassava-based rotation with the bush fallow treatment (T5) in the 1995B cropping period. It was an outlier value caused almost entirely (89%) by a single event taking place the day after planting that caused more than 12 t ha^{-1} of soil loss in the bush fallow and only 3.1 t ha^{-1} in the sole cassava treatment, the treatment that produced the greatest soil loss values during all other cropping periods. In particular, the two cropping systems with erosion control measures, namely minimum tillage (T4) and vetiver barriers (T6), showed very low soil losses.

Whilst soil losses from the bare fallow plots were much higher in all the cropping periods, average soil loss amounts from the cropped treatments only reached levels of between 0.2 and 3.9% of the bare fallow plots. Therefore, only the seven cropped treatments were compared with each other for the periods 94B to 97A.

Table 30. Soil losses from treatments 2-8 expressed as a percentage of soil loss from bare fallow plots for the periods 94B to 97A at Quilichao

Treatment		Soil loss from cropped treatments in % of soil loss from bare fallow treatment						
		1994B[1]	1995A[1]	1995B	1996A	1996B	1997A	mean
T2	Farmer rotation	3.9	1.0	2.0	1.0	0.8	1.0	1.6
T3	Sole cassava	9.3	1.8	7.7	2.6	1.0	1.2	3.9
T4	Minimum tillage	1.0	0.3	0.2	0.1	0.0	0.0	0.3
T5	Bush fallow	1.7	1.2	18.3	0.6	0.3	1.4	3.9
T6	Grass barriers	1.1	0.1	0.1	0.0	0.0	0.0	0.2
T7	Legume strips	3.9	1.1	1.5	0.7	0.7	0.6	1.4
T8	Improved fallow	1.2	0.7	1.4	0.4	0.4	0.0	0.7

1 A and B stand for the first and second cropping season in each year respectively.

During the cassava cropping period 94B, lasting from June 94 to April 95, the soil loss of 5.0 t ha^{-1} from the sole cassava treatment (T3) was significantly greater ($p<0.05$) than that from the other six treatments. As shown in Figure 25, there were no significant differences between the farmer rotation, minimum tillage, bush fallow, grass barrier and legume strips treatments, although soil losses from the farmer rotation and legume strips treatments were as much as three times greater than those from the minimum tillage, grass barrier and improved fallow treatments. The improved fallow treatment showed the smallest soil loss, probably induced by the positive aftereffects of the previous two years of grass and legume mixture fallow. This effect was also observed during the final observation period, where soil losses from this treatment were very small in contrast to most others.

Table 31. LS-corrected soil losses from all treatments at Quilichao for the cropping periods from June 1994 to July 1997

Treatment		Soil loss (t ha^{-1})					
		94B	95A	95B	96A	96B	97A
T1	Bare fallow	37.072	78.497	68.145	163.524	58.691	17.985
T2	Farmer rotation	1.706	0.817	1.373	1.686	0.467	0.185
T3	Sole cassava	4.950	1.376	5.231	4.261	0.585	0.218
T4	Minimum tillage	0.544	0.274	0.156	0.116	0.022	0.000
T5	Bush fallow	0.829	0.946	12.502	1.025	0.177	0.258
T6	Grass barriers	0.591	0.107	0.095	0.080	0.018	0.000
T7	Legume strips	1.516	0.846	0.992	1.184	0.396	0.104
T8	Improved fallow	0.543	0.519	0.959	0.600	0.254	0.000

1 A and B stand for the first and second cropping season in each year respectively.

The first maize cropping cycle 95A (5.95-9.95), shown in Figure 26, produced low levels of soil loss for all cropped treatments. The sole cassava treatment showed the greatest soil loss at 1.3 t ha^{-1}, being significantly greater only than the grass barrier treatment with 0.107 t ha^{-1}. The soil loss amounts of all the other treatments were below 1 t ha^{-1}. However, the farmer rotation, minimum tillage, bush fallow, legume strips and improved fallow treatments did not differ significantly from either the sole cassava or grass barrier treatments.

During the second maize cropping cycle (95B), the total soil losses from the bush fallow treatment were significantly greater compared to those in all the other treatments (Figure 27). 89% of the 12.5 t ha^{-1} total soil loss from this treatment were produced by only one event, taking place immediately after seeding. This event was the fourth most erosive event for the whole period described here (see also Table 16). It also produced 32% of the soil loss from the legume strips treatment, as well as 34% from the improved fallow, 61% from the sole cassava and 41% from the farmer rotation. Although, due to the high variability between the repetitions, there were no significant differences between the soil loss amounts from the sole cassava treatment and those from the farmer rotation, legume strips, improved fallow, minimum tillage and grass barrier treatments, the sole cassava treatment produced soil loss amounts of as much as 50 times greater than the grass barrier treatment, more than 30 times the amount of the minimum tillage and still more than five times the soil loss amount from the legume strips and improved fallow treatments.

The cassava cropping period 96A was basically a repetition of the 94B period, except for the improved fallow treatment where a two-year improved fallow component was established, and the legume strips treatment where the wide strips of forage legumes were changed to single strips of grain legumes (Figure 28). Climate erosivity values during both rotation phases were very similar, reaching 6,318 MJ ha^{-1} mm h^{-1} in 94B and 6,751 MJ ha^{-1} mm h^{-1} in 96A. Soil loss amounts from most treatments were in the same range as in 94B. The soil loss amount of 4.3 t ha^{-1} from the sole cassava treatment was significantly greater compared to that of the other treatments. Soil losses from the vetiver and minimum tillage treatments were very low, whereas soil losses from the farmer rotation and legume strips treatments were as much as 20 times greater when compared to the grass barrier treatment, however the differences were not significant.

During the first three months of the 96A period, cowpea was intercropped with cassava in the legume strips treatment. Although forming part of 96A, this time span from April 96 to July 97 was also treated as a separate period and presented as 96B. Soil losses in all the treatments were below 0.6 t ha^{-1}. Figure 29 shows that there were no significant differences between the treatments, although the improved fallow and grass barrier treatments showed very small soil losses (<50 kg ha^{-1}).

Soil losses during the last observed cropping period 97A, lasting from April to July 1997, were very small (Figure 30). Only two rainfall events during the 90 days caused a soil loss on the cropped treatments, whereas the soil loss on the bare fallow plots for the same time period was 18 t ha^{-1}. The improved fallow, grass barrier and minimum tillage treatments did not produce any soil loss.

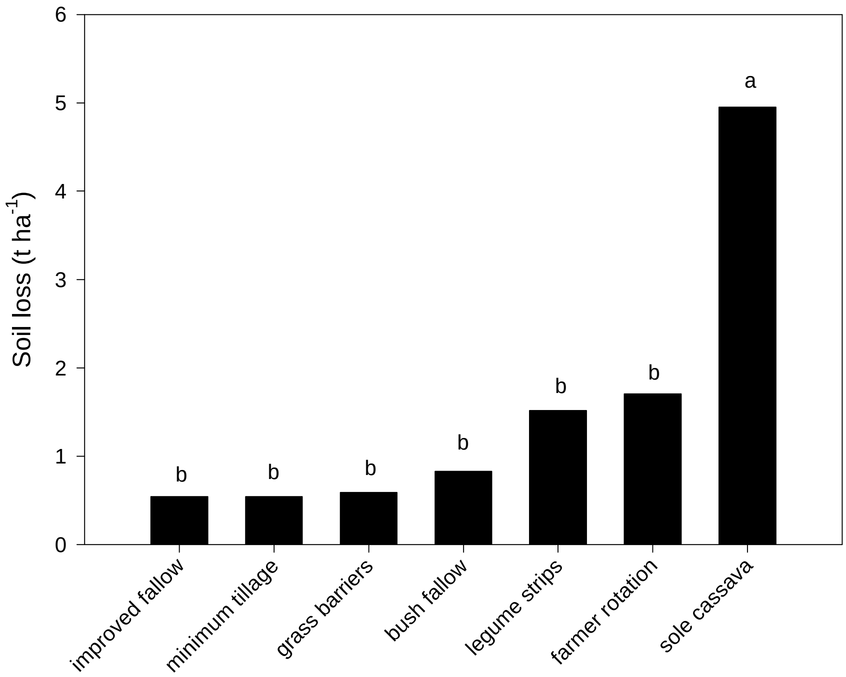


Figure 25. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 94B from June 1994 to April 1995 at Quilichao

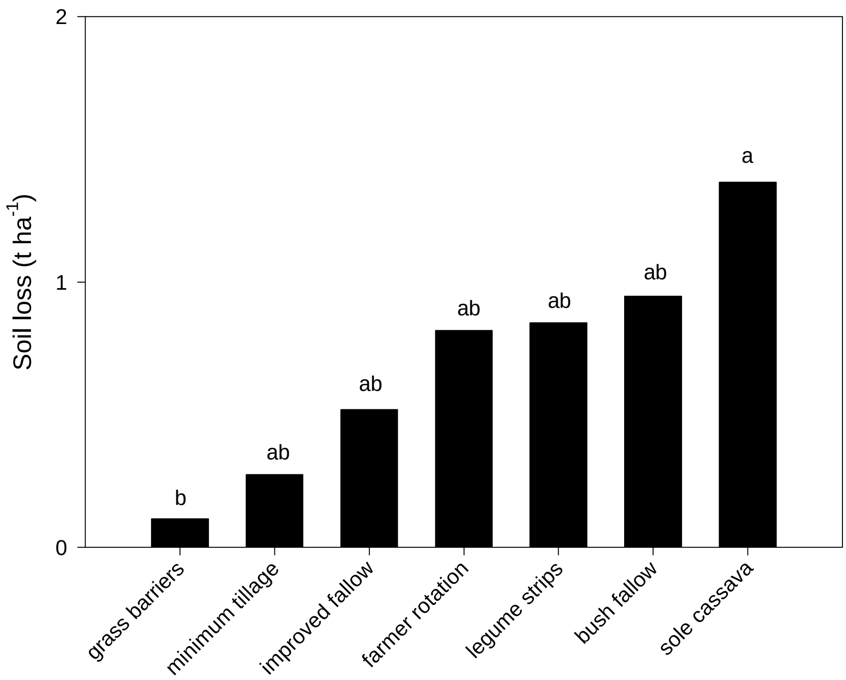


Figure 26. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 95A from June 1995 to September 1995 at Quilichao

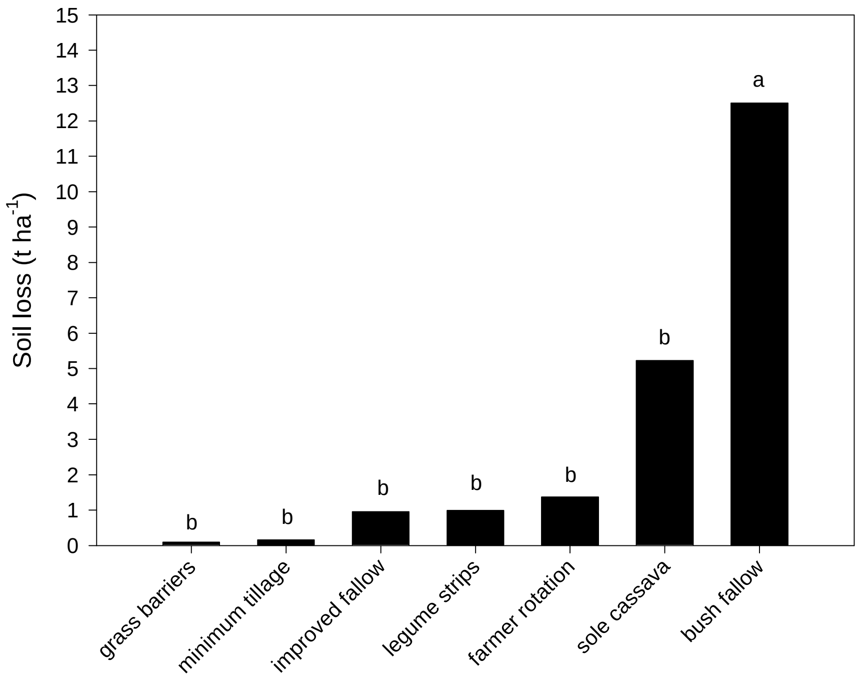


Figure 27. LS-corrected cumulated soil losses from treatments 2-8 for crop phase 95B from November 1995 to March 1996 at Quilichao

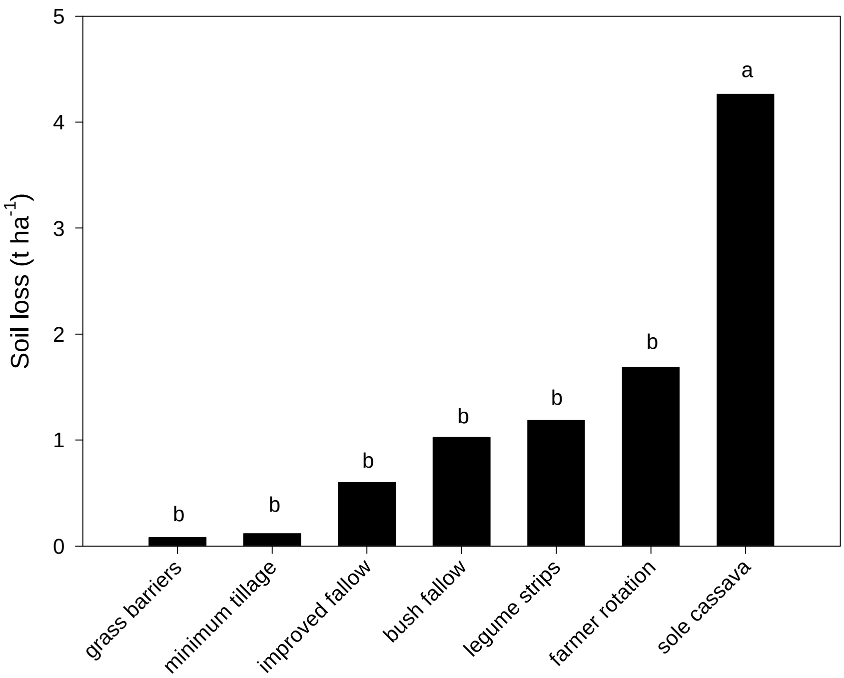


Figure 28. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 96A from April 1996 to March 1997 at Quilichao

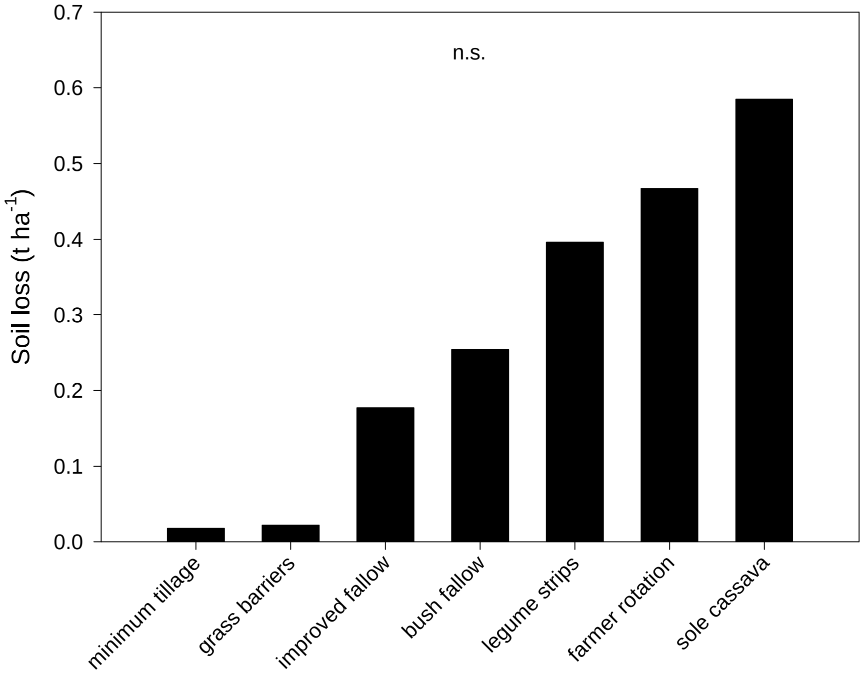


Figure 29. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 96B from October 1996 to January 1997 at Quilichao

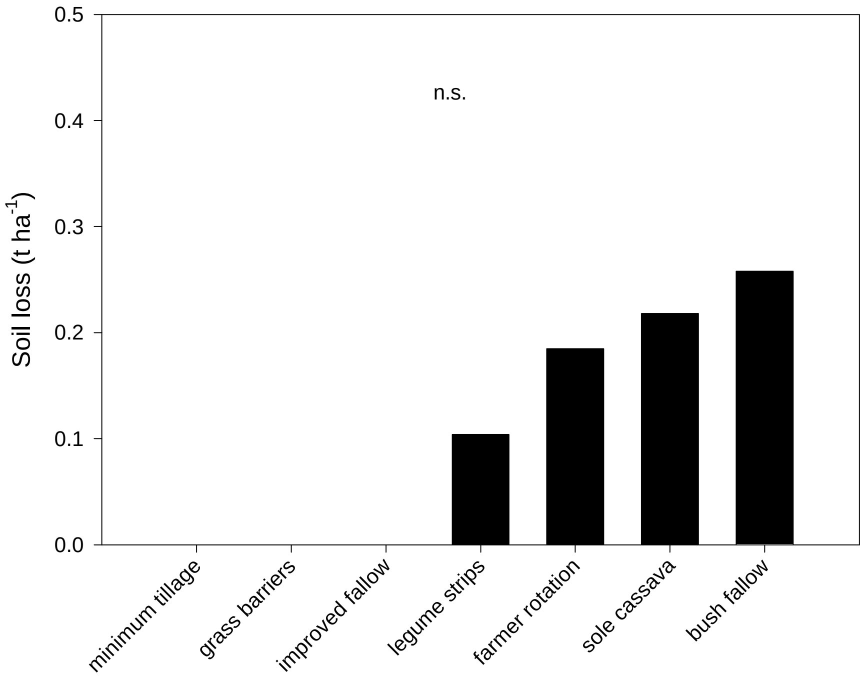


Figure 30. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 97A from April 1997 to July 1997 at Quilichao

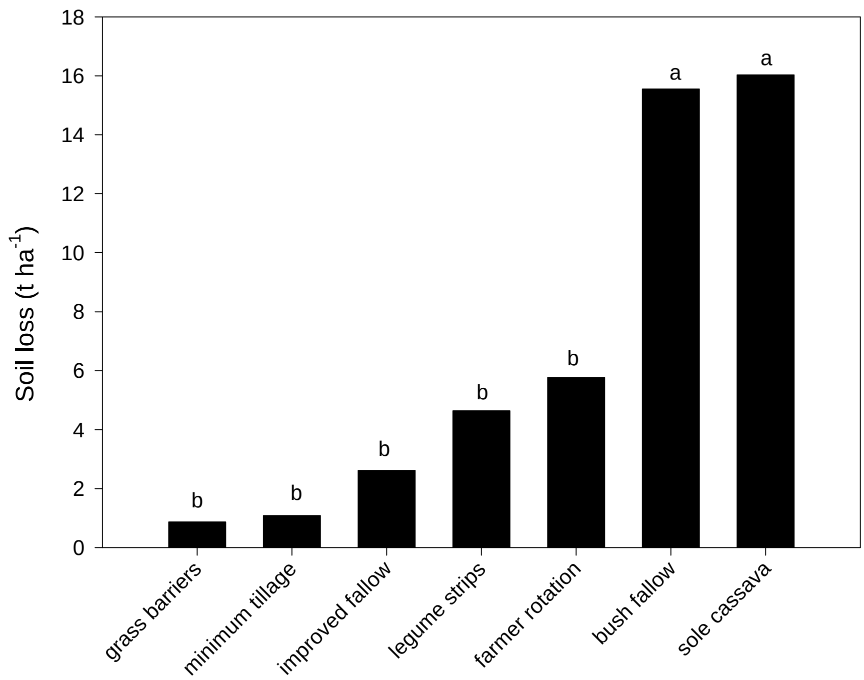


Figure 31. LS-corrected accumulated soil losses from treatments 2-8 for the complete period from June 1994 to July 1997 at Quilichao

When comparing the seven cropping treatments for the entire trial period from June 1994 to July 1997, soil losses from the sole cassava and bush fallow treatments were significantly ($p<0.05$) greater than those from the other five treatments (Figure 31). The large amount of eroded soil in the bush fallow treatment was due to the 95B cropping period, where one event after seeding caused great damage. There were no significant differences between the other treatments, although the minimum tillage and vetiver grass barrier treatments recorded only between one-fifth and one-sixth of the soil loss amounts measured on the farmer rotation and legume strips treatments.

4.3.2 Mondomo

Table 32 shows, like the observations made at Quilichao, that the soil losses from most of the treatments in Mondomo were small in comparison to those from the permanent bare fallow treatment. Only the sole cassava treatment recorded one-third of the soil loss amounts from the bare fallow soil plots during three consecutive cropping periods. The highest value reached by any cropping treatment was 61.4% of the bare fallow soil loss.

This was reached by the legume strips treatment in period 95A. This high soil loss amount was an outlier value provoked by two heavy rainfall events which also caused high soil loss in the bush fallow treatment on that date. The soil loss from this treatment amounted to 16.5% of the bare fallow plots, which is also far higher than the other cropping period values.

Table 32. Soil losses from treatments 2-8 expressed in percentage of soil loss from bare fallow plots from Mondomo for periods 94B to 97A

Treatment		Soil loss from cropped treatments in % of soil loss from bare fallow plot						
		1994B	1995A	1995B	1996A	1996B	1997A	Mean
T2	Farmer rotation	0.6	1.4	0.7	0.9	0.7	0.0	0.7
T3	Sole cassava	35.6	33.6	33.4	1.2	1.3	0.0	17.5
T4	Minimum tillage	0.2	0.5	0.3	0.2	0.1	0.0	0.2
T5	Bush fallow	0.6	16.5	3.2	1.0	1.0	0.0	3.7
T6	Grass barrier	0.4	0.3	0.1	0.4	0.3	0.0	0.3
T7	Legume strips	3.1	61.4	4.7	0.9	1.5	0.0	11.9
T8	Improved fallow	0.6	0.6	1.5	1.0	0.9	0.0	0.8

Due to the extreme differences (one event produced no soil loss in repetition one and 13 t ha^{-1} in repetition two) between measurements from the plots during the 94B cassava cropping period, the sole cassava treatment had to be eliminated from the statistical calculations. The number in italics in Table 33 shows the corrected value. Therefore, the potential soil loss for this treatment would be greater than its corrected value. Of the rest of the treatments, only the cassava rotation with legume strips treatment showed a significantly ($p<0.05$) greater soil loss than the farmer rotation, improved fallow, bush fallow, grass barrier and minimum tillage treatments (Figure 32). These five treatments showed generally small soil losses (<0.5 t ha^{-1}).

Table 33. LS-corrected soil losses from all the treatments at Mondomo for the cropping periods from June 1994 to July 1997

Treatment		Soil loss (t ha^{-1})					
		94B	95A	95B	96A	96B	97A
T1	Bare fallow	62.476	20.408	46.995	65.001	23.318	1.991
T2	Farmer rotation	0.404	0.295	0.328	0.588	0.000	0.000
T3	Sole cassava	*6.800*[1]	6.867	15.691	0.758	0.175	0.000
T4	Minimum tillage	0.122	0.111	0.151	0.145	0.073	0.000
T5	Bush fallow	0.391	3.367	1.502	0.622	0.187	0.000
T6	Grass barrier	0.221	0.071	0.037	0.276	0.185	0.000
T7	Legume strips	1.937	12.536	2.201	0.616	0.048	0.000
T8	Improved fallow	0.404	0.123	0.701	0.642	0.206	0.000

1 corrected value due to extreme differences in measurements

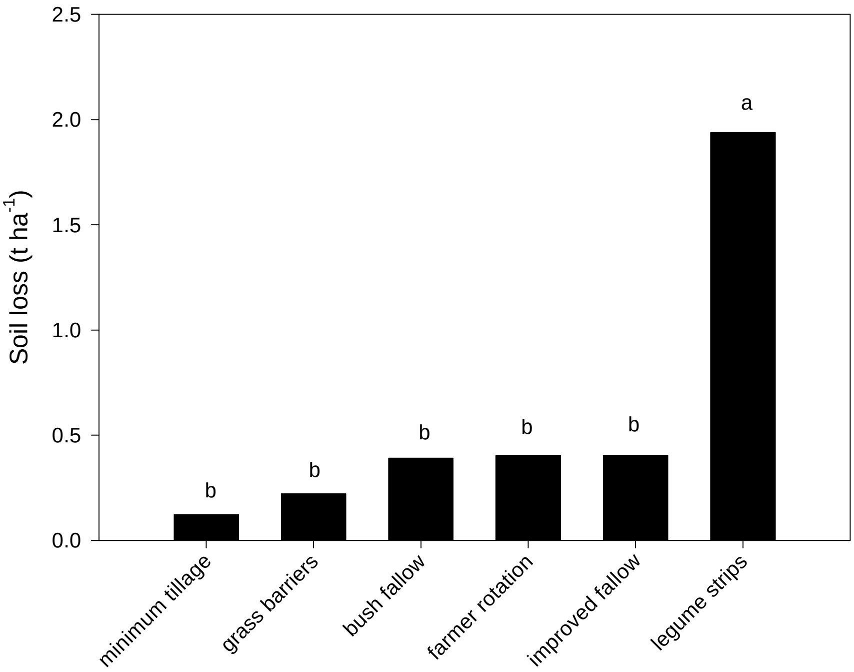
The greatest soil loss during the first maize cropping phase (95A) was measured on the legume strips treatment. It was significantly greater than the soil losses from the farmer rotation, improved fallow, minimum tillage and grass barrier treatments. Although soil loss amounts from the legume strips treatment were four times greater than those from the bush fallow and twice as great as those from the sole cassava treatment, these differences were not significant (Figure 33). The farmer rotation, improved fallow, minimum tillage and grass barrier treatments showed soil loss amounts of below 0.3 t ha^{-1}, but did not differ significantly from the bush fallow (3.4 t ha^{-1}) and sole cassava (6.9 t ha^{-1}) treatments.

Figure 34 shows that during the second maize cropping phase the grass barrier, minimum tillage, farmer rotation and improved fallow treatments produced very low levels of soil erosion (<0.7 t ha^{-1}). However, they were only significantly lower than the sole cassava treatment which showed a high level of soil erosion at 15.7 t ha^{-1}. The bush fallow and legume strips treatments reached slightly higher erosion levels of between 1.5 t ha^{-1} and 2.2 t ha^{-1}, but they did not differ significantly from the other treatments with the exception of sole cassava.

The 96A cassava cropping phase, shown in Figure 35, was characterized by generally very low levels of erosion for all the cropping treatments. Whereas soil loss from the bare fallow treatment for the period was 65 t ha^{-1}, that from all the other treatments was below 0.7 t ha^{-1}. There were no significant differences between the cropping treatments.

Soil losses from the legume strips treatment during the 96B period were greater in relation to most of the other treatments (Figure 36). Whilst a positive effect due to the early soil cover provided by phaseolus beans cannot be excluded, the erosion levels from all the treatments were very low (<0.2 t ha^{-1}) and the differences were not significant.

No measurable soil loss occurred during the last cropping period 97A from April to July 1997 on the cropped treatments (Tables 32 and 33). Even the bare fallow treatment only showed a soil loss amount of 1.9 t ha^{-1}. The climate erosivity during this 90-day phase was very low, with a total R-Factor of 946 MJ ha^{-1} mm h^{-1}, a value often reached by single events in the research region. Only 4.5 mm of rain fell during the last 30 days before harvest.



Note: The sole cassava treatment showed a soil loss of 6.8 t ha^{-1} in repetition one and 37.1 t ha^{-1} in repetition two and had to be discarded for the cropping period. Taking the other years into account, it would probably have been the treatment with the greatest soil losses.

Figure 32. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 94B from June 1994 to April 1995 at Mondomo.

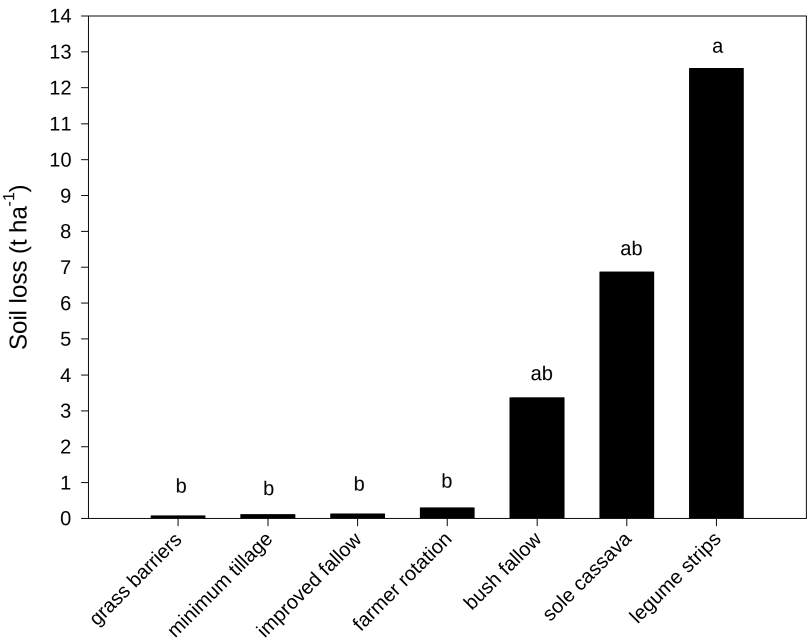


Figure 33. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 95A from June 1995 to September 1995 at Mondomo

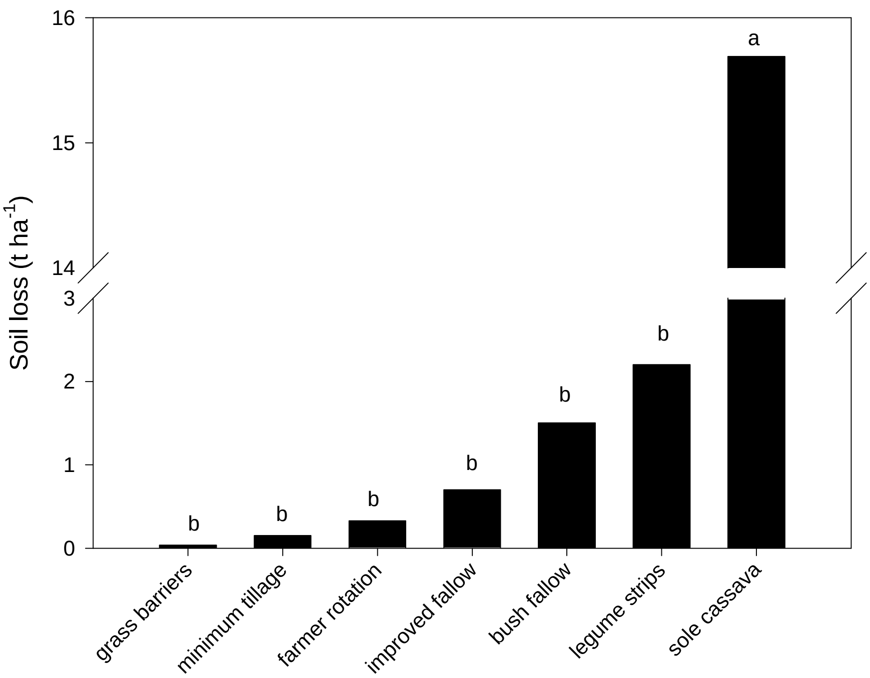


Figure 34. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 95B from November 1995 to March 1996 at Mondomo

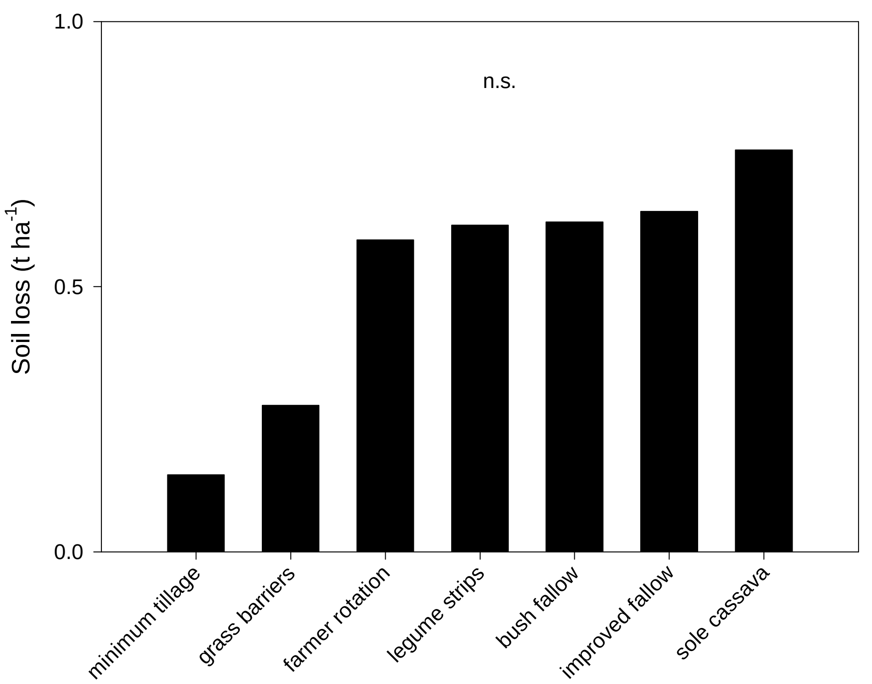


Figure 35. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 96A from April 1996 to March 1997 at Mondomo

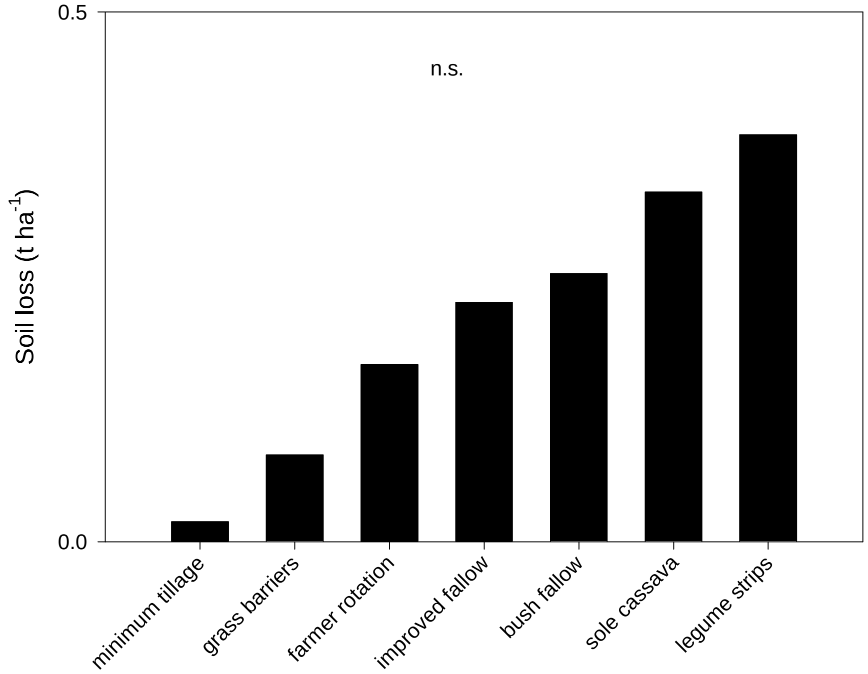
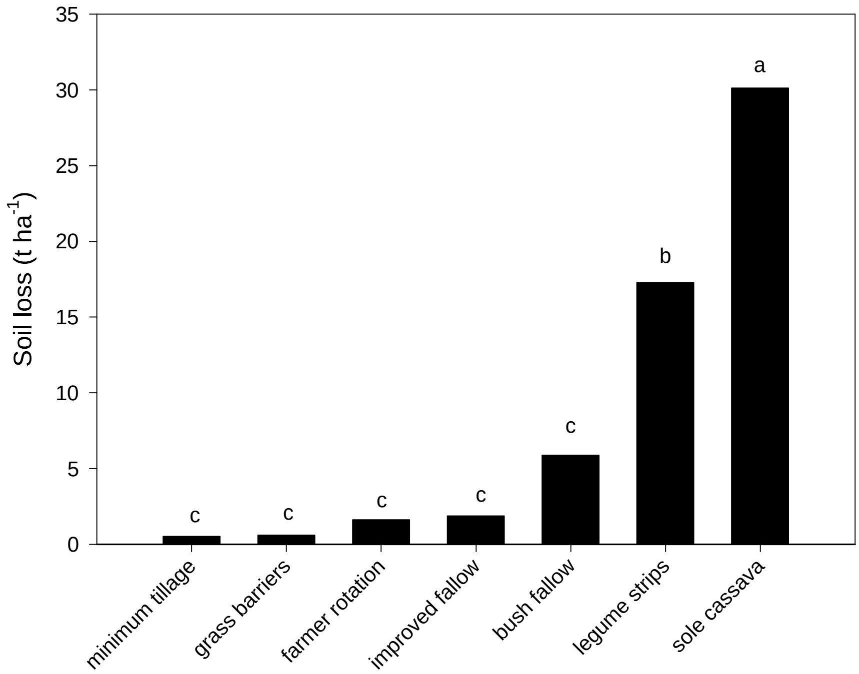


Figure 36. LS-corrected accumulated soil losses from treatments 2-8 for crop phase 96B from October 1996 to January 1997 at Mondomo



Note: Extreme values from the sole cassava treatment during the 94B cropping period were eliminated due to the high differences between repetitions

Figure 37. LS-corrected accumulated soil losses from treatments 2-8 for all crop phases from June 1994 to July 1997 at Mondomo

Taking account of the entire cropping cycle from June 1994 to July 1997, the sole cassava treatment produced the highest soil loss level of 27.8 t ha^{-1} (Figure 37). The soil loss was significantly greater (p>0.05) than with all the other cropping treatments. The second highest soil loss level was found for the legume strips treatment at 17.3 t ha^{-1}, being significantly lower than that of the sole cassava treatment and significantly higher than that of the bush fallow, improved fallow, farmer rotation, grass barrier and minimum tillage treatments. There were no significant differences between these five treatments, although soil losses from the minimum tillage and grass barrier treatments were very small (<0.5 t ha^{-1}) and soil losses from the farmer rotation and improved fallow were more than 3.6 times greater (1.6 t ha^{-1}) in comparison. The soil loss from the bush fallow treatment was even twelve times greater, (5.9 t ha^{-1}) compared to the minimum tillage and grass barrier treatments.

4.4 Effect of establishment of bare fallow conditions in all cropped treatments

The main purpose of the last period of the research project presented here was basically to examine the possible effects of different cassava-based cropping systems upon soil quality parameters, such as the structural stability of the soil, and to identify those parameters that show the highest correlations with the soils' susceptibility to water-induced erosion. To eliminate possible inconsistencies between the plots in relation to crop cover, all the plots were maintained under permanent bare fallow from September 1997 to June 1998. The results concerning the soil quality parameters are not presented in this work.

However, the observation period offered a good opportunity to monitor the positive and negative aftereffects of the different cassava-based cropping systems evaluated and to compare the effectiveness of the erosion control measures under identical conditions for all the treatments. Also, similar conditions to the bare fallow condition can be found for short periods before planting and after harvesting in all treatments when the soil is free of crops, except for the minimum tillage treatment with mulch.

4.4.1 Quilichao

Figure 38 shows that the levels of soil erosion measured during the observation period were very high for all the treatments, except the cassava-based rotation with improved fallow elements and the cassava-based rotation with vetiver grass barriers. The largest soil loss amounts were measured for the sole cassava and the bush fallow treatments and these were significantly greater ($p<0.05$) than in the other previously cropped treatments. The bare fallow treatment showed even slightly smaller soil losses than the sole cassava and bush fallow treatments, but the differences were not significant. The LS-corrected soil loss values for both trial sites after the establishment of bare fallow conditions in all treatments are presented in Table 34.

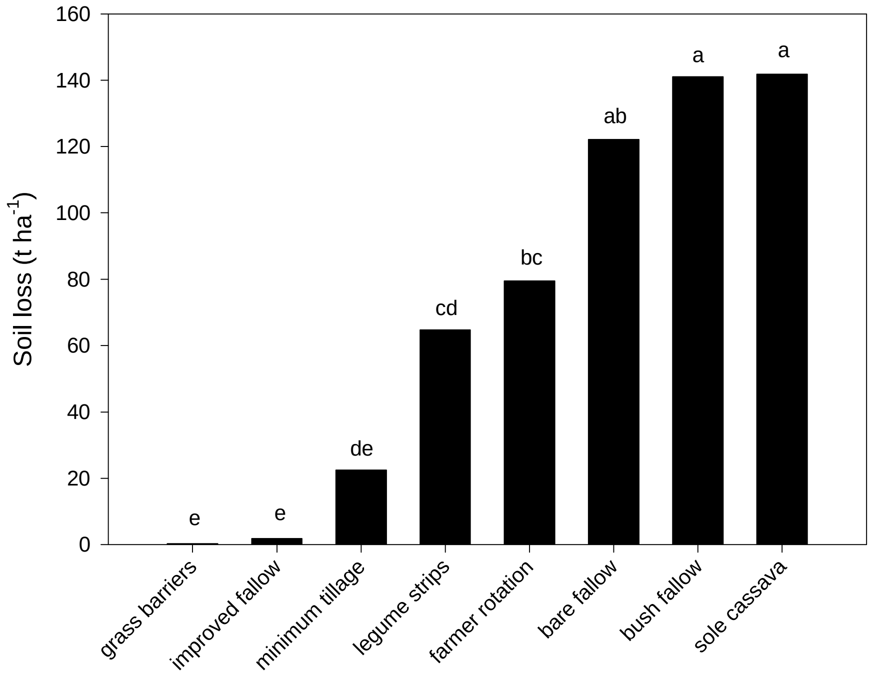


Figure 38. LS-corrected accumulated soil losses from all treatments for the observation period from September 1997 to June 1998 when all treatments were kept under permanent bare fallow conditions at Quilichao

Soil losses from the bare fallow plots were 42.6 t ha^{-1} greater than those from the farmer rotation treatment but the difference was not significant. The bare fallow treatment showed significantly greater soil losses than the legume strips, minimum tillage, improved fallow and grass barrier treatments. The difference in the soil losses between the farmer rotation and the legume strips treatment amounted to 14.8 t ha^{-1} without being significant. Soil losses measured for the minimum tillage, improved fallow and grass barrier treatments were significantly lower than from the farmer rotation treatment. The soil loss amounts from the legume strips treatment were not significantly larger than from the minimum tillage treatment, although the difference amounted to 42.3 t ha^{-1} (Table 34). The minimum tillage plots produced a more than 20 t ha^{-1} greater soil loss than the improved fallow and grass barrier treatments, but the differences were not significant. Both the improved fallow and grass barrier treatments showed very low levels of soil erosion for the whole period. Soil loss amounts from the improved fallow were 5.5 times greater than from the grass barrier treatment however the differences were not significant. During all the other research periods the soil losses from the bare fallow plots were far higher than those from the cropped treatments. The reason for the greater soil losses in the sole cassava and bush fallow treatments compared to bare fallow is probably the high level of soil losses from the bare fallow plots during previous years which might have led to a more stable soil condition with lower erodibility. In contrast the previously cropped treatments still possessed a topsoil with a higher erodibility being exposed for the first time to continuous bare fallow conditions.

Table 34. LS-corrected cumulative soil losses from all treatments for the observation period from September 1997 to June 1998 when all treatments were kept under permanent bare fallow conditions at Quilichao and Mondomo

	Previous treatment	Quilichao	Mondomo
		Soil loss (t ha^{-1})	
T1	Bare fallow	122.134	12.460
T2	Farmer rotation	79.524	4.075
T3	Sole cassava	141.798	20.679
T4	Minimum tillage	22.493	2.013
T5	Bush fallow	141.052	17.733
T6	Grass barriers	0.332	0.000
T7	Legume strips	64.760	10.760
T8	Improved fallow	1.837	0.129

4.4.2 Mondomo

At Mondomo the LS-corrected soil losses, after establishing bare fallow conditions for most treatments at Mondomo, were much smaller compared to those from Quilichao, as shown in Table 34. This was probably caused by the lower climate erosivity. The greatest soil losses were observed in the sole cassava treatment; the amount of 20.7 t ha^{-1} was significantly larger than the amounts of eroded soil from the other treatments except the bush fallow treatment (17.7 t ha^{-1}) (Figure 39).

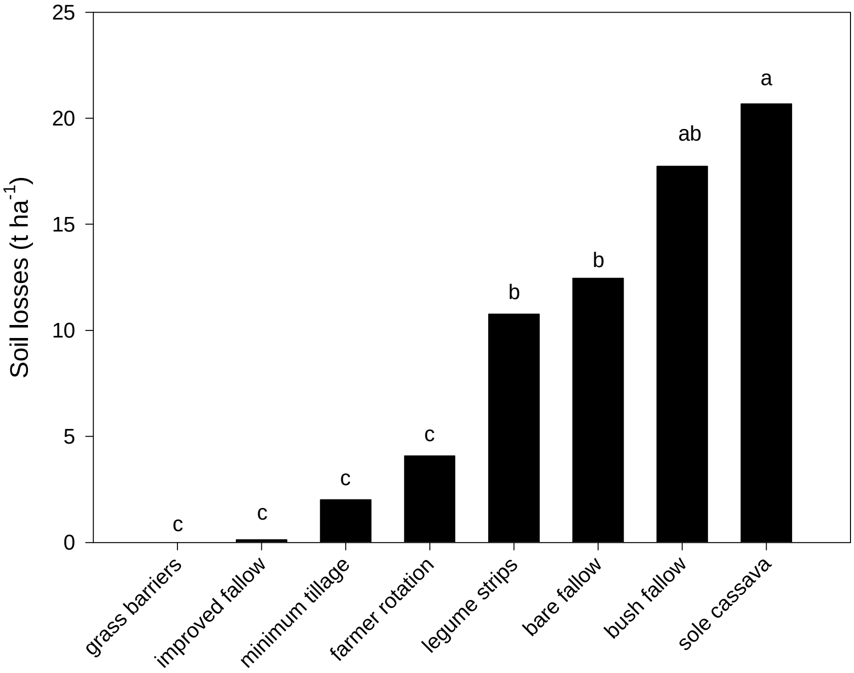


Figure 39. LS-corrected accumulated soil losses from all treatments for the observation period from September 1997 to June 1998 when all treatments were kept under permanent bare fallow conditions at Mondomo

The soil loss from this treatment was not significantly greater compared to the bare fallow and legume strips treatments but significantly greater than the farmer rotation, minimum tillage, improved fallow and grass barrier treatments. Soil losses from the bare fallow and legume strips treatments were significantly greater than those from the farmer rotation, minimum tillage, improved fallow and grass barrier treatments. The last four showed no significant differences amongst each other although no soil loss at all was registered from the grass barrier treatment and soil loss from the improved fallow plots was nine times lower than from the minimum tillage and eighteen times lower than that from the farmer rotation treatment.

4.5 Soil loss tolerance levels and sustainability of the cropping systems evaluated

The annual soil loss tolerance gives the amount of soil that can be lost indefinitely without reducing the productivity of a given soil to a level where crop production is no longer economically interesting (Bergsma, 1996). The soil loss tolerance varies greatly depending on soil type and factors, such as depths of top- and subsoil and parent material. The maximum tolerable soil loss rate for the USA is held to be about 12.5 t ha^{-1} a^{-1} and for shallow tropical soils with low fertility the tolerance levels may be even lower than 1 t ha^{-1} a^{-1} (Lal, 1985; Stocking and Peake, 1986). Hamel (1986) reports soil loss tolerances for ferrallitic soils in West Africa of between 3 and 6 t ha^{-1} a^{-1}. The tolerance threshold depends basically on the formation rate and depth of the soil. Amezquita (2001; pers. comm. Soil Physics Unit, CIAT) estimates soil formation rates for Quilichao and Mondomo at 4 and 2 t ha^{-1} a^{-1} respectively. Reining (1992) and Ruppenthal (1995) estimated even lower soil loss tolerance values of between 1 and 2 t ha^{-1} per year for the degraded hillsides of the Cauca department.

To apply the LS-corrected results to the different soil conditions of Quilichao and Mondomo to wider areas, an average field - representative of the situation in the Cauca department - with a 25% gradient and a slope length of 50 m was assumed. Standardized values are multiplied by 7.55 in accordance with the USLE LS-Factor methodology. The dimensions were taken from Flörchinger (1999), who used data from previous project phases to estimate the effects of several cassava-based cropping systems. However, the field conditions under which most farmers work in the Cauca can be considered as more extreme (FIDAR, 1999). When applying the Quilichao soil conditions and assumed formation rate to the assumed average field, all the treatments, except the grass barrier and minimum tillage treatments, exceeded the soil tolerance level of 4 t ha^{-1} (Table 35).

Table 35. Average annual soil loss amounts for the Quilichao and Mondomo conditions for USLE standard plot dimensions (9% gradient and 22.1 m slope length) and an average field in the Cauca department (25% gradient and 50 m slope length).

Treatment	Quilichao		Mondomo	
	USLE standard	Average field	USLE standard	Average field
	Annual soil loss (t ha^{-1})			
Rotation with vetiver grass barriers	0.291	2.2	0.202	1.5
Minimum tillage	0.363	2.7	0.176	1.3
Rotation with improved fallow element	0.874	6.6	0.623	4.7
Rotation with legume strips	1.547	11.7	5.763	43.5
Farmer rotation	1.922	14.5	0.538	4.1
Rotation with bush fallow element	5.187	39.2	1.961	14.8
Sole cassava	5.345	40.4	10.039	75.8

The sole cropped cassava and bush fallow treatments would reach soil loss amounts of up to ten times above the tolerance level, whereas the farmer rotation and the legume strips treatments would exceed tolerance limits by a factor of 3.6 and 2.9 respectively. The improved fallow treatment was close to the tolerance limit of 4 t ha^{-1} a^{-1}, but still exceeded it by a factor of over 1.6.

The average field under Mondomo soil and climatic conditions showed that, as in Quilichao, only the grass barrier and minimum tillage treatment could be considered as sustainable. All the other treatments would exceed the soil tolerance threshold of 2 t ha^{-1} a^{-1}. Both the improved fallow and farmer rotation treatments would surpass the tolerance level by factors of 2.4 and 2.1 respectively. Both the legume strip and sole cassava treatments can be considered as extremely erosive and degrading to the soil even in the short term as the soil losses would exceed the tolerance level by factors of 21.8 and 37.9 respectively.

4.6 K-Factor

4.6.1 Single events

K values for single events measured at Quilichao ranged from 0.0005 to 0.094 t h MJ^{-1} mm^{-1} (Table 34). Erosive events from the two rainy seasons showed a wider range compared to the dry season and this was probably influenced by the far larger number of erosive events during the rainy seasons. At both trial sites, the smallest K values from the rainy seasons were about 50% lower than those from the dry seasons.

Table 34. Minimum, maximum and average K-Factors from single rainfall events for the period from June 1994 to June 1998

	Quilichao			Mondomo		
	K min	K max	mean	K min	K max	Mean
	t h MJ^{-1} mm^{-1}					
1st rainy season	0.0005	0.088	0.026	0.0003	0.061	0.010
2nd rainy season	0.0007	0.094	0.021	0.0003	0.075	0.015
1st dry season	0.0009	0.059	0.018	0.0006	0.092	0.014
2nd dry season	0.0017	0.090	0.013	0.0006	0.048	0.012

K values for single events monitored at Mondomo were between 0.0003 and 0.092 t h MJ^{-1} mm^{-1}. As in Quilichao, the minimum K values established during the rainy seasons were only about 50% of those in the dry seasons. With the exception of the first dry season, the maximum K values were lower in comparison to Quilichao.

4.6.2 Annual K-Factor

The annual K values, as shown in Table 37, oscillated considerably between the years in accordance with the differences between the erosivity and distribution of rainfall in those years. The values were in the range reported for inceptisols in literature (Bergsma, 1996) and are deemed to be between moderate and low according to Foster (1981).

Table 37. K-Factor values established on the bare fallow plots in Quilichao and Mondomo for the entire project period from April 1987 to June 1998. Values before May 1994 are not expressed as complete years but on a cropping season basis, which were between 20 days longer or shorter than a 365 day year.

Cropping season/year	K-Factor Quilichao (t h MJ^{-1} mm^{-1})	K-Factor Mondomo (t h MJ^{-1} mm^{-1})
1987-88	0.004	0.003
1988-89	0.013	0.010
1990-91	0.015	0.012
1991-92	0.018	0.012
1992-93	0.007	0.011
1993-94	0.026	0.018
1995	0.022	0.009
1996	0.019	0.009
1997	0.013	0.003
1998[1]	0.015	0.004

1 1998 only includes data from January to June. Data from research period 87-89 from Reining (1992), 90-92 from Ruppenthal (1995) and Castillo (1992), 92-94 from Felske (2000)

The annual K values for Mondomo also oscillated considerably between the years, being especially low in 1997. This year was probably affected by low erosivity and the long dry spell between the rainy seasons.

4.7 Relationship between Erosivity indices and soil loss

Wischmeier and Smith (1958) found a highly significant (r^2=0.92) linear relationship between the R-Factor and soil loss data representing 10 years. Other scientists such as Hudson (1995) and Lal (1977A) found that the erosivity indices KE>25 and AI_{max} were more suitable for explaining the relationship between rainfall erosivity and soil loss for tropical areas. Reining (1992), Ruppenthal (1995) and Felske (2000) found relatively high correlations between soil loss and some of the erosivity indices tested, particularly EI_{30}, EIA and AI_{max}, but results varied considerably between the years. These former researchers working at Quilichao and Mondomo tested a wide variety of erosivity indices and reported very contrasting results. Castillo (1992) reported very low correlations between soil loss and the EI_5, EI_{10}, EI_{15} indices, EI_{20} and EI_{30}, being lower at Mondomo than at Quilichao. As erosivity may vary considerably between individual years, Hudson (1995) reported differences between annual EI_{30} values and the long-term average of 50% to 200%, indicating that contradictory results representing the range can be expected. A similar variability was found for the wider research area described in this study (see chapter 3.4.8), where the differences between long-term average and single annual values for the El Tambo station in the Cauca department were between 43 and 192% within 42 years. Testing several erosivity indices against soil loss values of single rainfall events brought results which were similar to the previous project phases. Correlations for some years were high, whereas other years showed only low correlation coefficients between any of the erosivity indices tested and soil loss amounts of single rainfall events.

4.7.1 EI_{30}

According to the USLE methodology, the USLE plots have to be maintained in continuous bare fallow for two years before reliable data can be measured (Wischmeier and Smith, 1978). Therefore, the first two years of soil loss data from 1987 to 1989 were not considered in the K-Factor calculations and the application of the USLE. The necessity of this measure was evident when contemplating the relationship between soil loss and erosivity during these first two years, where soil loss amounts were low especially during the first year in Quilichao, whilst corresponding erosivity was above average. The soils presented in this study seem to gain a certain structural stability when under bush fallow or pasture and this enhanced stability protects them against erosion for some time. This became evident when, in 1996, new bare fallow plots were installed for the purpose of analyzing aggregate stability, which did not produce any soil losses for about one and a half years.

A highly significant linear relationship was found between the R-Factor and annual soil loss amount for the period from 1990 to 1998 at both trial sites as shown in Table 38. The correlation coefficient of the relationship for Quilichao was higher than that at Mondomo. However, when the outlier year 1997 was eliminated from the Mondomo data, which showed an extremely small annual soil loss in relation to the R-Factor value, the correlation coefficient was improved considerably (Figure 40).

Table 38. Equation parameters for linear regressions between soil loss and the R-Factor for the period from 1990 to 1998 at Quilichao and Mondomo

Site and duration	Intercept	Slope	r^2
Quilichao 90-98	-84.65	0.0281	0.85
Mondomo 90-98	-21.85	0.0127	0.76
Mondomo 90-98 excl. 97	-11.56	0.0123	0.89

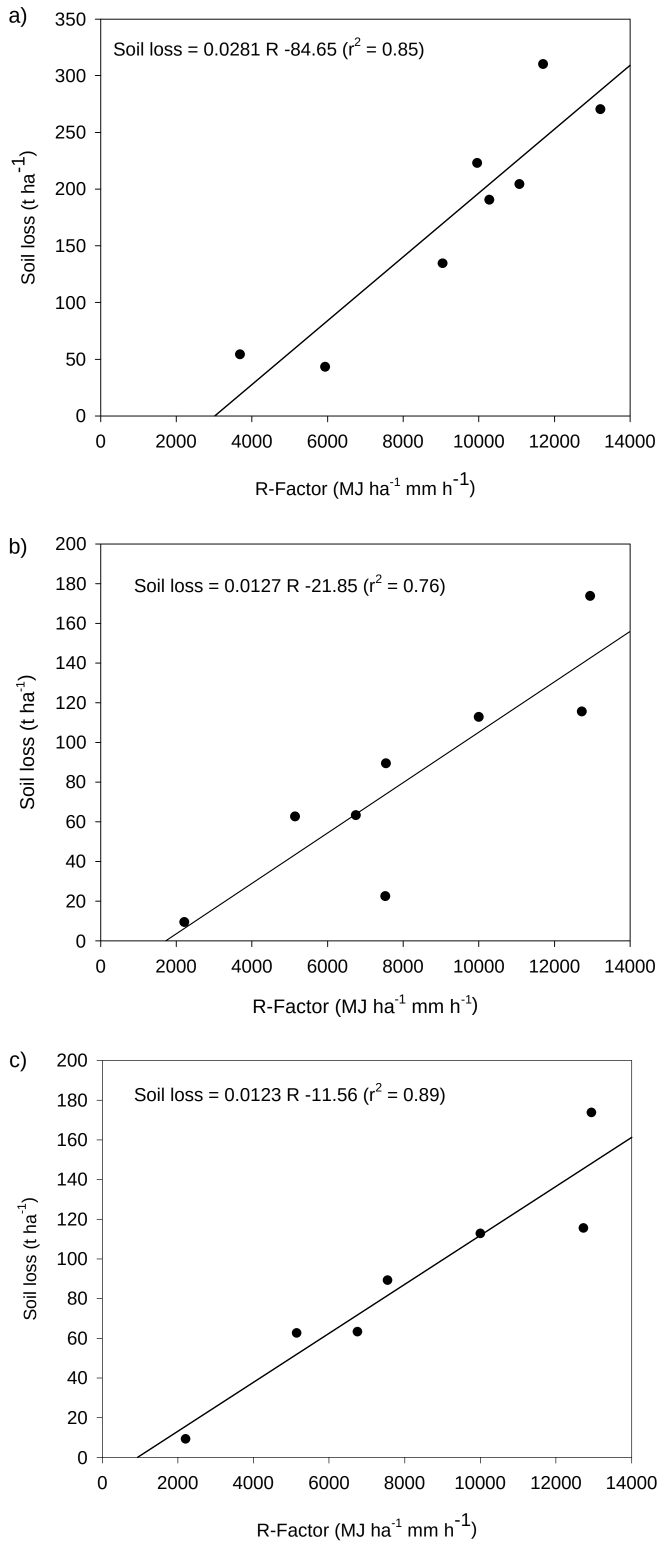


Figure 40. Linear regressions for the relationship between annual erosivity (R-Factor) and soil loss amount for the USLE plots in the period from 1990 to 1998: a) Quilichao field station, b) Mondomo c) Mondomo excluding the outlier year 1997.

4.8 Influences of erosion upon organic matter and nutrient contents

The organic matter content in the original USLE plots in Quilichao fell by one-third during the first three years, namely from 8.4%, this value representing the soil before installation of the bare fallow plots, to 5.6% in 1989 (Figure 41). After this strong initial decrease the organic matter oscillated around a value of about 6% and fell to 5% in 1995, the last year before these plots were abandoned. The loss for the whole period was 40.5%. Due to the complete loss of the topsoil the plots had to be abandoned and were replaced by new bare fallow plots established in 1993. These new plots also showed a strong decline of organic matter content during the first four years, falling from 7.6% in 1993 to 5.7% in 1997, a reduction of 26%. This was followed by a slight rise to 6.2% in the final year of 1998. Thierfelder (2001; Pers. comm. Soil physics unit, CIAT) reported a further slight decrease to 5.5% on the same plots for the period 2000 to 2001, which would imply a loss of 27.6% of organic matter within eight years.

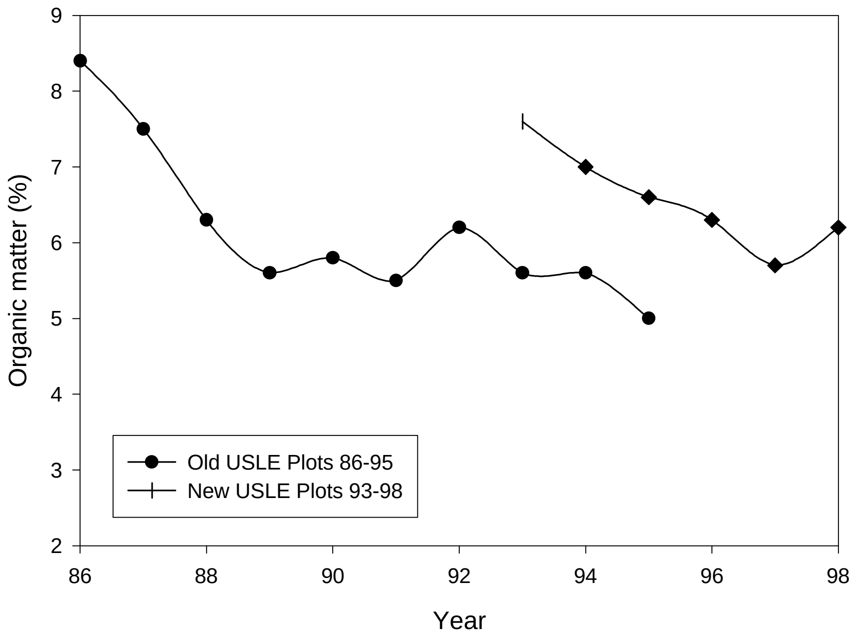


Figure 41. Development of organic matter in bare fallow plots for the period from 1987 to 1998 at Quilichao.

Compared to Quilichao, the organic matter content in Mondomo decreased slowly but almost continuously from 6.5% in 1986 to 2.7% in 1998 as shown in Figure 42. This implies that almost 52% of the organic matter content in the topsoil was lost within 12 years.

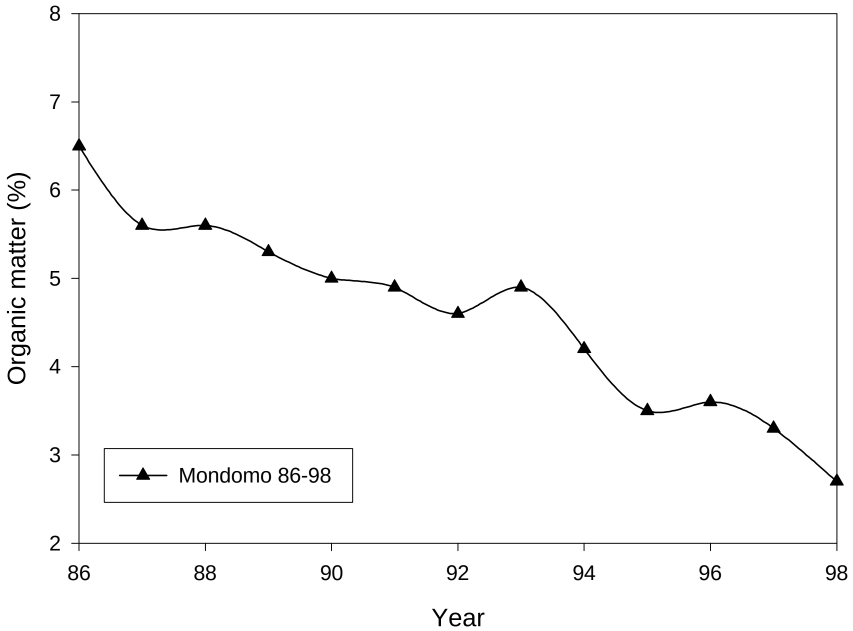


Figure 42. Development of organic matter in bare fallow plots for the period from 1987 to 1998 at Mondomo.

Most of the cropped treatments showed no clear tendencies with regard to the increase or decrease of organic matter (corresponding data are presented in the appendix). Values at both trial locations oscillated from year to year and these oscillations were probably caused by the incorporation of chicken manure, harvest residues and the *Brachiaria* mulch on the minimum tillage treatment. The organic matter content was slightly lower in Mondomo than in Quilichao in all treatments, except the rotation with vetiver barriers, and this difference was probably caused by the lower initial organic matter levels in Mondomo as reported by Reining (1992).

The organic matter content in the sole cassava treatment decreased considerably at both locations, falling from 6.7% to 5.2% in Quilichao and from 7% to 5.2% in Mondomo. This signifies a total reduction of the organic matter content of 22.4% in Quilichao and of 25.7% in Mondomo within eight years. In Quilichao the value oscillated at around 7% and then decreased during the last two years. In Mondomo the first notable decrease took place during the first two years, subsequently remaining stable for four years and decreasing again during the last two years. The cassava-based rotation with legume strips showed a slight declining tendency over the period 1990 to 1998 in Mondomo, falling to 5.4% at the end of the period, equivalent to a 19.4% reduction of organic matter content.

Table 39. Contents of organic matter and selected nutrients of the USLE plots for Quilichao and Mondomo at the end of the research period. As the USLE plots had to be re-established in 1993 due to the almost complete topsoil loss in Quilichao, both sets are presented. The old plot values are from the last used year of 1993 and the new plot values from the end of the research period in 1998.

	O.M.	P Bray II	Total P	Total N	Exchangeable K
	%		mg kg^{-1}		cmol$^{[+]}$ kg^{-1}
Quilichao old plots	5.0	4.7	261	1,711	0.09
Quilichao new plots	6.2	3.5	302	2,000	0.06
Mondomo	2.7	1.4	363	1,463	0.04

A comparison of organic matter and selected nutrient contents between bare fallow plots after several years of exposure to a highly erosive climate (Table 39) to newly-established bare fallow plots (Table 40) showed that organic matter as well as total N and K contents decreased strongly, whereas total and plant available phosphorus remained in the same range. Low phosphorous contents under long-term pasture had already been reported for the research site by Ruppenthal (1995).

Table 40. Contents of organic matter and soil nutrients from new bare fallow plots established in 1996 in Quilichao and Mondomo

Site	O.M.	P Bray II	Total P	Total N	$K_{exch.}$
	%		mg kg^{-1}		cmol$^{[+]}$ kg^{-1}
Quilichao	9.4	3.1	362	3,146	0.38
Mondomo	8.9	2.2	434	2,937	0.43

Over the whole three-year cropping period from June 1994 to July 1997 at Quilichao the average annual losses from the bare fallow plots amounted to 7.2 t ha^{-1} of organic matter (Table 41). The average annual nitrogen loss was 233 kg ha^{-1}. Plant available P was lost at an average rate of 0.66 kg ha^{-1} per year, whereas the total P loss was 35.5 kg ha^{-1}. The average exchangeable K losses were 5.38 kg ha^{-1} per year. These findings coincided well with earlier research by Ruppenthal (1995). Due to the large differences in the total soil loss between the bare fallow and cropped treatments, organic matter and nutrient losses from the cropped treatments were much smaller. The sole cassava and the bush fallow treatments recorded the largest amounts of nutrient losses for the cropped treatments due to the considerably greater total soil losses. In the case of organic matter, the cropped treatments only reached between 0.4% and 5.0% of the amount lost from the bare fallow plots.

Table 41. Average annual organic matter and nutrient amounts lost with LS-corrected sediments at Quilichao for the period June 1994 to July 1997

Treatment	O.M.	P Bray II	Total P	Total N	$K_{exch.}$
	t ha^{-1} a^{-1}	kg ha^{-1} a^{-1}			
Bare fallow	7.18	0.66	35.5	233.0	5.38
Farmer rotation	0.13	0.06	1.0	4.8	0.25
Sole cassava	0.34	0.13	2.3	12.8	0.54
Minimum tillage	0.03	0.02	0.2	1.0	0.04
Rotation with bush fallow element	0.36	0.15	2.4	13.3	0.51
Rotation with vetiver barriers	0.02	0.00	0.1	0.8	0.04
Rotation with legume strips	0.11	0.03	0.7	4.1	0.14
Rotation with improved fallow element	0.06	0.03	0.5	2.4	0.08

Total P, total N and exchangeable K amounts showed very similar relationships compared to the bare fallow plots. Only in the case of plant available P, both the sole cassava and bush fallow treatments reached values of up to 22% of the losses from bare fallow treatment due to the considerably higher levels brought about by fertilizer applications.

The values for Mondomo as shown in Table 42 were very similar to those at Quilichao. It has to be considered that real nutrient losses would be higher due to the LS-correction factors, in some treatments between 1.4 and 2.9 times higher than as presented in the Tables 41 and 42.

Additionally, nutrient losses from runoff can be expected to be greater than those from the sediments of the cropped treatments, especially in respect of plant available P and exchangeable K. Former research on the same plots at Quilichao and Mondomo had shown that up to 95% of the K and 74% of the P Bray II lost from a cropped treatment were found in the runoff (Ruppenthal, 1995).

Table 42. Average annual organic matter and nutrient amounts lost with LS-corrected sediments at Mondomo for the period from June 1994 to July 1997

Treatment	O.M.	P Bray II	Total P	Total N	$K_{exch.}$
	t ha^{-1} a^{-1}	kg ha^{-1} a^{-1}			
Bare fallow	5.844	0.380	35.1	244.1	4.44
Farmer rotation	0.125	0.053	0.9	5.1	0.21
Sole cassava	0.331	0.074	2.0	12.9	0.37
Minimum tillage	0.023	0.008	0.1	0.9	0.02
Rotation with bush fallow element	0.342	0.089	2.8	12.3	0.60
Rotation with vetiver barriers	0.022	0.004	0.02	0.9	0.01
Rotation with legume strips	0.094	0.025	0.6	4.1	0.10
Rotation with improved fallow element	0.061	0.018	0.4	2.5	0.06

4.8.1 Selectivity of the erosion process with regard to nutrients and organic matter

In order to analyze the degree of selectivity of the erosive process, calculating the enrichment ratio (ER) can be an useful exercise as it shows the relation between nutrient concentration in the sediments and topsoil. According to Hashim et al. (1998), it can be calculated as shown in the following equation:

$$(19)\quad ER = \frac{\text{nutrient concentration in sediment}}{\text{nutrient concentration in topsoil}}$$

The ER can be used to more accurately predict the nutrient losses induced by water erosion without the need for the continuous analysis of eroded soil material.

The enrichment ratios coincided well with results from former periods of this long-term study (Reining, 1992; Ruppenthal, 1995; Felske, 2000) and were generally low. The average values for the organic matter content of sediments from Quilichao and Mondomo were close to one and varied little between the treatments (Tables 43 and 44).

Table 43. Average enrichment ratios of organic matter and selected nutrients for all treatments from Quilichao. Data for the bare fallow treatment include the full research period from 1987 to 1998. All the other treatments are based on the final phase from 1994 to 1998.

Treatments	O.M.	P Bray II	Total P	Total N	$K_{exch.}$
Bare fallow	1.0	1.3	1.1	1.3	1.1
Farmer rotation	0.9	1.2	1.0	1.2	1.0
Sole cassava	1.0	1.1	1.2	1.1	1.0
Minimum tillage	1.0	1.2	1.3	1.1	1.1
Rotation with bush fallow element	1.0	1.1	1.2	1.2	1.1
Rotation with vetiver barriers	1.2	0.9	1.6[1]	1.3	1.1
Rotation with legume strips	1.0	0.8	1.1	1.0	1.0
Rotation with improved fallow element	1.0	1.2	1.1	1.2	1.0

1 Values above one indicate selective nutrient losses by erosion

Table 44. Average enrichment ratios of organic matter and selected nutrients for all treatments from Mondomo. Data for the bare fallow include the full research period from 1987 to 1998. All the other treatments are based on the final phase from 1994 to 1998.

Treatment	O.M.	P Bray II	Total P	Total N	$K_{exch.}$
Bare fallow	1.0	1.1	1.3	1.1	1.1
Farmer rotation	1.0	1.4[1]	1.0	1.3	1.1
Sole cassava	1.0	1.2	0.9	1.2	1.1
Minimum tillage	1.0	1.5	1.3	1.2	1.1
Rotation with bush fallow element	1.1	1.3	1.2	1.2	0.9
Rotation with vetiver barriers	0.9	0.8	0.5	0.7	0.9
Rotation with legume strips	1.0	1.3	1.1	1.1	1.1
Rotation with improved fallow element	1.0	1.1	1.3	1.3	1.1

1 Values above one indicate selective nutrient losses by erosion

Organic matter and nutrient status of all treatments in comparison to long-term grass fallow

In 1996, the organic matter and nutrient content of all the treatments were compared with each other as well as with the newly established bare fallow plots that had previously been under long term *Brachiaria* pasture. The aim was to determine any changes in the nutrient and organic matter status after several years under the cropping evaluated and to compare this status with the contents usually encountered after long-term fallow.

Quilichao

With regard to the organic matter status at Quilichao, the highest content was measured in the improved fallow treatment, although it was only significantly higher than the bare fallow treatment. This high level of organic matter content showed the positive aftereffects of the improved fallow, considering that the last fallow period had been in 1993 and the content previous to this period had been at a lower level.

The lowest content for the cropped treatments was found in the continuously sole cropped cassava treatment, confirming the decay of organic matter content as evidenced by the development from 1990 to 1998. A comparison of all the treatments with the soil after long-term fallow showed that all the treatments had reached significantly lower organic matter levels, varying from 75% of the long-term fallow in the case of improved fallow to 61% in the bare fallow treatment (Table 45).

Plant available P contents were much higher in the cropped treatments compared to the bare fallow treatment, although only the minimum tillage and improved fallow treatments were significantly higher. All the cropped treatments showed significantly higher available P concentrations when compared to soil under long-term *Brachiaria* fallow. This low status of P Bray II and total phosphorus for the Quilichao and Mondomo soils under grass fallow had already been observed by Reining (1992) and Ruppenthal (1995).

As to total P contents, the highest levels were found in the minimum tillage treatment and these were significantly higher compared to all other treatments except improved fallow. All the other treatments showed between 40 and 84% higher total P contents than the bare fallow treatment, with significantly higher levels in the farmer rotation, bush fallow, legume strips and improved fallow treatments.

Table 45. Comparison of the nutrient status of topsoil in all the treatments at Quilichao from 1996.

Treatments	O.M.		P Bray II		Total P		Total N		$K_{exch.}$	
	%		mg kg^{-1}						$cmol^{[+]}$ kg^{-1}	
Bare fallow	5.7	b	4.2	c	358	c	1,960	C	0.01	c
Farmer rotation	6.3	ab	26.0	bc	577	b	2,408	abc	0.29	ab
Sole cassava	5.9	ab	18.7	c	513	bc	2,214	bc	0.19	abc
Minimum tillage	6.8	ab	49.9	a	814	a	2,652	ab	0.32	a
Rotation with bush fallow element	5.9	ab	24.9	bc	568	b	2,240	abc	0.24	ab
Rotation with vetiver barriers	6.0	ab	17.0	c	524	bc	2,283	abc	0.24	ab
Rotation with legume strips	6.3	ab	23.9	bc	589	b	2,549	ab	0.21	abc
Rotation with improved fallow element	7.0	a	37.2	ab	667	ab	2,788	A	0.16	bc
Long-term *Brachiaria* fallow	9.4		3.1		362		3,146		0.38	

Figures with different captions differ significantly (p=0.05)

All the cropped treatments except the vetiver barrier and the sole continuously cropped cassava had significantly higher total P contents than the soil under long-term *Brachiaria* fallow used as an additional comparison.

The highest total N levels were measured in the improved fallow treatment, being significantly higher than the values of the sole cassava and bare fallow treatments. The next highest were found in the minimum tillage and legume strips treatments, although total N values were only significantly higher than the bare fallow treatment. A comparison of all treatments with the long-term *Brachiaria* fallow soil showed that the total N contents from all treatments except improved fallow, minimum tillage and legume strips were significantly lower, reaching between 77 and 62% of the long-term *Brachiaria* fallow levels.

When considering the general status of organic matter and nutrient contents, the conclusion was that the minimum tillage and improved fallow treatments had the consistently highest concentrations, with the exception of the K content for the improved fallow treatment. In contrast to this observation, the sole continuously cropped cassava treatment showed generally lower nutrient contents although receiving equal or even higher amounts of fertilizers.

Mondomo

At Mondomo, the vetiver grass barrier treatment showed the highest organic matter content, but was only significantly higher than the bare fallow treatment. Also the improved fallow and minimum tillage treatments showed considerably higher organic matter contents in comparison to the bare fallow. There were no significant differences between the cropped treatments. When comparing the eight treatments with the long-term *Brachiaria* fallow, organic matter contents from all eight were between 21% and 67% lower, but only the minimum tillage, bush fallow, farmer rotation, sole cassava, legume strips and bare fallow treatment were significantly lower (Table 46).

The highest plant available phosphorus levels were measured in the minimum tillage treatment, but no significant differences were found among the cropped treatments. As at Quilichao, P Bray II contents were much higher in all fertilized treatments when compared to the long-term grass fallow. All the values were significantly higher and ranged between 670 and 1,220%. Only the bare fallow treatment reached 72% of the long-term fallow and this difference was not significant.

Table 46. Comparison of the nutrient status of topsoil in all treatments at Mondomo from 1996

Treatments	O.M.		P Bray II		Total P		Total N		$K_{exch.}$	
	%		mg kg^{-1}						cmol$^{[+]}$ kg^{-1}	
Bare fallow	3.0	b	1.6	b	397	b	1,513	b	0.05	c
Farmer rotation	5.7	ab	20.8	a	729	a	2,401	ab	0.40	a
Sole cassava	5.4	ab	16.4	a	610	ab	2,246	ab	0.34	ab
Minimum tillage	6.1	a	26.3	a	819	a	2,448	ab	0.41	a
Rotation with bush fallow element	5.7	ab	14.9	a	641	ab	2,456	ab	0.26	ab
Rotation with vetiver barriers	7.1	a	15.7	a	568	ab	2,921	a	0.29	ab
Rotation with legume strips	5.4	ab	14.5	a	636	ab	2,334	ab	0.25	ab
Rotation with improved fallow element	6.3	a	20.3	a	658	a	2,339	ab	0.14	bc
Long-term *Brachiaria* fallow	8.9		2.2		434		2,937		0.43	

Figures with different captions differ significantly (p=0.05)

As to total P contents, minimum tillage, farmer rotation and improved fallow showed the highest levels, but these were only significantly higher than those of the bare fallow treatment. The total P contents from these three treatments exceeded those from long-term grass fallow by 52 to 89% and these were significant differences. The rest of the cropped treatments showed total P contents that were between 48 and 57% greater than the long-term grass fallow treatment but these differences were not significant. The bare fallow treatment had the lowest level of total P and reached only 92% of the long-term *Brachiaria* fallow.

There were no significant differences among the cropped treatments with regard to total N contents and only the content from the vetiver grass barrier treatment was significantly greater compared to the bare fallow treatment. The long-term *Brachiaria* fallow showed only a slightly greater total N content compared to the cropped treatments which reached between 77 and 100% of the total N level. No significant differences were found. As in Quilichao, the minimum tillage treatment showed consistently high N, P and K contents, whereas the sole cassava treatment showed low P and total N levels. It was evident that most cropped treatments had maintained something like the nutrient levels of long-term *Brachiaria* fallow due to the fertilizer input whilst P contents had even shown a considerable increase.

4.9 Productivity of cassava-based cropping systems

When analyzing cropping systems in respect of their susceptibility or resistance to erosion, an important additional aspect is the evaluation of their productivity. The optimal soil conservation system in a farmer's view is not necessarily the one with the highest level of protection against erosion (Kerr, 1998). Also, farmers tend to favor short-term benefits rather than waiting for the long-term benefits derived from conservation measures (Ashby, 1985). Thus, a cropping system with excellent anti-erosion performance may be unacceptable to farmers if the yields are not competitive compared to traditional farming systems. In general, a farmer will only change the cropping system he uses when new technologies offer immediate gains in income and a rapid return of investment (Morgan, 1995).

Hudson (1995) defines the requirements of erosion control measurements as follows. They have to guarantee a high and quick financial return, a reduction in risk, no loss of existing benefits, accessibility to the farmer in terms of extra input of labor and capital, social acceptability, particularly in terms of gender issues, and be an extension or modification of an existing practice rather than something new.

Among the seven cropping systems evaluated, there were only two that were traditionally used in the research region, namely the cassava-based rotation with organic manure (farmer rotation) and the cassava continuous sole cropping. However, due to increasing soil degradation, the number of farmers that only grow cassava has increased in the last fifteen years. The performance of the other five systems was compared in relation to both traditional systems.

4.9.1 Quilichao

The farmer rotation produced the greatest yields of fresh cassava roots during the 1994B cropping period (June 1994 to April 1995) at slightly more than 30 t ha^{-1} (Figure 43). Although the yield in this treatment was only significantly greater than the grass barrier, sole cassava and the legume strips treatments, yields were between 11 and 38% greater compared to the other three treatments (Table 47). In comparison to the sole cassava treatment, all the other treatments, except the legume strips treatment where close to 40% of the plot area was occupied by the legume strips, showed between 10 and 77% greater yields.

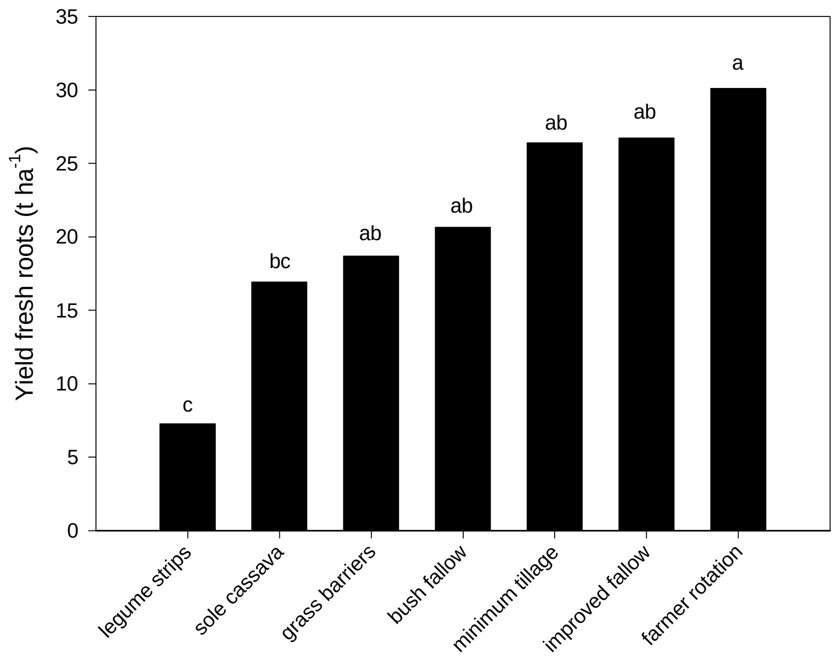


Figure 43. Cassava fresh root yields for the 94B period (June 1994 to April 1995) at Quilichao. The legume strips treatment delivered an additional 6.8 t ha^{-1} of dry matter from the forage legumes *Centrosema macrocarpum* Benth, *Chamaechrista rotundifolia* (Persoon) Greene, and *Galactia striata* (Jacq.) used. The vetiver grass barriers produced 4.98 t ha^{-1} of dry matter.

Although only the traditional rotation produced significantly greater yields, the 10% higher yield level of the vetiver grass barrier treatment as compared to the sole cassava treatment may be regarded as impressive as the vetiver treatment produced this amount from a 12.5% smaller area. The good results from the minimum tillage plots with a 55% greater yield as compared to the sole cassava are also remarkable although the differences were not significant.

Table 47. Cassava fresh root yields expressed in % of the traditional farmer rotation and the sole cassava system for the 94B period (June 1994 to April 1995) at Quilichao.

Treatments		in % of the farmer rotation	in % of sole cassava
T2	Farmer rotation	100.0	177.8
T3	Sole cassava	56.2	100.0
T4	Minimum tillage	87.6	155.9
T5	Bush fallow	68.5	121.9
T6	Grass barriers[1]	62.1	110.4
T7	Legume strips1	24.2	43.0
T8	Improved fallow	88.8	157.9

1 Setting the cassava production area of the other treatments as 100%, T& reached 87.5% and T/ reached 61.5% of that area.

During the first maize cropping period from June 1995 to September 1995 no significant differences were found between the treatments (Figure 44). The greatest grain yield was produced by the farmer rotation treatment at 3.3 t ha^{-1} and the other treatments reached between 61.8 and 90% of the yield level of the farmer rotation. The smallest yield was produced by the vetiver grass barrier treatment at 2.0 t ha^{-1}.

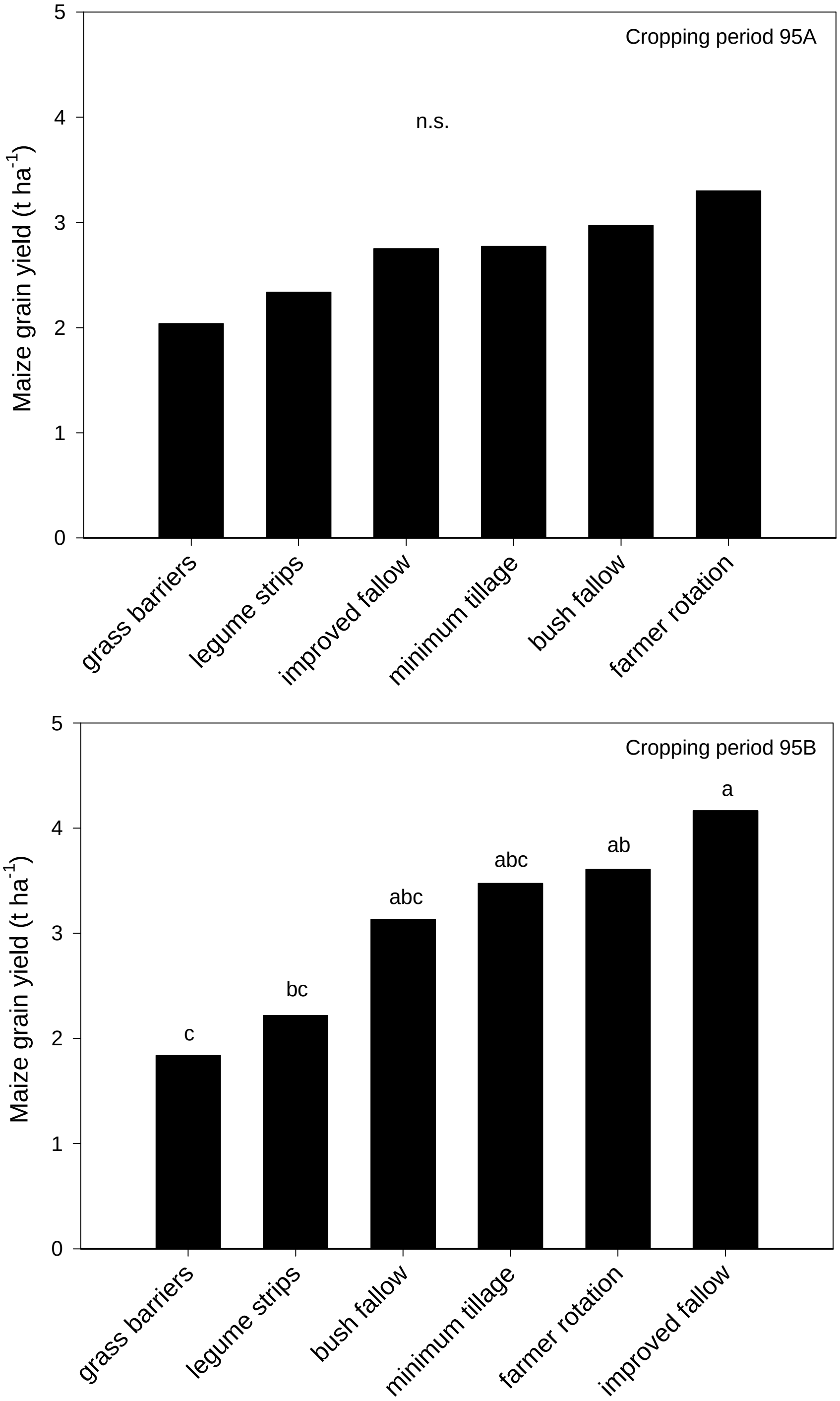


Figure 44. Maize grain yields for the 95A (June 1995 to September 1995, above) and 95B periods (October 1995 to February 1996, below) at Quilichao.

The cassava fresh root yield for the whole period June 1995 to February 1996 of the sole cassava treatment was 22.6 t ha^{-1}. *Chamaechrista rotundifolia* was used as a cover crop in the legume strips treatment but the yield was not recorded.

The maize grain yield in the improved fallow treatment was the greatest for the second maize cropping period from October 1995 to 1996 at 4.2 t ha^{-1}, but only the yields from the legume strips and the grass barrier plots, with the reduced maize production area, were significantly smaller. The yield levels of the improved fallow, farmer rotation, minimum tillage and the bush fallow treatments were very similar.
Considering the farmer rotation as the control showed yield differences ranging from -13% to +15%, however these were not significant except for the grass barrier treatment which reached only 50.9% of the control. The legume strip plots reached yield levels of only 61.5% of the farmer rotation but did not differ significantly (Table 48).

Table 48. Maize grain yield expressed in % of the farmer rotation for the two periods 95A (June 1995 to September 1995) and 95B (October 1995 to February 1996) at Quilichao

Treatment		95A	95B
		in % of the farmer rotation	
T2	Farmer rotation	100.0	100.0
T4	Minimum tillage	84.0	96.3
T5	Bush fallow	90.0	86.9
T6	Grass barriers	61.8	50.9
T7	Legume strips	70.9	61.5
T8	Improved fallow	83.4	115.4

The greatest yield during the 96B cassava cropping period from April 1996 to March 1997 was harvested in the minimum tillage treatment at 27.0 t ha^{-1} of fresh roots (Figure 45). It was significantly greater than in the sole cassava, grass barrier and legume strips treatments. No significant differences were found between the minimum tillage, farmer rotation and bush fallow treatments.

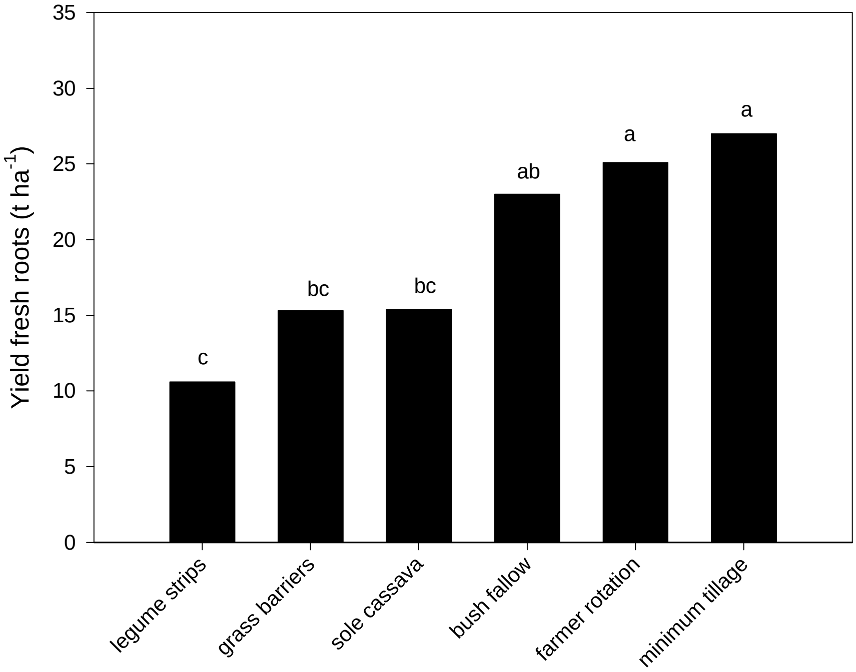


Figure 45. Cassava fresh root yields for the 96A period (April 1996 to March 1997) at Quilichao. The legume strips treatment produced an additional cowpea dry grain yield of 980 kg ha^{-1}. The dry matter production from the improved fallow treatment for 15 months was 29.2 t ha^{-1}.

Comparing the farmer rotation with the other treatments showed yield differences ranging from +7.7 to -37.5% which were significantly higher than those from the sole cassava grass barrier and legume strips treatment (Table 49). The minimum tillage, farmer rotation and bush fallow treatments showed between 50 and 75% higher yield levels compared to cassava sole cropping. Nevertheless, only the yields from the minimum tillage and farmer rotation treatments were significantly greater. The yield from the vetiver grass barrier treatment was nearly identical to that from the sole cassava.

Table 49. Cassava fresh root yields expressed in % of the traditional farmer rotation and the sole cassava system for the 96A period (April 1996 to March 1997) at Quilichao

Treatments		in % of the farmer rotation	in % of sole cassava
T2	Farmer rotation	100.0	162.9
T3	Sole cassava	61.4	100.0
T4	Minimum tillage	107.7	175.5
T5	Bush fallow	91.8	149.5
T6	Grass barriers	61.1	99.5
T7	Legume strips	42.5	69.2

During the last cropping period cowpea was grown on all the treatments at Quilichao, even replacing cassava in the sole cassava treatment, to ensure more homogenous conditions for the final observation period. The yields from all the treatments during this period differed only marginally, ranging from 1.4 t ha^{-1} in the vetiver grass barrier and 2.0 t ha^{-1} in the farmer rotation treatment. Only the farmer rotation and the legume strips treatments produced significantly greater yields than the grass barrier treatment (Figure 46).

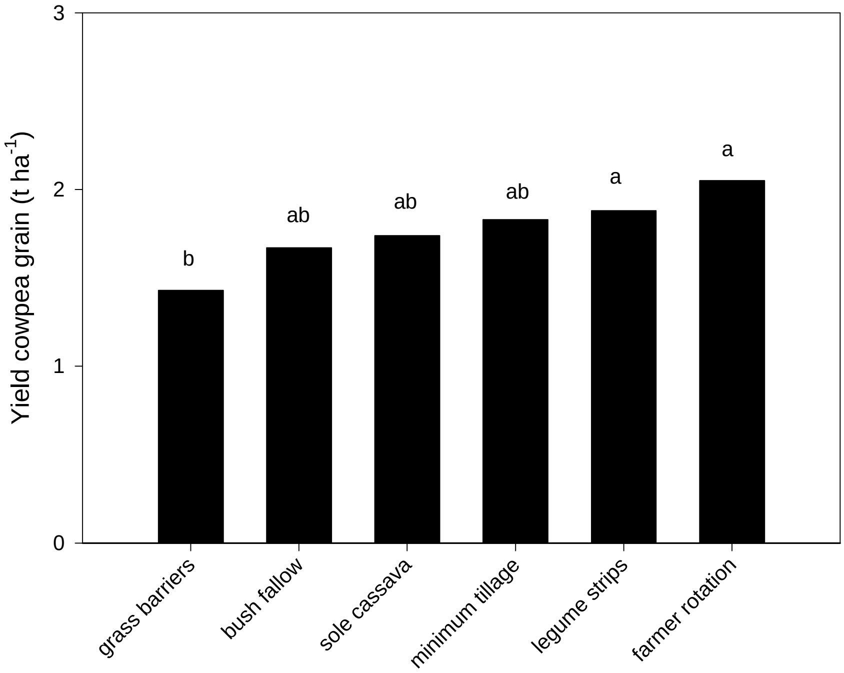


Figure 46. Cowpea grain yields for the 97A period (April 1997 to July 1997) at Quilichao. The improved fallow treatment produced a dry matter yield of *Brachiaria decumbens* Stapf and *Centrosema macrocarpum* Benth of 29.2 t ha^{-1} during 15 months.

No significant differences were found between any of the other treatments. Consequently the differences between the two standard and the other treatments, with exception of the grass barrier treatment, were small as shown in Table 50.

Table 50. Cowpea grain yield expressed in % of the traditional farmer rotation and the sole cassava system for the 97A period (April 1997 to July 1997) at Quilichao

Treatments	in % of the farmer rotation	in % of sole cassava
T2 Farmer rotation	100.0	118.0
T3 Sole cassava	84.7	100.0
T4 Minimum tillage	89.3	105.4
T5 Bush fallow	81.5	96.2
T6 Grass barriers	69.9	82.5
T7 Legume strips	91.5	108.1

4.9.2 Mondomo

Due to a large variation among the repetitions, no significant differences were found between the treatments during the 94B cassava cropping period (June 1994 to April 1995) (Figure 47). The legume strips treatment, however, produced very low yields (2.9 t ha^{-1} of fresh roots) that reached about 22% of both the farmer rotation and the sole cassava treatments (Table 51).

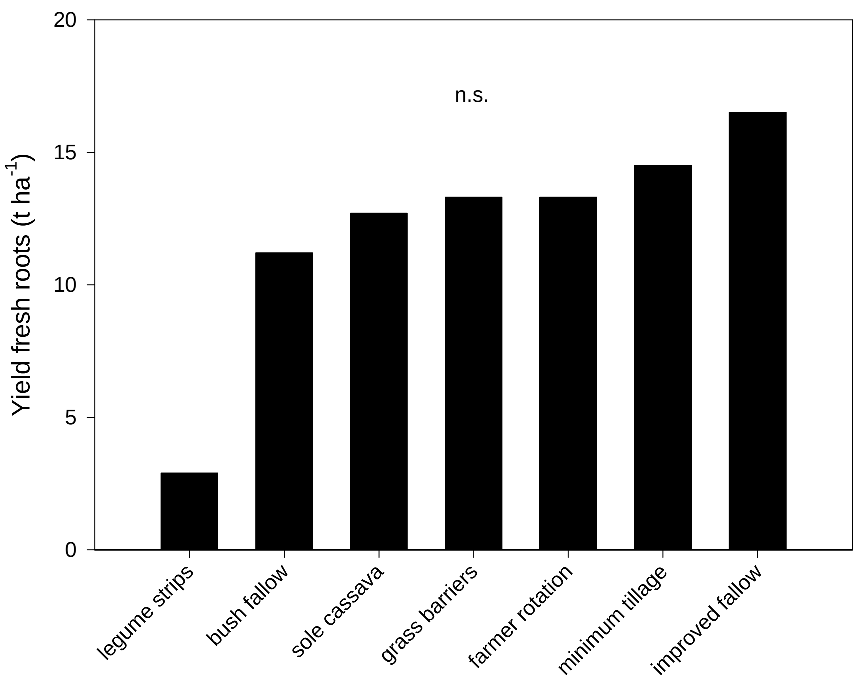


Figure 47. Cassava fresh root yields for the 94B period (June 1994 to April 1995) at Mondomo

Table 51. Cassava fresh root yields expressed in % of the traditional farmer rotation and sole cassava system for the 94B period (June 1994 to April 1995) at Mondomo

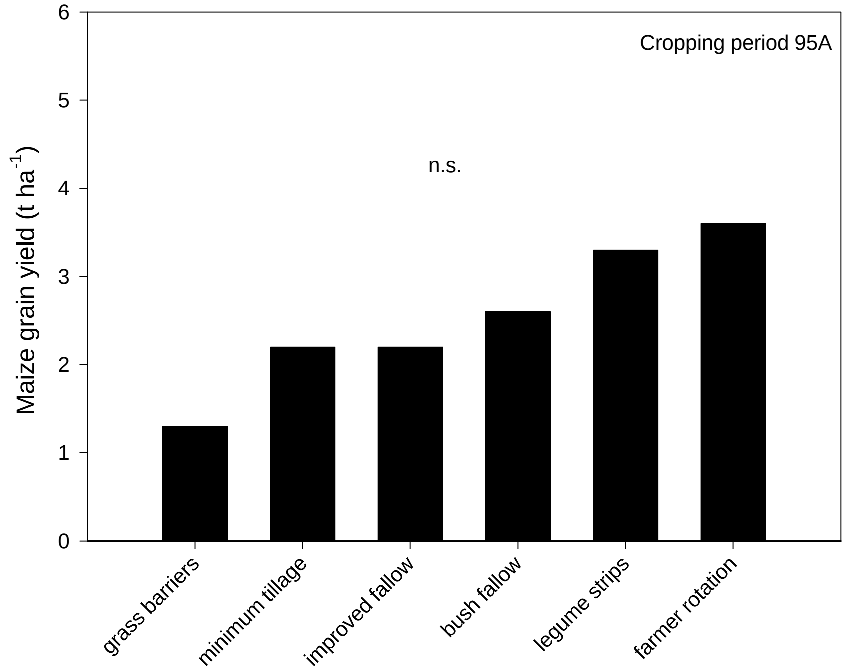
Treatments	in % of the farmer rotation	in % of sole cassava
T2 Farmer rotation	100.0	104.8
T3 Sole cassava	95.4	100.0
T4 Minimum tillage	108.8	114.0
T5 Bush fallow	84.1	88.1
T6 Grass barriers	99.6	104.3
T7 Legume strips	21.7	22.7
T8 Improved fallow	123.5	129.4

The maize grain yields during the 95A cropping period (June 1995 to September 1995) were between 1.3 and 3.6 t ha^{-1}, the greatest yield being produced on the farmer rotation plots (Figure 48). All the other treatments showed between 8.5% and 62.9% smaller yields, but no significant differences were found between any of the treatments (Table 52).

Table 52. Maize grain yield expressed in % of the farmer rotation for the two periods 95A (June 1995 to September 1995) and 95B (October 1995 to February 1996) at Mondomo

Treatments	95A	95B
	in % of the farmer rotation	
T2 Farmer rotation	100.0	100.0
T4 Minimum tillage	60.5	149.8
T5 Bush fallow	71.8	149.4
T6 Grass barriers	37.1	55.2
T7 Legume strips	91.5	81.8
T8 Improved fallow	62.1	122.5

Yield levels during the second maize cycle 95B (October 1995 to February 1996) were generally higher than in the first one and ranged between 1.8 and 4.8 t ha^{-1} (Figure 49). Both the minimum tillage and bush fallow treatments produced the greatest grain yields at 4.8 t ha^{-1} which were only significantly greater than the vetiver grass treatment at 1.8 t ha^{-1}. Comparing the performance of the farmer rotation with all the other treatments showed yield differences of between +49.8% and –44.8%, as shown in table 52, but these differences were not significant. The sole cassava treatment produced a fresh root yield of 25.9 t ha^{-1} for the whole period.



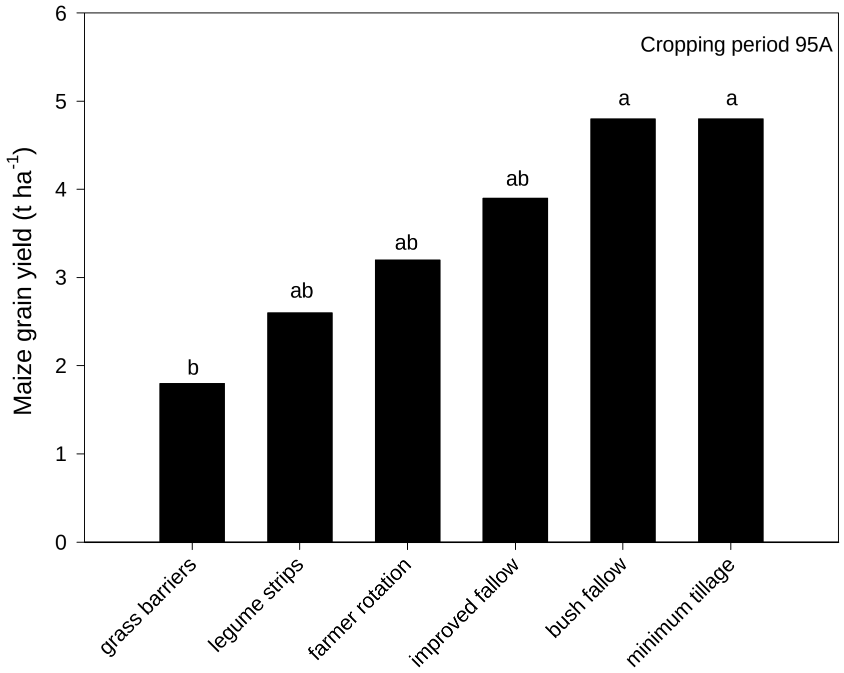


Figure 48. Maize grain yields for the 95A (June 1995 to September 1995; above) and 95B periods (October 1995 to February 1996) at Mondomo. The cassava fresh root yield from the sole cassava treatment for the whole period from June 1995 to February 1996 was 25.9 t ha^{-1}.

No significant differences were found between the cassava fresh root yields of any treatment during the 96A cropping period (April 1996 to March 1997). The smallest yields were registered in the minimum tillage treatment at 16.3 t ha^{-1} and the legume strips treatment at 19.1 t ha^{-1} (Figure 49).

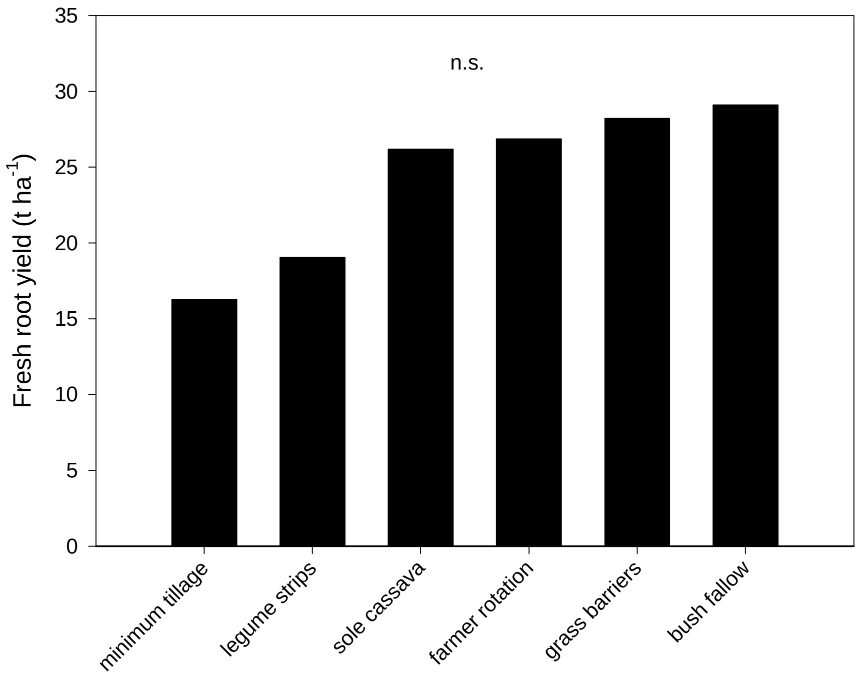


Figure 49. Cassava fresh root yields for the 96A period (April 1996 to March 1997) at Mondomo. The legume strips treatment produced an additional *Phaseolus vulgaris* grain yield of 503 kg ha^{-1}. The dry matter production from the improved fallow treatment for 15 months was 30.4 t ha^{-1}.

An additional *Phaseolus* bean grain yield of 503 kg ha^{-1} was harvested on the legume strip plots. The other four treatments produced very similar cassava yields of between 26.2 t ha^{-1} and 29.1 t ha^{-1}. Comparing the productivity of the farmer rotation with the six other treatments produced yield level differences of between +8.4% and –39.4%. Using the sole cassava treatment as a reference showed yield differences of between +11.2% and –37.9% in relation to the other treatments (Table 53).

Table 53. Cassava fresh root yields expressed in % of the traditional farmer rotation and the sole cassava system for the 96A period (April 1996 to March 1997) in Mondomo

Treatments	in % of T2	in % of T3
T2 Farmer rotation	100.0	102.5
T3 Sole cassava	97.5	100.0
T4 Minimum tillage	60.6	62.1
T5 Bush fallow	108.4	111.2
T6 Grass barriers	105.1	107.8
T7 Legume strips	71.0	72.8

During the last research period with crop cultivation from April 1997 to July 1997 (97A), all treatments were seeded to *Phaseolus* beans to achieve homogenous conditions for the final bare fallow observation period. In addition this procedure allowed easier comparison of the various treatments with regard to their yield performance and residual effects on soil fertility. The yield levels of *Phaseolus* ranged between 0.8 and 1.5 t ha^{-1}. The greatest *Phaseolus* dry bean yields were produced on the farmer rotation treatment and these were significantly greater than the minimum tillage, bush fallow, sole cassava and legume strips treatments (Figure 50), the latter producing the smallest yield recorded. The second greatest yield was produced on the vetiver grass barrier plots at 1.3 t ha^{-1}. It did not differ significantly from those of the farmer rotation and the minimum tillage treatments, but was significantly greater than the yields from the bush fallow, sole cassava and legume strips treatments.

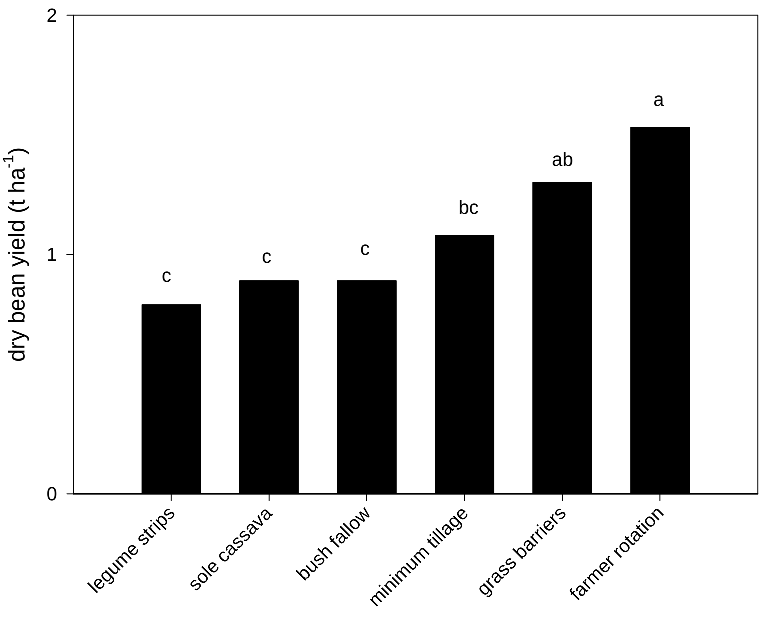


Figure 50. *Phaseolus vulgaris* grain yields for the 97A period (April 1997 to July 1997) at Mondomo

Evaluating the performance of the farmer rotation treatment compared to the six other treatments showed yield differences of between –15.3% and –48.8%, all but the 15% smaller yield of the grass barrier being significantly lower (Table 54).

Table 54. Phaseolus dry bean yield expressed in % of the traditional farmer rotation and the sole cassava system for the 97A period (April 1997 to July 1997) at Mondomo

Treatments		in % of the farmer rotation	in % of sole cassava
T2	Farmer rotation	100.0	172.5
T3	Sole cassava	58.0	100.0
T4	Minimum tillage	70.7	121.9
T5	Bush fallow	58.0	100.0
T6	Grass barriers	84.7	146.1
T7	Legume strips	51.8	89.3

Using the sole cassava treatment as the control showed yield differences of between +72.5% and –10.7%. However, only the yields from the farmer rotation and grass barrier treatments were significantly greater than those from the sole cassava treatment.

A comparison of the productivity of all the treatments with the farmer rotation treatment over the whole research period (1994 to 1997) demonstrated that the greatest average yield was always obtained by the farmer rotation (Table 55). This was followed by the rotation with improved fallow element, which reached an average of 95.9% of the yield levels of the farmer rotation treatment. However, it has to be considered that the 96A and 97B periods are not included as they were under improved fallow. The minimum tillage treatment achieved an average yield of 93% of that of the farmer rotation. Both the minimum tillage and the improved fallow treatments were the only treatments producing greater yields than the farmer rotation in any of the production periods. Except for the first cropping period (94B), immediately after two years of bush fallow, yield levels in the bush fallow treatment were relatively close to those of the farmer rotation, reaching an average yield of 83.7% of the farmer rotation treatment.

Table 55. Performance of all the treatments in relation to farmer rotation for the 94B to 97A periods at Quilichao

Treatments	94B	95A	95B	96A	97A	Mean
	In % of the farmer rotation treatment					
Farmer rotation	100.0	100.0	100.0	100.0	100.0	100.0
Sole cassava	56.2	-[2]	-[2]	61.4	84.7	67.4
Minimum tillage	87.6	84.0	96.3	107.7	89.3	93.0
Rotation with bush fallow element	68.5	90.0	86.9	91.8	81.5	83.7
Rotation with vetiver barriers	62.1	61.8	50.9	61.1	69.9	61.1
Rotation with legume strips	*24.2*[1]	*70.9*[1]	*61.5*[1]	*42.5*[1]	91.5	*58.1*[1]
Rotation with improved fallow element	88.8	83.4	115.4	-[2]	-[2]	95.9

1 Figures in italics represent the yields from the reduced cropped area of the legume strips rotation; for this treatment the additional yields of the legume component have to be considered. 2 Cassava yield during the two Maize cropping periods (95A, 95B) and the *Brachiaria decumbens* and *Desmodium ovalifolium* yield (96A, 97A) were not included in the table. The corresponding yields can be found below figures 44, 45 and 46

The sole cassava treatment reached an average of 67.4% of the farmer rotation yield, being particularly low in both seasons with cassava cropping. The performance was better during the last cropping period with cowpea. The yields of the two maize cropping periods were not included.

The grass barrier treatment, where the vetiver barriers occupied 12.5% of the production area, was kept under the same cropping sequence and fertilization management as the farmer rotation. Average yields, however, reached only 61.1% of the control, probably due to competition effects by the barriers.

A comparison of the performance of the legume strips rotation with the other treatments is difficult and the yields from this treatment have to be analyzed with caution. This is basically due to several changes in the treatment itself during all the cropping seasons presented, whereas the others remained within the same rotation scheme. During the 94B period about 50% of the plot area was seeded with three different forage legumes. For the duration of the following two maize cycles only *Chamaechrista rotundifolia* (Persoon) Greene was undersown as a cover crop. This was changed to intercropping of cassava with grain legumes (Phaseolus and Cowpea beans) during the 96A period. Castillo and Müller-Sämann (1996) reported yield declines of cassava of between 20 and 50% at the Quilichao field station due to the presence of *Centrosema macrocarpum* Benth, *Chamaechrista rotundifolia* (Persoon) Greene and *Galactia striata* (Jacq.). Yields were generally low, even when the yield calculations were based on the reduced production area of this treatment as compared to the other treatments. It was only during the last cropping period, when the whole plot area was cropped with cowpea, that this treatment reached 91.5% of the farmer rotation.

When considering the sole cassava treatment as the control it was evident that all other treatments with complete cropping areas were superior in yield performance (Table 56). The farmer rotation, minimum tillage and rotation with bush fallow element treatments showed yield levels that were between 22.5 and 52.9% higher than the control. Although the available cropping area was only 87.5% of the total production area, the grass barrier treatment reached almost the same yield level on an average basis at 97.5% compared to the sole cassava treatment.

Table 56. Yield performance of all the treatments in relation to the sole cassava treatment for the 94B to 97A periods at Quilichao

Treatments	94B	96A	97A	Mean
	In % of the sole cassava treatment			
Sole cassava	100.0	100.0	100.0	100.0
Farmer rotation	177.8	162.9	118.0	152.9
Minimum tillage	155.9	175.5	105.4	145.6
Bush fallow	121.9	149.5	96.2	122.5
Grass barriers	110.4	99.5	82.5	97.5
Legume strips	*43.0*[1]	*69.2*[1]	108.1	*73.4*[1]
Improved fallow	157.9	-[2]	-[2]	-[2]

1 Numbers in italics represent the yields from the reduced cropped area of the legume strips rotation; for this treatment the additional yields of the legume component have to be considered. 2 The *Brachiaria decumbens* and *Desmodium ovalifolium* yield (96A, 97A) was not included in the table. The corresponding yields can be found below Figure 45, 46.
During the 97A cropping period all treatments except the improved fallow were sown with cowpea.

At Mondomo, only the rotation with improved fallow element produced greater average yields compared to the farmer rotation treatment (Table 57). Both the bush fallow and minimum tillage treatments showed a good performance with yield reductions in relation to the farmer rotation of between -5.7 and –9.9%. The sole cassava treatment reached 83.6% of the farmer rotation, basically due to the very poor performance of the Phaseolus beans in the last cropping period. Yield levels during the cassava cropping phases were almost equal. A possible explanation would be the higher adaptability of cassava to the already degraded soils and its tolerance of low nutrient levels.

Table 57. Yield performance of all treatments in relation to the farmer rotation for the 94B to 97A periods at Mondomo

Treatments	94B	95A	95B	96A	97A	Mean
	In % of the farmer rotation treatment					
Farmer rotation	100.0	100.0	100.0	100.0	100.0	100.0
Sole cassava	95.4	-[2]	-[2]	97.5	58.0	83.6
Minimum tillage	108.8	60.5	149.8	60.6	70.7	90.1
Rotation with bush fallow element	84.1	71.8	149.4	108.4	58.0	94.3
Rotation with vetiver barriers	99.6	37.1	55.2	105.1	84.7	76.3
Rotation with legume strips	*21.7* [1]	91.5	81.8	*71.0* [1]	51.8	*63.5* [1]
Rotation with improved fallow element	123.5	62.1	122.5	-[2]	-[2]	102.7 [2]

1 Numbers in italics represent yields from the reduced cropped area of the legume strips rotation; for this treatment the additional yields of the legume component have to be considered. 2 Only periods with the same species as main crop on the various treatments were considered.

Comparing average yield levels, the vetiver barrier treatment reached only 76.3% of the farmer rotation. This was basically due to the poor performance during the two maize cropping cycles, whereas the yields achieved during the three other cropping seasons were similar or even greater than the farmer rotation.

As in Quilichao, any comparison of the performance of the legume strips treatment with the other treatments should be undergone with caution. A lower competitiveness of the Phaseolus beans compared to the cowpea grown at Quilichao was observed during the 96A cropping season as the cassava yields in Mondomo reached 71% of the farmer rotation treatment. During this cropping season, the cowpea cultivar grown showed massive vegetative growth at Quilichao, due to the favorable climatic conditions, to the extent that every second cowpea row had to be eliminated in order to reduce competition for light and water. Still, cassava yields reached only 42% of the farmer rotation treatment yield level, probably as a result of the reduced initial development of the cassava plants due to the competition effects.

Comparing all the treatment averages with the sole cassava treatment illustrated that both the farmer rotation and the vetiver treatment exceeded the yield levels of the sole cassava by +19.4 and +26.6% respectively (Table 58). The vetiver barrier treatment outstripped the yields of the sole cassava in all the cropping periods compared, although the differences were only significant during the 96B cassava cropping period. However, it has to be considered that the cropped area in the grass barrier treatment was 12.5% smaller. Both the minimum tillage and the bush fallow treatments reached almost identical yield levels when compared to the sole cassava treatment.

Table 58. Yield performance of all the treatments in relation to the sole cassava treatment for the 94B to 97A periods at Mondomo.

Treatments	94B	96A	97A	Mean
	In % of the sole cassava treatment			
Farmer rotation	104.8	102.5	172.5	126.6
Minimum tillage	114.0	62.1	121.9	99.4
Bush fallow	88.1	111.2	100.0	99.8
Grass barriers	104.3	107.8	146.1	119.4
Legume strips	*22.7* [1]	*72.8* [1]	89.3	61.6
Improved fallow	129.4	- [2]	- [2]	-

1 Numbers in italics represent yields from the reduced cropped area of the legume strips rotation; for this treatment the additional yields of the legume component have to be considered. Only the cassava crop phases are compared

4.10 Discussion

4.10.1 Situation in the Cauca Department and other regions of Colombia

Although the erodibility of the soils at the test site is held to be between moderate and low (Foster, 1981), high soil loss rates from the bare fallow plots were observed, possibly due to the extreme climate erosivity combined with the inadequate or missing soil cover. In order to show the importance of soil cover, Hudson (1995) compared both erosion plots covered with fine mesh wire gauze and plots with no protection. Soil loss from the uncovered erosion plots was 100 times greater than that from the gauze covered plots. During erosion trials in the Eastern plains region of Colombia, Obando (1999) reduced erosion amounts from bare fallow plots by 95% when using a mesh that provided a 33% soil cover. Based on the classification of soil loss amounts proposed by Bergsma (1996, see Table 59), complete year observations from bare fallow plots at Quilichao showed extremely high soil losses in six years, very high losses in two years, and high losses in the remaining two years. Soil losses recorded during the first six months of 1998 amounted to more than 60 t ha^{-1}, which also places this year in at least the very high category.

Annual soil loss amounts from eight years out of the ten evaluated from the Mondomo research site can be regarded as extremely high, whereas during the remaining two years soil loss amounts fall into the high category.

Table 59. Frequently used soil erosion classes

Relative classes	Quantitative classes		
	Soil loss range in t ha^{-1} a^{-1}		
Very low	0	-	5
Low	5	-	12
Moderate	12	-	25
High	25	-	60
Very High	60	-	130
Extremely High	>150		

(Source: Bergsma, 1996)

In contrast to observations from temperate climates, the erodibility of tropical soils is of less importance compared to climate erosivity, topography and crop and soil management (Lindsay and Gumbs, 1982). Considering the shallow A_h horizons and the low fertility of the lower horizons of the soil types found in the research region the high to extremely high soil losses must be seen as alarming. This would lead to the complete loss of the fertile topsoil within a few years. During the twelve years of the project duration a total soil amount of 1,840 t ha^{-1} was lost in Quilichao, whereas soil loss in Mondomo for the same period was 2,380 t ha^{-1}. This would imply the loss of most of the upper soil layer within a decade. The A_h horizon in Quilichao had a thickness of 18 cm in 1987 with that in Mondomo being thicker at 27 cm. Due to the high soil losses in Quilichao the original USLE standard plots had to be abandoned in 1993 as the upper soil layer had already been removed by the erosive action. Although the permanent bare fallow condition does not represent a normal state of a field, it can be found during several periods of the cropping systems in the research region, especially after soil preparation and harvest.

The burning of hillsides in order to clear land under fallow, still a widespread custom in the research region, is usually performed at the end of the dry season and leaves the soil exposed and unprotected thus contributing considerably to erosion risk. A survey performed by CIAT in the municipality of Buenos Aires, Cauca, in the vicinity of the experimental sites, showed that about 80% of the farmers burned the fallow residues before cultivation (Müller-Sämann, 1995). Large areas were often burned without the intention to cultivate due to the unplanned spreading of fire or arson during the dry season, leaving the soil unprotected just before the start of the rainy season. The landscape of the Cauca department hillsides frequently shows areas where the upper soil layer is completely lost due to severe erosion and the original deep red or yellow volcanic ash material is uncovered. Some of these areas probably resulted from heavy rainfall events after the bush and grass vegetation had been burned leaving the soil surface unprotected. Regeneration of such areas is only possible with a considerable input of time and labor.

Potential soil losses from the greater research region can be expected to be considerably higher as farmers often cultivate on far steeper slopes than those at the research sites. A study in the micro watershed El Pital, lying adjacent to the Mondomo trial site, reported that of the total area of 1,245 ha 83% was on slopes with a gradient of between 12 and 50%, whereas 16% of the area had slope gradients of between 50 and 75%. Only 0.4% of the total area was qualified as being adequate for the cultivation of annual crops in terms of the quality and stability of soil, although even these slopes had gradients of between 25 and

50% (FIDAR, 1999). However, most farmers used soils considered too steep and too vulnerable for the cultivation of annual crops due to their economic situation and lack of suitable land. The 7,000 ha watershed of the Cabuyal river, including the Mondomo research site, is reported to have slopes with gradients of more than 30% on half of its area with a further third of the area having slopes of between 12 and 30% (Urbano et al., 1995; cited in Ravnborg and Rubiano, 2001).

The soil is especially vulnerable when left unprotected as is often the case after soil preparation and also during the first weeks after planting or harvesting. An example of the higher erosion risk during the initial stages of plant development would be the high soil loss from a single event immediately after seeding during the second maize cycle at Quilichao. The region's principal annual crop, cassava, further enhances the risk due its slow initial growth rates and subsequent poor soil cover. In erosion trials with cassava in the Quindio department, 75% of the soil losses occurred during the first 120 days when soil cover was low (Rivera, 1999). Erosion experiments in the Andean region of the Santander department showed that the first month after the planting of cassava produced the highest soil losses (Méndez, 1996). Oster (1980) found during erosion experiments on Andosols in the highlands of Panama that soil losses under vegetable production were only two to three times smaller compared to continuous bare fallow (183 t ha^{-1} a^{-1}), whereas soil losses from pasture were 1400 times smaller. The high soil losses from the vegetable plots were produced primarily in the period before soil cover was established by the plants and when the soil remained unprotected.

After eight to ten months of cassava growth a period is apparent when the leaf area is again reduced, either by physiological changes or phytopathological problems, which once more reduces soil cover (Howeler, 1984). In addition, the loosening of the soil during the harvest, caused by digging up the roots, considerably increases the vulnerability of the soil to erosion. During erosion trials on a volcanic ash soil with a 60% slope gradient in Colombia, 30% of the soil loss was produced five days after the harvest (Gomez, 1975 cited in Howeler, 1980).

The coincidence of the planting times falling in the months of highest climatic erosivity increases the erosion risk considerably. The large differences in soil losses encountered between the years indicate that multiple factors play a role in a soil's vulnerability to water erosion, particularly antecedent soil moisture content.

4.10.2 Vulnerability of the different cassava-based cropping systems to erosion

When evaluating the different cassava cropping systems, it was evident that both the minimum tillage treatment and the rotation with vetiver barriers may be considered highly efficient in respect of erosion control. The annual soil losses for the assumed average field with a slope length of 50 m and a slope gradient of 25% would be 2.2 t ha^{-1} for the grass barrier and 2.7 t ha^{-1} for minimum tillage treatments under the soil and climatic conditions of Quilichao. Under the Mondomo conditions, losses would be even lower at 1.3 t ha^{-1} for the minimum tillage and 1.5 t ha^{-1} for the grass barrier treatments respectively. The Brachiaria mulch proved to be a highly effective protection method for the soil of the minimum tillage treatment during phases of low soil cover by the crops. In a cassava erosion trial near Mondomo, maize mulch had proved to effectively reduce soil erosion to about one-quarter of the soil erosion amounts of traditional cassava production systems in the region (Howeler, 1984). Additionally, the positive effects of the minimum tillage treatment with its Brachiaria mulch cover upon soil water-holding capacity was observed quite clearly. After the harvest of the last crop in 1997, the cowpea plants of all other treatments dried up and died because of the prolonged drought in June, where no rain fell at all, rainfall of only 5 mm in August and only three events with a total of 14 mm until 20th September. Due to the higher soil moisture available in the minimum tillage treatment, the cowpea plants maintained green leaves in this treatment and even started flowering again. During dry years, this capability could be considered a great additional benefit as the yield potential of this treatment would be much higher compared to the less water-efficient ones. In addition to the fine performance of the minimum tillage treatment in respect of low erosion amounts, it showed the highest levels of N, P and K in the soil at Quilichao and P and K at Mondomo. The main advantage of the minimum tillage treatment lies in the continuous soil cover that is maintained either by the mulch or natural vegetation on the plots. Cassava erosion trials in the Quindio department of Colombia showed that a conventional cassava cropping system with low initial soil cover produced between 11 and 18 t ha^{-1} of soil losses, whereas a minimum tillage system reduced these losses significantly to between 2 and 5 t ha^{-1} with no significant differences concerning yields (Rivera, 1999).

All the other treatments would induce soil degradation by erosion over a longer period as the average annual soil losses would be above the estimated soil formation rate. The continuously sole cropped cassava treatment in particular can be regarded as highly degrading, as the calculated annual soil loss would be about ten times higher than the soil formation rate at Quilichao and almost 40 times higher at Mondomo. Assuming the topsoil depths of between 18 cm and 27 cm reported by Reining (1992), this would imply a complete loss of the topsoil under Quilichao soil and climate conditions after 45 years and after 35 years under the conditions found at Mondomo. Cassava is predominantly grown as a sole crop in the research region; 12% of the plots under crop cultivation in the Cabuyal watershed were cultivated with cassava, as the second most important crop after coffee, which occupied about 50% of the area under crop cultivation. Cassava was grown principally on the already eroded “red” soils (Ravnborg and Rubiano, 2001).

The improved fallow treatment showed low erosion rates both at Quilichao and Mondomo, however when contemplating the steeper gradients common in the wider research region, soil losses would be higher than the tolerance levels. This treatment still could be considered an interesting alternative for farmers with cattle or dairy production working on slopes of below a 25% gradient. Furthermore, the stabilizing effects of the improved fallow upon the soil were observed during the bare fallow observation period at the end of this study (see below). Earlier phases of the research activities presented here had shown that this treatment considerably enhanced the formation of water-stable aggregates (Müller-Sämann, 1996) and that the stabilizing effects on the soil lasted longer compared to the conventional bush fallow treatment. Combing the farmer rotation treatment with the improved fallow system could improve soil stability and thus diminish soil erodibility, whilst achieving consistently high yields.

With regard to the conventional fallow treatment, it became evident that two years are not long enough to restore the structural stability and improve the resistance against soil erosion. At both sites this treatment produced the second highest soil losses during the observation period under bare fallow conditions. However, it has to be considered that, in contrast to the improved fallow treatment, there was no second fallow period in 1996-1997 so a direct comparison can only be made of the initial performance after the first fallow period. It also demonstrated a high vulnerability to single events causing soil loss levels which were up to three times higher than the assumed tolerance levels under the given conditions both in Quilichao and Mondomo. When considering average field dimensions, soil losses would have been ten times greater than the tolerance level under the Quilichao and over seven times higher under the Mondomo soil formation conditions. Soil losses immediately after the fallow period were low but increased during the second cropping season. Whereas fallow periods in the research area used to be long enough to restore and improve soil fertility and stability, the recent development towards shorter fallow periods must be considered alarming (Ashby, 1985). The benefits of the improved fallow system should be considered in this context.

The cassava rotation with legume strips produced an average annual soil loss that was three times greater than the tolerance level at Quilichao and over twenty times greater than that at Mondomo. The higher soil loss levels at Mondomo were probably caused by the inferior ground cover of the Phaseolus strips compared to the higher degree of soil cover provided by the cowpea strips. In the 1996 cassava cropping period, every second strip of cowpea had to be eliminated as the vegetative growth was so strong that the cassava would have suffered excessively from competition. Howeler (1984) reported a 10-month soil loss of more than 100 t ha^{-1} from erosion plots planted to a cassava-cowpea intercrop. These plots, established near the research site of Mondomo, had a slope gradient of 27%. The recorded soil loss was equivalent to 5% of the topsoil and at that rate would have led to a complete loss of the topsoil within 20 years. Insufficient soil cover due to the poor development of the cowpea was considered to be the main cause for this rapid degradation process. Considering the last three years of the experiment reported here, intercropping of legumes with cassava or maize did not appear to be an efficient solution in terms of both erosion risks and yields.

4.10.3 Sustainability of cropping systems in terms of the resilience of the soil to erosion

In order to study the possible effects of different cropping systems upon the structural changes in the soil, all the plots were kept in bare fallow from September 1997 to June

1998. This also enabled the comparison of all treatments under prolonged extreme conditions.

The high grade of effectiveness of the vetiver barriers against erosion was clear. Although soil erosion between the barriers was evident due to the formation of rills, only 300 kg ha^{-1} of sediments were accumulated in the collecting canals at Quilichao and no eroded soil at all was observed on the downslope side of the barriers at Mondomo. On the other hand, losses from the sole cassava and bush fallow treatments exceeded 140 t ha^{-1} at Quilichao. An important factor in this context is the need to maintain the barriers, as most of the sediments collected came through gaps in the barriers caused by diseases. These findings imply that vetiver barriers can basically eliminate soil losses due to erosion even under extreme conditions.

Whilst the improved fallow treatment was not considered to be sustainable under the typical conditions found in the wider research region, it showed that the relatively short period of pasture was a much more efficient means of improving the soil stability in relation to erosion than the bush fallow treatment.

Due to the necessity of homogenous soil preparation, it is difficult to evaluate the aftereffects of the minimum tillage treatment. Although having been maintained under minimum tillage conditions for seven years and having been one of the two treatments with the lowest soil loss amounts, a single pass with a rotary tiller produced considerably higher soil losses during the final observation period, when all plots were kept under bare fallow, compared to the vetiver barrier and improved fallow treatments. This would imply that whilst it is an excellent system for protecting the soil, minimum tillage would be less effective at enhancing the soil’s structural stability than the improved fallow treatment.

4.10.4 Fertility losses

Whilst the soil loss amounts from bare fallow plots were considerably larger compared to the cropped treatments, the negative effects on productivity may already occur at low rates of soil loss. Several factors are affected by erosion such as effective rooting depth, content of organic matter and water-holding capacity (Andraski and Lowery, 1992). Depending on the soil type and the depth of the fertile upper horizon as well as the parent material of the lower horizons, even small amounts of soil loss may have dramatic effects. Stocking and

Peake (1986) reported a yield decline of 50% on an Alfisol in Nigeria with a slope gradient of 1% after soil losses of between 20-40 t ha^{-1}. According to these authors, this severe decline was caused mainly by a decrease in clay and organic matter content as well as reduced rooting depth and, related to this, a lower water holding-capacity and poorer infiltration. The same authors reported a 15% yield reduction caused by a topsoil loss of 2 mm on an Ultisol in Indonesia.

The physical properties of a particular soil are determined by factors such as particle size distribution, chemical and mineralogical characteristics of the clay fraction and by the form and amount of organic matter it contains (Larson and Padilla, 1990). Organic matter, one of the key reactive fractions of a soil, can be selectively removed by erosion (Lal, 1999; Lowery et al., 1999). It is highly important as a bonding agent for soil aggregates and, thus, also influences infiltration, water transport and as water-holding capacity. The erodibility of a soil depends on its organic matter content as it enhances the stability of surface soil aggregates, thus diminishing possible crust formation and surface sealing, as well as increasing water infiltration. Further beneficial effects are the improved plant availability of macro and micronutrients as well as a higher adsorption and exchange capacity for both (Stott et al., 1999).

The productivity of a soil is affected by erosion because it changes chemical, physical and biological properties. Soil erosion leads to a loss of available plant nutrients and organic matter, degradation of the soil structure, decreased rooting depth and decreased available soil water, thus diminishing productivity. In the US, yield reduction rates of maize were between 4.4 and 8.0% for every inch of topsoil lost (Lyles, 1975 cited in Brown and Wolf, 1984). The soils in the research area are much shallower than the ones investigated in the above-mentioned study and therefore the impact on productivity can be assumed to be considerably higher.

Nutrient depletion of soil is not only caused to a great degree by erosion, but can further increase and speed up the erosive process. As low levels of plant available nutrients constrain root growth as well as canopy development, the soil cover and the ability of the plants to hold and stabilize soil are diminished (Hashim, 1999).

Flörchinger (1999) estimated yield losses using results from scalping plots established next to the erosion plots on the Quilichao field station, along with earlier results from Reining

(1992) and Ruppenthal (1995). She reported a potential yield decline to zero for the traditional cassava cultivation system after only 30 years in the worst-case scenario and after 92 years assuming the lowest soil erosion levels. Plots under natural erosion selectively lost more organic matter when compared to the artificially scalped plots and the impact of five centimeters of topsoil loss on crop productivity was far greater under natural erosion conditions than on the scalped plots.

The decrease of organic matter content in the bare fallow plots in Mondomo was considerable and evident for the whole research period, whereas the results from Quilichao were not as conclusive. With regard to the cropped treatments only the continuously cropped cassava showed a decreasing tendency at both experimental sites. The high organic matter losses from the bare fallow and sole cassava treatments were caused by the high soil losses of the treatments as well as normal decomposition processes without replenishment. No specific selectivity concerning organic matter could be found as evidenced by the enrichment ratios of close to one.

Organic matter levels at both research locations, however, were well above the critical limits of about 2% (Morgan, 1995). Due to the high original levels found in the soils after long-term fallow or pasture, the decline did not reach critically low levels during the twelve years of this research. It has to be considered, however, that many parts of the research region have soils where actual organic matter levels are much lower compared to those at the Quilichao and Mondomo sites, as prolonged erosion processes have exposed the subsoil containing considerably less organic matter than the topsoil. Soil erosion and organic matter loss must be considered as spirally cyclic (Pierce and Lal, 1994) and any decrease in the soil organic matter may destabilize the soil structure and diminish the water and nutrient storage capacities of the soil. In addition, it has to be considered that the soil organic matter is the only source of nutrients when the farmers cannot afford mineral or organic fertilizers and any loss of this critical source due to erosion will lead to further yield declines (Palm et al., 2001).

The nutrient losses from the cropped treatments for both sites may be regarded as low. For comparison, in an erosion trial at two locations in Laos, annual nitrogen losses from plots cultivated with the farmers' practice were between 54 and 104 kg ha^{-1}, whereas phosphorus losses were between 9 and 32 kg ha^{-1} (Phommasack et al, 1996; cited in Hashim et al,

1998). The much lower values at Quilichao and Mondomo could be a consequence of the high degree of aggregation of both soils, leading to the low enrichment ratios encountered. Additionally the generally low nutrient status of the soils has to be considered. Earlier research phases in Quilichao and Mondomo showed that nutrient losses from runoff can be considerably higher than losses with sediments. Except for the bare fallow plots, where between 70% and 85% of the total nutrient losses were found in the sediments, all cropped treatments reached far higher percentages, up to 95% for exchangeable K and up to 74% for plant available P (Reining, 1992 ;Ruppenthal, 1995).
According to Ashby (1985), the fallow periods in the research area have diminished considerably from between 10 - 15 years to 3 - 5 years, three years being the minimum time span acceptable to the local farmers. Generally, the shorter grass or longer duration bush fallow are followed by a few years of continuously sole cropped cassava. Cassava is the main crop nowadays as traditional subsistence crops such as beans and maize have been widely abandoned due to the declining soil fertility caused mainly by erosion. Another alarming development is that farmers in the area usually decide to leave their land under fallow due to economic constraints and not for fertility regeneration (Ravnborg and Rubiano, 2001). All these factors can be seen as parts of a vicious circle where a high degree of soil degradation forces the farmers to grow cassava which, due to its low initial soil cover and later problems due to leaf dropping, may lead to further soil degradation.

4.10.5 Productivity and erosion performance of all treatments

As mentioned above, a farmer will often not choose the system that provides the best protection against erosion but the farm operation will most likely be driven by economic factors. Therefore, all the treatments evaluated were compared to the performance of the two treatments traditionally used in the region. Also, it has to be considered that a much higher percentage of farmers presently grows continuously sole cropped cassava after bush fallow compared to the rotational system.
Cassava yields from all the treatments, even the legume strips with a greatly reduced cassava production area, were considerably higher than the average farmer yields reported from the research region. A survey in the Buenos Aires municipality, located about 20 km to the west of Quilichao with highly degraded soils, stated that the farmers’ average yields

were 6.8 t ha^{-1} of fresh roots when planting cassava as a continuous sole crop (Müller-Sämann, 1995), whilst a similar survey in several villages around Santander de Quilichao showed average yields of 6.0 t ha^{-1} of fresh roots (Müller-Sämann, 1996). The reasons for these low yields were fundamentally to be found in the high degree of degradation of the soils on which cassava was cultivated compared to the soils of the field trials. Furthermore, most farmers lack the economic means to purchase and apply fertilizers. Müller-Sämann (1996) states that of 77 farmers interviewed in the Santander de Quilichao area, 77.2% used no fertilizers at all when cultivating cassava. The main reasons for not applying fertilizers were the high costs (74%) and the view that cultivating cassava required no fertilizers (24%). However, these figures may vary from one location to another as in the nearby Cabuyal river watershed two-thirds of the farmers use organic fertilizers, predominantly chicken manure (Ravnborg and Rubiano, 2001). Cassava is considered by the farmers to be a crop that grows especially well on the highly degraded ”red soils” and is therefore principally grown on the more eroded parts of the farms (Ashby, 1985; Ravnborg and Rubiano, 2001).

The performance of most of the cropping systems evaluated showed that high yields can be achieved with moderate inputs of organic and mineral fertilizers. Furthermore, levels of nutrients and organic matter can remain stable with this moderate input. Comparing the performance of the cropped treatments showed that both the minimum tillage and vetiver grass barrier treatments produced equal or even higher yields compared to the sole cassava treatment, whilst at the same time reaching only between 1.8 and 6.8% of the soil loss amounts. It can be assumed that the benefits from the conservation measures would have a stronger impact under the more marginal soil conditions found on most farmers’ land and further increase the differences in yields.

Whilst being a highly effective means of reducing soil erosion, the grass barriers treatment showed consistently low yields at Quilichao. This was probably due to both the reduced cropping area as well as competition effects, as the farmer rotation, being an identical treatment except for the grass barriers, showed greater yields of close to 40% on average. The performance at Mondomo was far better with the exception of the two maize seasons. The consistently greatest yields however, were achieved by the traditional rotation treatment.

4.10.6 Applicability of the USLE in the research region

As the USLE provides the user with long-term average values for soil erosion amounts for the cropping systems analyzed, a database of sufficient depth is necessary to make the results reliable. Wischmeier and Smith (1978) had more than 10,000 plot years covering 22 years available to calibrate and fine tune the USLE, Hudson (1995) used more than 2,500 plot years covering 13 years of data evaluating KE>25 as a erosivity index. The database accumulated and used during the phases of the project described here holds 60 years of plot data in respect of USLE plots and about 420 plot years covering 12 years of research from the other treatments. In addition, about 140 years of rainfall data from several weather stations from the wider research region were analyzed and used to calculate long-term R-factor values. Due to this limited amount of data, results in accordance with the USLE have to be considered carefully. However, the validation of the R-factor for the research region and the high correlations between annual R and soil losses indicate that the USLE may be considered as a promising tool for estimating potential soil losses in the Andean hillsides of Colombia. The R-factor per se can be considered an useful means to characterize the erosive potential of the Colombian Andean region and application of the modified Fournier index should allow R-factor values to be calculated for those areas were no rainfall intensity data are available.

A limiting factor to applying this information to wider areas, however, is the lack of reliable data for the K-Factor. The experimentally derived K-Factor values are only valid for two soil types. Former project periods showed that the use of the USLE nomograph to estimate K-Factor values cannot be considered as a valid alternative to the experimentally determined K-Factor. It is hoped that the equations developed by Castillo (1992), based upon the analysis of the Quilichao and Mondomo soils and further research on local erodibility values, can be applied to a wider range of soil types. As 77% of the Cauca department soils are formed by inceptisols, this region should be adequately represented.

5 General conclusions and outlook

5.1 Rainfall erosivity

The USLE was created with the purpose of calculating potential long-term average soil loss values caused by erosion. These values serve to determine, in combination with an established tolerable soil loss threshold, to what degree conservation measures are necessary to maintain a cropping system that is sustainable over a longer period of time. The 12-year duration of the whole research project presented here together with the additional rainfall data provided by CENICAFE allowed reliable data to be gathered to derive the local values of the USLE's factors for the region.

The closeness of the physical rainfall parameters from the six meteorological data sets evaluated, representing a region of between 1,000 and 2,000 m of elevation and spanning a distance of 150 km, seems to indicate the feasibility of applying the erosivity-related results to other parts of the Colombian Andean region with similar conditions.

Considering the high reliability of the relationships developed between easily and widely obtainable long-term monthly rainfall amounts and R-factor values, the creation of erosivity maps for wider parts of the Colombian Andean Region will be possible, thus allowing a basic assessment of erosion risks.

5.2 Applicability of the USLE

Information about soil erodibility is still limited in Colombia. However, Inceptisols, as analyzed in this work, form about 70% of the Cauca Department's soils, which should allow the USLE to be applied in wider areas of this department. Reliable K-factor values for a great variety of soil types are needed. As mentioned above, the early phases of the project showed that the USLE's nomograph to calculate K-factor values from several physical soil properties was not applicable, at least not for the soils of the research region. A dependable and easy-to-perform method is needed to calculate K-values for other regions and the development of such a method was part of this research effort (Ph.D. thesis, J. Castillo).

In order to test the reliability of the data and relationships developed during this study, additional datasets from both comparable and different origins are necessary. A number of small bare fallow plots would have to be installed in all erosion-prone areas of the country to obtain a reliable database on soil erodibility which would be essential for the application of the USLE on a wider scale.

5.3 Efficacy of cropping systems

The aggressiveness of the research region's climate means that conservation measures are essential in order to conserve the already limited fertility of the soil. Most areas of the Andean hillsides investigated in this study should be used for forestry or at least agroforestry systems due to the extreme steepness of the slopes and the high erosivity of the rainfall. As socioeconomic reasons prevent application of these land use types for the rural population, the necessity to provide the farmers with cropping systems, which are economically and environmentally sustainable, is evident. Both the minimum tillage and the vetiver barrier systems fulfill both the economic and conservation aims by considerably reducing soil loss amounts whilst reaching or exceeding the yields obtained with the system most commonly used by the farmers. In both cases, however, a few additional factors have to be considered which might influence acceptance by the farmers. Whereas minimum tillage saves the farmer time and the cost of soil preparation, the mulch cover - of great importance as the direct protection against the impacting raindrops is crucial - necessitates additional efforts. Furthermore, the mulch material has to be easily available and the time needed to cut and distribute it has to be considered. A possible solution would be to use vetiver grass barriers on the extreme slopes of the farms and utilize the material collected during the necessary maintenance cuts for mulch. This scheme was tested on both demonstration plots installed by the NGO FIDAR and, within a combined income generation and soil conservation system, was implemented successfully as part of the extension activities of the Soil Conservation Project of CIAT and the University of Hohenheim. In the last case blackberry (*Rubus fructicosus* L.) was grown in contour lines together with a barrier of fodder grass in most areas of the farm and in combination with a barrier of vetiver grass for the extreme slopes and boundaries of the farm. This last system generated income for the farmers, as blackberry is an excellent cash crop, whilst the fodder grass also provided high quality fodder for the farmers' cattle as well as reducing erosion risks. Furthermore, the vetiver grass could be used as mulch to further reduce the potential damage by rainfall impact .

In the vetiver grass barriers treatment, the loss of planting space seems to be balanced by the excellent conservation performance and no yield deficiencies were registered in comparison with the traditional cassava monocropping. However, the installation and maintenance of the barriers also requires an additional input of time and labor. Whilst being an excellent plant for anti-erosion barriers due to low competition for water and nutrients as well as possessing a deep vertical rooting system for stabilizing even steep slopes, vetiver faces the problem that little additional use can be gained from it. During an earlier phase of the research activities presented here several multi-purpose grasses were screened for competition, production of fodder and additional uses. Among these were Imperial grass (*Axonopus scoparius*), Elephant grass (*Pennisetum purpureum*), Guatemala grass (*Tripsacum andersonii*), Partiña grass (*Andropogon leucostachyus*), Citronella (*Cymbopogon nardus*) and Lemon grass (*Cymbopogon citratus*). *Cymbopogon nardus*, from which an essential oil - used by the cosmetic and cleaning product industries - can be extracted, was adopted by a women's cooperative in the hamlet of El Pital near the Mondomo research site. The members of the cooperative planted 25 km of erosion barriers on their farms and extracted the basic oil with the use of a simple distilling unit. The basic oil was sold to the cosmetic and soap industry and was also used to manufacture marketable goods like scented candles and cleaning agents for household use.

In the hamlet of Cascajero, about 20 km from the Quilichao research site, women traditionally collect wild-growing Partiña grass which is then used for broom making. The use of the Partiña grass for erosion barriers was propagated in order to improve both the soil conservation within the cassava cropping system and to provide the farmers' households with an additional income from selling the broom grass and/or manufacturing brooms themselves. A further advantage was the far easier collection of the grass due to its concentration in delimited fields, thus reducing both the collection effort and the time spent to collect a certain amount of grass. These examples underline the necessity of giving the farmers incentives to apply soil conservation measures, as any measure that does not provide direct benefits but involves the additional input of labor or money without an evident return, is very unlikely to be adopted.

Noe Prieto, a small-scale farmer in the Cauca owning about 4 ha of land, and participant of the international workshop on soil conservation held by the CIAT-University of Hohenheim project at CIAT in 1997, implemented several types of soil conservation measures such as dual purpose grass barriers and maintenance of permanent soil cover. This example shows that a sustainable system can be successfully implemented and provide a good livelihood even in a relatively small farm.

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7 Appendix

Development of organic matter from the topsoil of all cropped treatments in Quilichao and Mondomo

Table 60. Development of organic matter in the topsoil of all cropped treatments in Quilichao

Year	Sole cassava	Minimum tillage	Bush fallow	Grass barriers	Legume strips	Improved fallow
			O.M. %			
1990	6.7	6.7	6.7	7.9	6.8	6.7
1991	7.2	7.7	6.5	7.2	8.2	7.2
1992	6.6	6.7	6.6	6.8	7.4	7.2
1993	6.6	7.1	7.1	7.0	7.7	7.4
1994	6.9	8.1	7.5	7.2	7.3	7.9
1995	6.6	7.0	6.5	6.8	6.9	7.0
1996	6.9	7.4	7.0	7.0	7.5	7.6
1997	5.9	6.8	5.9	6.0	6.3	7.0
1998	5.2	7.0	7.9	6.3	6.9	7.3

Table 61. Development of organic matter in the topsoil of all cropped treatments in Mondomo

Year	Sole cassava	Minimum tillage	Bush fallow	Grass barriers	Legume strips	Improved fallow
			O.M. %			
1990	7.0	5.9	6.2	7.5	6.7	7.0
1991	6.4	5.9	6.3	9.0	6.3	6.9
1992	5.7	5.7	5.8	8.7	6.1	6.4
1993	5.7	6.3	6.9	9.5	6.9	7.0
1994	5.6	6.6	6.5	8.8	6.7	6.7
1995	5.7	5.5	6.0	8.4	5.9	6.8
1996	5.6	5.9	6.7	8.9	6.2	7.1
1997	5.4	6.1	5.7	7.1	5.4	6.3
1998	5.2	5.4	5.4	6.5	5.4	6.3