SOIL EROSION STUDIES IN SPAIN
Soil Erosion Studies in Spain

M. Sala
J. L. Rubio &
J.M. García-Ruiz, Edrs

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1991
"This book has been composed in Logroño, Spain, by the crazy guests of the house of the rising sun"
J.M.G.R.

First edition, september, 1991

Cover photo: Badlands in Murcia, SE Spain.

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AUTHORS

J. ALBALADEJO
Centro de Edafología y Biología Aplicada del Segura (CSIC)
J. ARNAEZ-VADILLO
Colegio Universitario de La Rioja
E. BARAHONA
Estación Experimental del Zaidín (CSIC)
E. BENITO
Universidad de Santiago de Compostela
G. BENITO
University of Arizona, Tucson
C. E. BORGHI
Instituto Pirenaico de Ecología (CSIC)
A. CALVO-CASES
Universidad de Valencia
V. CASTILLO
Centro de Edafología y Biología Aplicada del Segura (CSIC)
F. DIAZ-FIERROS
Universidad de Santiago de Compostela
M.T. ECHEVERRIA ARNEDO
Universidad de Zaragoza
F. GALLART
Institut Jaume Almera de Ciencias de la Tierra (CSIC)
J.M. GARCIA-RUIZ
Instituto Pirenaico de Ecología (CSIC)
S.M. GIANNONI
Instituto Pirenaico de Ecología (CSIC)
A. GOMEZ-VILLAR
Colegio Universitario de La Rioja
J.C. GONZALEZ HIDALGO
Universidad de Zaragoza
M. GUTIERREZ ELORZA
Universidad de Zaragoza
A.M. HARVEY
University of Liverpool
A. IRIARTE
Estación Experimental del Zaidín (CSIC)
V. LARREA SAENZ
Instituto de Estudios Riojanos
T. LASANTA
Instituto Pirenaico de Ecología (CSIC)
F. LOPEZ BERMUDEZ
Universidad de Murcia
J. MACHIN
Estación Experimental de Aula Dei (CSIC)

M.A. MARQUES
Universidad de Barcelona

R. MARTINEZ-CASTROVIEJO
Instituto Pirenaico de Ecología (CSIC)

J. MARTINEZ FERNANDEZ
Universidad de Murcia

J.P. MARTINEZ-RICA
Instituto Pirenaico de Ecología (CSIC)

G. MONTSSERRAT
Instituto Pirenaico de Ecología (CSIC)

A. NAVAS
Estación Experimental de Aula Dei (CSIC)

A. OLLERO OJEDA
Universidad de Zaragoza

L. ORTIGOSA IZQUIERDO
Colegio Universitario de La Rioja

G. PARDINI
Institut Jaume Almera de Ciencias de la Tierra (CSIC)

J. PAYA-SERRANO
Universidad de Valencia

F. PELLICER CORELLANO
Universidad de Zaragoza

J.L. PENA MONNE
Universidad de Zaragoza

J. QUIRANTES
Estación Experimental del Zaidín (CSIC)

M.A. ROMERO DIAZ
Universidad de Murcia

A. ROLDAN
Centro de Edafología y Biología Aplicada del Segura (CSIC)

P. RUIZ-FLAÑO
Instituto Pirenaico de Ecología (CSIC)

C. SANCHO
Universidad de Zaragoza

B. SOTO
Universidad de Santiago de Compostela
CONTRIBUTIONS

PREFACE........................................................................................................... 7
  M. Sala, J.L. Rubio, J.M. García-Ruiz

ANALYSIS, EVALUATION AND CONTROL OF SOIL EROSION
PROCESSES IN SEMIARID ENVIRONMENT: S.E. SPAIN.............. 9
  J. Albaladejo, V. Castillo & A. Roldán

ENVIRONMENTAL AND TOPOGRAPHICAL CONTROLS IN
GEOMORPHOLOGICAL EVOLUTION OF HILL-ROADS (IBERIAN
SYSTEM, LA RIOJA, SPAIN)................................................................. 27
  J. Arnáez-Vadillo, V. Larrea Sáenz & L. Ortigosa Izquierdo

EROSION PATTERNS IN RILL AND INTERRILL AREAS IN
BADLANDS ZONES OF THE MIDDLE EBRO BASIN
(N.E.-SPAIN)......................................................................................... 41
  G. Benito, M. Gutiérrez & C. Sancho

SOIL EROSION IN NW. SPAIN............................................................... 55
  E. Benito, B. Soto & F. Díaz-Fierros

PROCESS INTERACTIONS AND BADLAND DEVELOPMENT IN
SE. SPAIN............................................................................................. 75
  A. Calvo-Cases, A.M. Harvey, J. Payá Serrano

LAND CONSERVATION AND HYDROLOGICAL STUDIES IN
THE HIGH LLOBREGAT BASIN (BARCELONA)......................... 91
  F. Gallart

EROSION IN ABANDONED FIELDS, WHAT IS THE PROBLEM?. 97
  J.M. García-Ruiz, P. Ruiz-Flaño, T. Lasanta, G. Montserrat,
  J.P. Martínez-Rica & G. Pardini

CHANNEL DEGRADATION AS A RESPONSE TO EROSION
CONTROL WORKS: A CASE STUDY................................................. 109
  A. Gómez-Villar & R. Martínez-Castroviejo

EROSION AND ECOLOGY IN THE MIDDLE OF THE EBRO BASIN.
SLOPE ASPECTS AS A FACTOR OF EROSIONAL PROCESSES,
AND INTRODUCTION APPROACH............................................... 123
  J.C. González-Hidalgo, M.T. Echeverría-Arnedo
  & F. Pellicer-Corellano
SOIL EROSION IN A SEMI-ARID MEDITERRANEAN ENVIRONMENT. EL ARDAL EXPERIMENTAL FIELD (MURCIA, SPAIN) ................................................................. 137
F. López-Bermúdez, M.A. Romero-Díaz & J. Martínez-Fernández

SOIL EROSION RESEARCH: EXPERIMENTAL PLOTS ON AGRICULTURAL BURNT ENVIRONMENTS NEAR BARCELONA 153
M.A. Marqués

RESEARCH ON BIOTURBATION IN THE SPANISH MOUNTAINS 165
J.P. Martínez-Rica, C. Borghi & S.M. Giannoni

APPLICATION OF SIMULATED RAINFALL FOR STUDYING RUNOFF YIELD AND EROSIVE BEHAVIOUR OF GYPSIFEROUS SOILS ................................................................. 181
A. Navas

A PRELIMINARY RESEARCH ON THE USE OF CESIUM-137 TO INVESTIGATE SOIL EROSION IN THE SEMIARID LANDSCAPE OF THE CENTRAL EBRRO RIVER VALLEY ................. 191
A. Navas & J. Machín

MIDDLE EBRRO RIVER CHANNEL AND FLOODPLAIN: GEOMORPHOLOGY, RECENT CHANGES, RISKS AND MANAGEMENT ON A FLUVIAL SYSTEM OF FREE MEANDERS 203
A. Ollero-Ojeda & F. Pellicer-Corellano

SOIL DEGRADATION AND EROSION IN SOUTHEASTERN SPAIN. CONTRIBUTIONS OF THE ZAIDIN EXPERIMENTAL STATION, CSIC (GRANADA, SPAIN) ........................................ 211
J. Quirantes, E. Barahona & A. Iriarte

EROSION AND SEDIMENTATION DURING THE UPPER HOLOCENE IN THE EBRRO DEPRESSION: QUANTIFICATION AND ENVIRONMENTAL SIGNIFICANCE 219
S. Sancho, M. Gutiérrez & J.L. Peña Monné
Studies about soil erosion in Spain have undergone a spectacular impulse in the last five years. Several research teams have been consolidated in different universities and in the National Research Council (Consejo Superior de Investigaciones Científicas). Many research projects have been approved, supported by the LUCDEME Project, the National Planning for Natural Resources and the European Community. Because of that, many research groups have been able to incorporate sophisticated field and laboratory equipment. In addition, Spanish scientists are becoming more and more involved in international meetings, organizations and cooperative research, and this has indubitably made their work more process oriented and significant.

This impulse is due fundamentally to two reasons. Firstly, the Spanish Geomorphology has quickly evolved towards the study and quantification of processes. Qualitative landscape observation and explanation -which had great importance in traditional Geomorphology in order to explain the great morphostructural unities of Spain- has been substituted by detailed analysis and measurement. Incorporation of complex field and laboratory techniques is common, among them all those related with experimentation and simulation. Perhaps the enviable capacity of old geomorphologists to imagine the evolution of a landscape is lost, although the detailed study of processes allows us to know and hierarchy more precisely the factors that act in the landscape transformation at different temporal scales.

Secondly, studies of soil erosion have, unfortunately, a place of exceptional interest in Spain. Thousands of square kilometers are in an advanced stage of degradation and many regions are threatened short term by the so-called desertification. The loss of fertility and of productive capacity of agricultural soils and the problems caused by fluvial floods or by sedimentation in reservoirs affect more than half of Spain and constitute a first order geoeccological and socioeconomic problem. In no other country of Europe so spectacular examples of soil erosion can be observed such as those prevailing in SE Spain. Moreover, thousands of hectares of forests and bushes are destroyed by wildfires and the consequences of land abandonment in mountain and in semiarid areas are not still well known.

This book includes some of the works that are being carried out in different Spanish research centers. Although this is not an exhaustive review, it can nevertheless
be considered as a good sample of how the Spanish geomorphologists are working at present and of which are the topics that engage the attention of the specialists.

The editors want to acknowledge the effort devoted by all the authors to ensure that the book was finished during the Conference on Soil Erosion and Degradation as a consequence of forest fires (Barcelona Valencia, 3-7 Sept., 1991). We have also a debt of gratitude with José Arnáez for the time spent in the design and organization of the book.

María Sala, José Luis Rubio & José M. García-Ruiz
ANALYSIS, EVALUATION AND CONTROL OF SOIL EROSION PROCESSES IN A SEMIARID ENVIRONMENT: S.E. SPAIN

J. ALBALADEJO, V. CASTILLO & A. ROLDAN

Centro de Edafología y Biología Aplicada del Segura (C.S.I.C.), 30080 Murcia

ABSTRACT
The studies on soil erosion and conservation began seven years ago in the Department of Natural Resources and Environmental Protection of CEBAS-CSIC. The specific topic tackled during this time have been: erosion risks, experimental evaluation of soil loss, soil erosion modelling, erosion-productivity relationship, soil quality improvement and land rehabilitation, hydrological behaviour of soils and microcatchments, microbiological component and soil aggregation and use of mycorrhizae for improving plant reclamation in eroded areas.
The work methodologies, experimental sites, global results and projects in execution are described in this chapter.

Key words: erosion risks, soil loss, erosion modelling, soil productivity, soil improvement, land rehabilitation, hydrological processes, runoff generation, soil microbiology, soil aggregation and mycorrhizal fungi.

RESUMEN
Los estudios en erosión y conservación de suelos comienzan en la U.E.I.: "Recursos Naturales y Protección Ambiental" del CEBAS-CSIC hace siete años. En este tiempo las líneas de investigación que se han abordado son: evaluación y cartografía de riesgos de erosión, medición experimental de pérdida de suelo, modelización de la erosión hídrica, relaciones erosión-productividad, mejora de la calidad del suelo y rehabilitación de áreas degradadas, comportamiento hidrológico de suelos y microcuencas, influencia de la microbiología del suelo en sus características físicas y uso de micorrizas para facilitar la revegetación de áreas degradadas.
En estudios sobre riesgos de erosión se ha diseñado una metodología basada en la delimitación y clasificación de unidades de erosión. Para la medición de pérdida de suelo se dispone de dos parcelas en las que se han instalado un equipo de medición automática, cinco
parcelas equipadas con colectores para la medición manual y cuatro microcuencas de las cuales dos de ellas se están automatizando.
La reducción de agua útil en el suelo como consecuencia de la pérdida de materia orgánica por erosión es el factor con mayor incidencia en la pérdida de productividad, a lo que hay que añadir la disminución de nutrientes, la degradación de las propiedades físicas y el aumento de la salinidad en las áreas topográficamente deprimidas. Se está trabajando en el desarrollo y comprobación de un modelo de erosión de suelo. El modelo tiene una estructura modular, basándose cada módulo en las características físicas de las diferentes fases del proceso.
La técnica que se está experimentando para mejorar la calidad del suelo es la incorporación superficial de residuos sólidos urbanos. Tras la adición se realiza un seguimiento de la evolución de los parámetros físicos, químicos y biológicos del suelo. Al mismo tiempo, se valora el efecto de la rehabilitación del suelo en su comportamiento hidrológico. Otros aspectos hidrológicos incluidos en nuestros proyectos son la identificación de los factores que controlan la generación de escorrentía en condiciones ambientales semiáridas y el análisis de la variabilidad espacial de los procesos hidrológicos.
En conexión con los estudios de regeneración de suelos, se llevan a cabo experiencias referidas a la evolución de las poblaciones de hongos y bacterias. Las mediciones realizadas hasta ahora muestran una buena correlación entre las poblaciones microbianas y el porcentaje de agregados estables del suelo. Asimismo, se está investigando en el conocimiento de la evolución de los hongos endomicorríceos y ectomicorríceos tras la adición del residuo, dada la importancia de un manejo adecuado de la simbiosis con micorrizas en los programas de revegetación.

The Mediterranean area of southeastern Spain has environmental characteristics that cause particular fragility and vulnerability in the ecosystems with regard to the human action (RAMOS, 1991). Once the inadequate anthropic interventions break the ecosystem’s equilibrium the onset of its degradation is continuous and progressive.

Among the environmental degradation processes in this area, soil erosion plays a major role due to: i) the low percentage of plant cover and the high state of degradation caused by aridity and anthropic action. This means poor protection of the soil, and ii) the high erodibility of some soils, mainly those developed from marls (ALBALADEJO, 1990).

Erosion causes a decline in soil productivity and the consequences of this are manifold in the physical, chemical and biological characteristics of the soil (FAO, 1984). As a result of this in some large areas of S.E. Spain the soil has lost its capability to maintain plant cover and the possibility of hydrological regulation. This increases the probability of natural risks.

In this process of degradation three main components can be identified:

a) Soil component
b) Biological component
c) Hydrological component
CONTROL OF EROSION PROCESSES IN SE SPAIN

In the Department of Natural Resources and Environmental Protection of C.E.B.A.S. in Murcia, we aim to tackle the problem of soil erosion from this triple component, studying it in an integrated way. Therefore is our purpose to constitute and consolidate a multidisciplinary research team with a specialised staff in the three above mentioned components.

Studies in soil erosion started in this Department in 1985. The specific topics tackled since then have been: erosion risks, experimental evaluation of soil loss, soil erosion modelling, erosion-productivity relationship, soil quality improvement and land rehabilitation, hydrological behaviour of soils and microcatchments, microbiological component and soil aggregation and use of mycorrhizae for improving plant reclamation in eroded soils.

In the following sections work methodologies and the main results from each studied topic, are shown.

Table 1. Site details for the four experimental microcatchments

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot size (m²)</td>
<td>785</td>
<td>452</td>
<td>570</td>
<td>750</td>
</tr>
<tr>
<td>Relative relief (m)</td>
<td>15</td>
<td>6</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Average slope (%)</td>
<td>21</td>
<td>23</td>
<td>26</td>
<td>29</td>
</tr>
</tbody>
</table>

Soils

<table>
<thead>
<tr>
<th>Soil Tax. Classif.</th>
<th>Torriorthent</th>
<th>Torriorthent</th>
<th>Gipsorthid</th>
<th>Paleorthid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture</td>
<td>loamy clay</td>
<td>loamy sand</td>
<td>l. clay-sand</td>
<td>sandy loam</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>38.5</td>
<td>9.1</td>
<td>28.0</td>
<td>5.10</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>37.5</td>
<td>16.1</td>
<td>30.0</td>
<td>36.69</td>
</tr>
<tr>
<td>Fine sand (%)</td>
<td>22.9</td>
<td>29.8</td>
<td>25.5</td>
<td>20.50</td>
</tr>
<tr>
<td>Med. coarse sand (%)</td>
<td>1.1</td>
<td>45.0</td>
<td>16.5</td>
<td>37.67</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>0.21</td>
<td>1.0</td>
<td>0.7</td>
<td>1.20</td>
</tr>
<tr>
<td>Stoniness (%)</td>
<td>20-30</td>
<td>50</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Base Infl. (mm/min)</td>
<td>0.3</td>
<td>8.6</td>
<td>3.1</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Vegetation

<table>
<thead>
<tr>
<th>Type</th>
<th>Salsola</th>
<th>Rosmarinus</th>
<th>Thymus</th>
<th>Stipa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lycium</td>
<td>Thymus</td>
<td>Teucrum</td>
<td>Rosmarinus</td>
</tr>
<tr>
<td></td>
<td>Artemisia</td>
<td>Stipa</td>
<td>Helianthemum</td>
<td>Thymus</td>
</tr>
<tr>
<td></td>
<td>Thymus</td>
<td>Helianthemum</td>
<td>Teucrum</td>
<td></td>
</tr>
</tbody>
</table>

Vegetal cover

|                | 2  | 60 | 30 | 50 |

1. Work methodologies

1.1. Experimental sites

At present we have arranged the following experimental areas:

- Four plots similar to microcatchments. Site details are in table 1.
ALBALADEJO, CASTILLO & ROLDAN

- Set of five plots of 15 m. x 5 m. on very degraded soil (xeric torriorthent developed from marls) with 10% slope. These plots are equipped with a collector device for runoff and sediments and a rainfall recorder.

- Set of two plots of 15 m. x 5 m. on forestry soil (Lithic Haploxeroll) with 23% slope. One plot is in natural condition and the other is artificially devegetated. These plots are equipped with an automatic recorder which registers rainfall, soil temperature and runoff.

- Set of five plots of 10 m. x 5 m. on Xeric Torriorthent developed from marls in flat land.

1.2. Soil loss measurements

Runoff and sediment is concentrated along natural channels on the plots to a collecting device consisting of a first tank connected to a second with two 1:5 divisors so that only one-twentyfifth of the overflow from the first tank enters the second. Sampling of sediments from the tanks was carried out after thorough stirring. Five aliquots of one litre were taken from different depths and a further five when draining the thanks. Sediment concentration was taken to be the average of these.

Runoff volume is measured as depth in the tanks using a pressure transducers connected to a datalogger. The software of datalogger is set up to take a date each 10 second and keep the average at 1 minute. So a hydrograph is made up so as to know the runoff distribution along the storm.

The rainfall parameters are measured with a rain-gauge connected to the datalogger in the same way as above.

1.3. Erosion risks

In the evaluation and mapping of erosion risks we use a methodology designed by ourselves (ALBALADEJO, 1987, 1988), based on the delimitation of erosion units. Once the different erosion units are identified soil loss is assessed through the USLE. In the section 3.1. more details of this methodology are shown.

1.4. Soil microbiology

1.4.1. Bacterial and fungal populations

Total bacterial measurements were obtained with acridin-orange stain over polycarbonate (millipore) filters 0-2 μm pore size and observation with epi-fluorescence microscopy (HOBBIE et al, 1977). Homogenization of soil samples was obtained with addition of triton X-100 and cold-sonication. This methodology appears to be the more effective in our soils. Similar techniques with sonication employment by several
authors (HATTORI, 1988) also have shown higher effectiveness levels than traditional homogenization methods.

![Flowchart showing factors affecting erosion](image)

**Fig.1. General scheme of methodology**

Fungal biomass has been measured through quantification of total mycelia length. Counts were obtained directly with contrast-phase microscopy after spreading on agar films (JONES & MOLLISON, 1948; VISSER et al, 1983).

1.4.2. Mycorrhizae

Because vesicular-arbuscular mycorrhizae (VAM) are obligatory symbiotic fungi it is impossible to obtain a xeric inoculum in quantities. So VAM fungi are cultivated in plots with *Medicago sativa* and this substrate containing spores, mycelia and infected roots is used as a source of inoculum in our experiments.
ALBALADEJO, CASTILLO & ROLDAN

The amounts of infective propagules are measured using the most probable number method (PORTER, 1979). In the establishment of the infection percentage in roots the staining method of PHILIPS & HAYMAN (1970) has been followed and calculated with the protocol described by GIOVANNETTI & MASSE (1980). The isolation of spores was made by wet sieving and decanting method as described by GERDEMANN & NICOLSON (1963). Other methods occasionally used are described in MILLNER (1990).

Most ectomycorrhizal fungi produce great amounts of spores which can be recolected and used to inoculate seedlings through direct irrigation (CASTELLANO & MOLINA, 1990). Sometimes esporocarps of these fungi can be collected in forest and shaken with distilled water.

This mixture carries a lot of spores, as well as microorganisms (yeasts and bacteria) that can be advantageous to improve mycorrhizal symbiosis (LI & CASTELLANO, 1987; LINDERMAN, 1988). This source of inoculum can be stored under refrigerated conditions for more than three years without decreasing spore germination. Infection percentage of roots can be estimated by direct observation with stereomicroscope under moderate magnification.

2. Results

2.1. Soil erosion Risks

In this research line a system of erosion units classification is developed. Erosion unit is defined as: "physiographic homogeneous unit as for the form and rate of erosion, which is delimited by soil climate, relief and vegetation or soil use characteristics". The classification system in general, able to be used in different environments, is objective and subject to development and adaptation to specific areas.

The methodology for the mapping of erosion risks is based on the previous classification and delimitation of erosion units. Erosion rates in each unit are quantified through the Universal Soil Loss Equation. (fig. 1).

The methodology has been checked in Fortuna Basin and in the agricultural land of Murcia Region, and has shown the following advantages:

- the application of prediction models of soil loss to erosion mapping
- the exact delimitation of the whole area for erosion risk
- the determination of the main causes of erosion in the different parts of the area
- a reduction in the complexity of the natural environment so that an erosion model can be accommodated
CONTROL OF EROSION PROCESSES IN SE SPAIN

In this way, the methodology provides the basic information for the planning of erosion control alternatives by:

- specifying the most appropriate actions in each place to reduce erosion
- the economic evaluation of the alternatives.

2.2. Quantitative evaluation of soil erosion in experimental plots.

Since 1985 we have been carrying out experimental measurements on soil loss and runoff volume. Details of the methodology and plot characteristics are above. The specific objectives of this measurement are:

- Construction of a data bank of soil loss for the establishment of the degradation rate in the semiarid mediterranean area.

- Verification and validation of soil erosion models.
- Study of the mechanisms of soil erosion processes.
- Economic evaluation of natural resources degradation.
- Determination of land productivity loss induced by soil erosion.

2.3. Soil quality improvement and land rehabilitation

In the project: "Effect of soil degradation on desertification in mediterranean areas: Evaluation of soil quality loss and regeneration techniques", the main objective is to experiment with methods to improve soil quality and to control land degradation. The experiments are being carried out in five experimental plots located in a degraded area of S.E. Spain (photo 1). The technique used to improve soil quality was the addition of different doses of urban refuse in the first 30 cm. with a rotovator.

With the addition of urban refuse a notorious improvement in the physical soil characteristics occur. So, the total moisture, the water holding capacity, the infiltration rate and the percentage of stable aggregates increases with the addition of refuse. This improvement is directly proportional to the dose added, but the rate of increase is higher between the control plot and the plot with the lower dose that between the other plots with refuse.

This evolution in physical properties means an improvement in the hydrological characteristics of the soil. With the increase in infiltration rate and structural stability a very marked decrease in runoff and soil erodibility occurs. In addition to this, the urban refuse incorporation produced a soil fertilization and a reactivation of soil microbiology and all things considered showed a marked increase on soil productivity measured by the biomass production. On the other hand, problems do not occur with contamination by heavy metals, but there seems to be an enhancement in the electrical conductivity proportional to the amount of added refuse. At the end of the experiment we want to do an economical analysis to evaluate the effectiveness of the experimented technique and to stablish the most suitable dose.
2.4. - Soil erosion modelling

The current empirical models of soil erosion do not perform well when extrapolated to conditions for which they were not designed. As it is, in the Mediterranean area, we only have imperfect tools for predicting erosion at the moment. Further refinement of the erosion models is needed. To this end, we are involved in a project of the EEC to develop a process-based prediction model of soil erosion (EUROSEM).

The model has a modular structure with each part being developed in as much detail as the existing level of research allows. This structure enables improvements to be made in the light of new research. The elements of the model are: rainfall interception, soil surface condition, runoff generation, soil detachment by raindrop impact, soil detachment by runoff, transport capacity and net erosion and deposition. The model computes soil loss by comparing the transport capacity of the runoff with the supply of sediment made available for transport through the detachment processes. Soil loss is equated to the lower of two rates. (MORGAN, 1990).

EUROSEM is designed to operate for successive time stages within a storm, usually with durations of one to five minutes. The model simulates changes in soil surface condition during the storm in terms of microtopographic roughness, depression storage and cohesiveness of the surface material.

EUROSEM differs from most other process-based soil erosion models in the particular attention that is given to the dynamic nature of soil erodibility, tillage and crop cover. Because of this an outcome of this approach is that the model requires input data on soils, soil surface state and vegetation that are not normally collected in field studies of erosion. Erosion plots have therefore been established in United Kingdom, Italy and Spain, with the specific purpose of providing data for model validation.

Sensitivity analysis and validation work have still to be carried out. It is hoped to have a first version of the model operational by the end of 1991.

2.5. - Erosion-productivity relationships

From the results of the studies carried out in this field together with the overall knowledge of soil in S.E. Spain, we infer the following conclusions:

- The percentage of soils in S.E. Spain that have not undergone some degradation symptoms are low. Only agricultural areas with appropriate management practices and very particular forest areas do not show degradation processes.

- The soils developed on marls show the highest rate of degradation. Most of them have lost their biological productivity.
CONTROL OF EROSION PROCESSES IN SE SPAIN

Photo 1. Set up of experimental plots arranged to study soil improvement techniques. These plots are equipped with a collector device for runoff and sediments and a rainfall recorder.

Photo 2. Set up of two plots for validation and verification of soil erosion model and to study erosion-productivity relationships.
Marginal soils show parameters of soil quality poorer than agriculturally used soils.

The reduction in available water capacity and infiltration rate as a outcome of the soil organic matter loss are the major effects of erosion in reducing soil productivity in the Mediterranean area of S.E. Spain. This is aggravated by the aridity of the area and high rates of runoff.

Other changes in soil characteristics with degradation processes are:

* Decrease of absorbable P.
* Decrease in water holding capacity.
* Degradation of soil structure by reduction of percentage in stable aggregates. The most relevant aspect is the formation of a laminar structure on the marl soil surface.
* Considerable increase in electrical conductivity in soils from low-lying areas.

In the last years we continue working in this topic being a part in the Network of FAO on Soil Erosion and Productivity. The Network has the following specific objectives (STOCKING, 1988):

- To develop erosion-yield-time relationships for the major soils, climates and land uses.

- To investigate the controlling variables which cause yield change with erosion.

- To monitor all variables that might potentially explain erosion-yield variations.

- To provide the maximum useful information in the minimum time without over-elaborate experimental procedures.

For this research we have arranged two experimental plots (photo 2), one plot with induced erosion (artificially devegetated) and the other in natural condition. In both plots we are monitoring soil parameters, runoff and soil loss and eroded sediments. Comparing the results we study the evolution of soil parameters with different rates of soil erosion.

Because of the short amount of time and the few rainy events, the differences between soil parameters in both plots are still not significant. Nevertheless the hydrological behaviour was similar for the first twenty months, and since this time runoff and soil loss have been bigger in the devegetated plot showing that the degradation of soil parameters by erosion is beginning.

In the eroded sediments, the concentration in organic carbon and total nitrogen is similar to the concentration in the soil. On the contrary, the concentration in P and K assimilable is significantly bigger in the eroded sediments.
CONTROL OF EROSION PROCESSES IN SE SPAIN

2.6. Hydrological behaviour of soils and microcatchments

The development of physically based models for the prediction of soil erosion losses requires a profound knowledge of the hydrological behaviour of soils and landforms. As MORGAN (1980) pointed out, the erosion model will be more adjusted to the reality as more as accurate is its hydrological and hydraulic basis.

In this general context, our team is beginning to work in the study of hydrological behaviour in first order catchments and hillslopes of Mediterranean semiarid environments, with special attention to the following aspects:

a) The effect of soil rehabilitation techniques in the hydrological behaviour of soil.

b) Identification of controlling factors of runoff generation in semiarid environment.

c) Analysis of the space variability of the hydrological processes and its modelling.

Below is described the research lines in each one of these aspects

a) Parallel to the study of soil regeneration with the addition of organic refuse (section 3.3.) we have carried out an evaluation of the hydrological and erosive behaviour in the five plots studied, measuring in each storm the runoff volume and the amount of eroded soil. The results obtained on a total of 20 events show that there are significant differences in the production of runoff and soil losses depending on the amount of organic matter added (table 2).

In this way, the runoff average is 10.6 l. in the plot with the higher dose of added refuse and it increases gradually to 96 l. in the plot with the lower dose. On the other hand, the soil loss average is 0.58 g/m² in the plot with the higher dose of added refuse and it increases to 9.76 g/m² in the plot with the lower dose. In the control plot the average is 39.26 g/m².

Table 2. Effects of urban refuse addition on runoff and soil loss in the five experimental plots arranged for the study of soil improvement (average values of measured events)

<table>
<thead>
<tr>
<th>Amount of refuse added (Kg/m²)</th>
<th>Organic matter (%)</th>
<th>Runoff volume (litres)</th>
<th>Runoff coefficient (%)</th>
<th>Soil loss (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>277.71</td>
<td>12.96</td>
<td>39.26</td>
</tr>
<tr>
<td>6.5</td>
<td>0.5</td>
<td>96.08</td>
<td>3.54</td>
<td>9.76</td>
</tr>
<tr>
<td>13.0</td>
<td>1.0</td>
<td>39.39</td>
<td>0.92</td>
<td>2.33</td>
</tr>
<tr>
<td>19.5</td>
<td>1.5</td>
<td>30.44</td>
<td>0.90</td>
<td>1.13</td>
</tr>
<tr>
<td>26.0</td>
<td>2</td>
<td>10.65</td>
<td>0.33</td>
<td>0.58</td>
</tr>
</tbody>
</table>
These results are in agreement with the improvements observed in the physical properties of soil which determine infiltration and water storage conditions. These are key factors in the timing, amount and space distribution of hillslope runoff (SCOGING, 1982; SCOGING & THORNES, 1980).

b) The traditional approach to the analysis of runoff generation processes has rested in two basic models of antagonistic characteristics. Thus, in the model of Horton (HORTON, 1.933) characteristic of semiarid areas with scarce vegetation and low infiltration rates, the runoff generation is regulated by a simple rainfall-infiltration excess.

On the other hand the saturated model proposed by HEWLETT (1961) for well-vegetated soil in more humid environments draws out soil moisture storage as the key factor in runoff generation.

Nowadays, this dichotomy is being overcome, allowing a continuum of controls to determine the nature of runoff generation and relating them to variations in surface materials and the dynamic changes in surface hydrology caused by storms.

The aim of our research is to establish the controlling factors in runoff generation in semiarid hillslopes, and the relation of these processes to topographic variability, soil moisture, surface soil properties and infiltration variability. This research is carried out taking into account the differences in the hydrological behaviour among the four experimental microcatchments arranged (table 1) and the internal variation inside each microcatchment.

c) The third research line is closely related to the previous one and deal with the inclusion of the space heterogeneity in the modelling of the hydrological behaviour. The use of distributed models makes possible the inclusion of this space heterogeneity of the characteristics allowing the model parameters to vary in space across the solution grid (BINLEY et al., 1989). The final objective is the development of a distributed model of hydrological behaviour in semiarid basin and hillslope as a previous stage to a modelling of generation and production of sediments through the introduction of the concept of partial area contributions.

The basic scheme of the model would consist of a runoff generation function developed from the results obtained above in b) and a runoff routing component. Each one of the four equipped microcatchment has two controls of entry/exit: an automatic meteorological station and a discharge gauge.

2.7. Microbiological component and soil aggregation

Microbial activity is one of the major factors in the formation and maintenance of water-stable aggregates (WSA) in soils (LYNCH, 1989). Increases in WSA levels in soil yield a better water-holding and raise considerably the nitrogen fixation (FORSTER, 1980). The improvement of soil structure also implies a higher resistance of soil versus
CONTROL OF EROSION PROCESSES IN SE SPAIN

degradative processes. This advantages make evident that the study of soil microbiological processes is a major topic in soil conservation research.

There are plenty of microorganisms able to play a relevant role in soil aggregation processes. Amongst them algae (including cyanobacteria), bacteria and fungi are the most outstanding ones. There are many papers pointing out the role of cyanobacteria and green algae in soil aggregation (FLAIBANI et al, 1989; ISICHEI, 1990; RAO & BURNS, 1990) But because of soil aridity in S.E. Spain, bacteria and fungi are the dominant groups, so our research subjects deal exclusively with these two groups of micro-organisms.

![Graph showing bacterial populations](image)

**Fig. 2.** Total bacterial populations measured in a Xeric Torriorthent after addition of urban refuse (black) with high assimilable carbon levels or peat (white) with low assimilable carbon levels. Crescent numbers indicate crescent doses of urban refuse or peat added.

Bacteria and fungi promote aggregation either through the mechanical action or through the secretion of polysaccharidic cementing substances (TISDALL & OADES, 1982; CHESIRE et al, 1984; ELLIOT & LYNCH, 1984). In both cases to all appearances bacteria and fungi may predominate alternatively depending on soil conditions. Yet, some authors like METZGER et al (1987) experimentally proved that fungi are more effective in stabilizing aggregates, otherwise LYNCH (1981) claims that the effectiveness of bacteria and fungi are similar. In our own experience, bacteria seems to play a dominant role in stabilizing aggregates in marl soils from Southeastern Spain (LAX et al, 1991), probably due to low moisture levels in soil that decreases fungal activity considerably. Bacterial activity is also limited by water availability (KUSHNER, 1980; ACEA & CARBALLAS 1990), but since these micro-organisms excrete cementing polysaccharides this allow the aggregation levels to be kept even when dry periods yields low bacterial activity.

It seems evident that any action aimed at improving soil physical properties also increases soil microbial biomass. Nowadays our research team is conducting several experiments to rehabilitate degraded soils by addition of urban refuse (Section 3.3). The favourable effect of organic wastes addition in soil aggregation (ELLIO...
PAPENDICK, 1986) and microbial activity (LOVETT et al, 1982; STEVENSON, 1982) has been shown. This improvement is more marked when assimilable carbon levels in the waste are high (PAGLIAI et al, 1980), mainly if nitrogen is limiting (REINERSTEN et al 1984). The urban refuse used in our experiments has low nitrogen and high assimilable carbon levels, so it has proved excellent suitability in promoting soil microbial biomass (fig. 2).

Our research is dealing with the evolution of fungal and bacterial populations in experimental plots after the addition of urban refuse. The measurements of microbial populations clearly show good correlation with water stable aggregate levels. New experiments in explaining the relative effects of fungal and bacterial populations and polysaccharids secretion are being carried out in our laboratories. Our objective is to clarify the microbiological processes affecting aggregation stability in marl soils from Southeastern Spain, as a experimental support in increasing effectiveness in soil reclamation programmes.

2.8. Use of mycorrhizae for improving plant reclamation in eroded soils.

It is now well known that mycorrhizal fungi improve plant growth and establishment, mainly through phosphorus and other nutrients uptake. This symbiosis is extremely widespread, and not only are most of plants are mycorrhizal dependents but also in almost all natural habitats this particular relationship (AZCON & BAREA, 1980) can be found.

Mycorrhizal fungi are common soil inhabitants, colonizing roots and establishing biotrophic relationships with final advantages for both organisms. Basically, fungi obtains from plants a carbon source; on the other hand the fungus take nutrients from "edaphic solution" and transfers them to the plant. This fungal action is improved by the great surface of mycelia (SMITH & GIANINAZZI-PEARSON, 1988; TRAPPE, 1981).

Mycorrhizal fungi can be divided into two well defined groups according to morphological characteristics: vesicular-arbuscular mycorrhizae (VAM) and ectotrophic mycorrhizae (ECM).

Vesicular-arbuscular mycorrhizae predominate in most of the plants (NEWMAN & REDDELL, 1987). As a example, well known family plants such as Leguminosae, Solanaceae, Labiatae, Compositae, etc. are considered VAM dependent. This kind of mycorrhizal symbiosis appears to be the most relevant one in aridic soils. When these soils get highly eroded, only 1-2% of plants inhabiting them are considered mycorrhizal (REEVES et al, 1979). This subject partly explains how important an adequate management of mycorrhizal symbiosis can be in revegetation programmes in eroded sites.

Nowadays, our research group is particularly interested in the evolution of VAM fungi in marl soils after addition of urban refuse. On the other hand, we are
carrying out some inoculation experiences with legume plants (*Hedysarum* spp. and *Anthyllis cystisoides*). Among plant species, legumes are unique because of their ability to form symbiotic associations with nitrogen-fixing bacterial (*rhizobia*) and vesicular-arbuscular mycorrhizal fungi (BAREA et al., 1989; BAREA, 1990). These associations enable plants to establish in soils that are low in nitrogen and phosphorus. As can be seen in Fig. 3, phosphorus uptake can be improved when adequate inoculum is used. These observations will be used to establish leguminous plant species on eroded surfaces in Southeastern Spain. The final object is to develop an adequate methodology for establishment of a plant cover in those sites where, because of their high degradation levels, natural revegetation may be hard.

![Graph showing phosphorus content in plants of *Hedysarum spinosissimum*](image)

**Fig. 3.** Phosphorus contents in plants of *Hedysarum spinosissimum* inoculated with five different *Glomus* species (G) or grown in sterile soil without mycorrhizae (S.S.)

Ectomycorrhizal fungi are particularly important in Mediterranean forest plants (*Pinaceae, Fagaceae*, etc.). Our research with ECM is directed towards obtaining effective symbiosis to improve tree establishment in afforested lands. Seedlings of *Pinus halepensis* (the most used forest tree in reforestation programmes in Southeastern Spain)
have been inoculated with three different ECM fungi: *Suillus collinitus*, *Pisolithus tinctorius* and *Rhizopogon roseolus*, some of them have been used in other experiments successfully (MARX, 1974). Nowadays, these seedlings are being planted in experimental plots previously amended with urban refuse. The object is to determine the survival measure of each treatment, as a preliminary date for application on a greater scale.

References


CONTROL OF EROSION PROCESSES IN SE SPAIN


ALBALADEJO, CASTILLO & ROLDAN


ENVIROMENTAL AND TOPOGRAPHICAL
CONTROLS IN GEOMORPHOLOGICAL
EVOLUTION OF HILL-ROADS (IBERIAN
SYSTEM, LA RIOJA, SPAIN)

J. ARNAEZ-VADILLO (1), V. LARREA SAENZ (2) &
L. ORTIGOSA ÍZQUIERDO (1)

(1) Departamento de Geografía. Colegio Universitario de La Rioja,
26001-Logroño, Spain
(2) Departamento de Geografía. Instituto de Estudios Riojanos,
26001-Logroño, Spain

ABSTRACT.
In this paper the authors study the erosion processes which affect the geomorphological
evolution of hill-roads and their spatial distribution. These processes have also been related
to a group of environmental and topographical variables. The authors prove that the
behaviour of road-cuts (T1) differs from that of downslope sides of the road (T2). In the
former, mass movements occur, and in the latter, erosion processes linked with overland flow
are the most frequent. Close relationships between some of the environmental and
topographical factors, and the erosion processes have been observed. These variables help us
to understand the location and frequency of erosion processes.

Key words: Hill-road, erosion processes, Iberian System

RESUMEN
La construcción de pistas forestales en áreas de montaña puede suponer el incremento de los
aportes de sedimentos desde la ladera a los cauces y, en el peor de los casos, la generalización
de movimientos en masa que pueden inutilizar la propia pista. En este artículo se indican los
procesos de erosión más habituales tanto en el talud superior (T1) como en aquel que se forma
ladera abajo de la pista con el material extraído de su contrucción (T2). Los datos, refrendados
por un análisis discriminante, indican un comportamiento diferente de ambos sectores. En T1
pequeños procesos como la caída de tepés, deslizamientos y caída de rocas son los más
activos. En T2 destaca, sobre todo, el arroyamiento difuso severo y la erosión nula. En una
segunda fase del trabajo se han relacionado los procesos con un grupo de variables
ambientales y topográficas. Los resultados permiten deducir que los microprocesos de erosión

27
Mountain areas of temperate zones have recently changed from management by autochthonous population to integration into more extensive, complex and dynamic socioeconomic systems controlled by and from urban areas (LASANTA & RUIZ, 1990). With an important loss of productive capacity, mountains have turned into marginal spaces destined exclusively to the exploitation of hydraulic, forest or tourist resources. These mountain uses have demanded the building of hill-roads and paths with different techniques and budgets.

Road building in mountain areas has a notable impact because it involves the removal of thousand of cubic meters of rock, soil and vegetation. Subsequently, if minimal conservation techniques (retaining wall, systems of evacuation of runoff, etc) are not applied, hill-roads can be affected by runoffs which accelerate sediment transport (DISEKER et al., 1962) and mass movements, involving, at the worst, their abandonment and disablement (DYRNESS, 1967).

The variety and activity of erosion processes are related to environmental factors and to building techniques and further conservation of hill-roads. In mountain areas with strong slopes, high geomorphological activity and limited budgets, large mass movements can be found (HAIGH, 1984; HAIGH et al., 1989). In other cases, hill-roads cover more regular mountainous sectors, with gentle slopes and less extreme climatic conditions.

Hill-road building in the second type of areas does not imply strong environmental impact. These evolve through erosion processes of moderate activity. Nevertheless, these erosion processes, in some cases, cause seasonal interruptions of hill-roads -forcing reaconditionning works- and an increment of sediment yield. These hill-roads even become the main area-sources of sediment on mild hillslopes. Being aware of this reality, we have begun to study the geomorphological impact of hill-roads on the mountains of La Rioja. In this paper, we explain, by means of a descriptive-statistical method, the predominant erosion processes that contribute to hill-roads erosion and where they operate. It is also interesting to check the relationship established between erosion processes and environmental-topographical factors in order to know the most important variables causing the diversification and distribution of erosion processes. Finally, we try to describe the behaviour of hill-roads from a geomorphological perspective.
GEOMORPHOLOGICAL EVOLUTION OF HILL-ROADS

1. Study area

To carry out this study we have chosen a group of hill-roads located in the northwestern sector of the Iberian System, in Sierra de la Demanda and Cameros (Figure 1). Both mountain chains show a very similar general aspect, with smooth divides and hillslopes whose slope angles increase near ravines and in the contact with the Ebro Depression. However, the differences between both chains are very important from the lithological, climatic and biogeographical point of view.

![Fig. 1. Study area](image-url)

The Sierra de la Demanda, situated in the west of the Iberian System, between the provinces of La Rioja and Burgos, incorporates the highest summits of La Rioja (2000-2100 mts). Quartzites, shales and schists of Paleozoic are the most abundant materials, outcropping sandstones and limestones of Secondary in a narrow northern border and in the depression of Canales de la Sierra (ARNAEZ & GARCIA-RUIZ, 1990). The altitude and western position of the Sierra de la Demanda allow it to be reached by Atlantic influences, so that, as we go up, the climatic conditions show a more oceanic tendency, with rainfalls surpassing 1000 mm above 1500 m. The environmental moisture favours the growth of beeches (*Fagus sylvatica*) and oaks...
(Quercus pyrenaica), although a continuous antrophic action has reduced the forest in favour of scrub growth (Genista, Cytisus, Erica, Calluna).

Cameros includes a group of mountains with their altitude decreasing gradually from the west to the east, from Sierra de Cebollera (2000 m), to Sierra de Alcarama (1500 m). A large sediment deposit of Secondary (Weald) was affected by wide folds during alpine movement, forming a relief where cuestas are predominant (GARCIA-RUIZ & ARNAEZ, 1991). Quartzsandstones, sandstones and limestone are the most important materials. Climatic conditions change eastward, and a climate with a continental tendency in Sierra de Cebollera (T: 9°C/P: 991 mm) and a submediterranean climate in the rest of Cameros, with larger spatial representation, can be observed (T: 10.2°C/P: 585 mm) (MARTIN RANZ & GARCIA-RUIZ, 1984). These mountains of La Rioja have supported a strong demographic pressure that has caused the forest devastation of their hillslopes. The scrub and the afforestations are the most representative plant communities.

Table 1. Characteristics of selected hill-roads

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (Kms)</td>
<td>17</td>
<td>14.7</td>
<td>5.4</td>
<td>14.5</td>
<td>11.1</td>
<td>18.4</td>
<td>12.6</td>
</tr>
<tr>
<td>Minimum altitude (mts)</td>
<td>970</td>
<td>1190</td>
<td>980</td>
<td>755</td>
<td>750</td>
<td>700</td>
<td>740</td>
</tr>
<tr>
<td>Maximum altitude (mts)</td>
<td>1525</td>
<td>1983</td>
<td>1430</td>
<td>1145</td>
<td>1245</td>
<td>1320</td>
<td>1250</td>
</tr>
<tr>
<td>Mean slope (%)</td>
<td>5.8</td>
<td>4.0</td>
<td>7.8</td>
<td>2.8</td>
<td>-</td>
<td>2.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Mean width (mts)</td>
<td>6.4</td>
<td>7</td>
<td>3.4</td>
<td>6.3</td>
<td>8</td>
<td>6.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Cut of hillslope (mts)</td>
<td>2.0</td>
<td>-</td>
<td>1</td>
<td>2.1</td>
<td>1.6</td>
<td>2.3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

1) Sierra de la Demanda (Valgañón-Ezcaray); 2) Sierra de Cebollera (Hoyos de Iregua); 3) Cameros Nuevo (Nieva); 4) Cameros Viejo (Cenzano); 5) Cameros Viejo (Sta. Marina); 6) Conglomerados Terciarios (Ocón-Arnedillo); 7) Sierra de Alcarama

Table 1 includes the most representative characteristics of seven selected hill-roads. The length of the hill-roads ranges from 5 to 18 Km, going up from approximately 700-900 mts, at the beginning of the hill-road, to 1300-1400 m. Only the hill-roads 1 (Sierra de la Demanda) and 2 (Sierra de Cebollera) rise to 1500 mts and 1900 m, respectively. The route characteristics are variable. The width ranges from 3.5 to 7 m and the cut realized in the hillside ranges from 1 to 2.5 m.

2. Methodology

In the first stage we collected information "in situ" of seven hill-roads. Continuing along these hill-roads, the erosion processes on the road-cut (which we will designate in the paper T1) and on the first meters downslope of the road (which we will call T2) were noted every 1000-1500 m. approximately. The applied technique for data collection consisted in extending transversally a tape measure of 20 mts on T1 and T2, and recording all the erosion processes located under it. This system, used in other
GEOMORPHOLOGICAL EVOLUTION OF HILL-ROADS

studies on abandoned fields (GARCIA-RUIZ et al., 1990) and afforestation (ORTIGOSA, 1992), gives very good results when we try to record erosion processes of small size, enabling us to know their variety and intensity. In total we have worked 59 cases in T1 and other 59 in T2 (118 cases). Also other additional data were collected. In every sampling, we considered general environmental variables (altitude, as an indirect indicator of climatic conditions, lithology and type of vegetation upslope and downslope of the road-bed), hillside characteristics (slope, exposure and hillside shape) and hill-road characteristics (road-cut [T1] height, road-cut [T1] angle, percentage of vegetation cover [T1], T2 length, T2 angle, percentage of vegetation cover on T2 and road width). All information has been stored and handled by computer, applying different statistical methods (contingency tables, chi-square, correlations, regressions and multifactorial analysis) which enable us to establish relationships between the erosion processes and the variables and to describe the behaviour of hill-roads from a geomorphological point of view.

The erosion processes defined on hill-roads are the following:

a) Null Erosion. This term has been assigned to hill-roads in which T1 and T2, covered with vegetation, are not affected by runoffs or by mass movements.

b) Severe sheet wash erosion. In some hill-roads, T1 and T2 do not have deep incisions and scars. Nevertheless, a closer observation allows us to discover evidences of sheet wash erosion. To be precise, on T1 and T2 we detect a high percentage of stones -since the finest particles have already been washed away-, threads of water and microchannels which have served to lead runoffs partially.

c) Mild sheet wash erosion. We apply this term to hill-roads in which T1 and T2 are situated in an intermediate phase between null erosion and severe sheet wash erosion. Here an important plant cover exists, although it is not sufficiently dense to prevent soil loss.

d) Rockfalls. On road-cuts, where bedrock outcrops, frost-thaw action breaks, fractures and slides the material. The rocks often reach the roadbed, although it is more common that they deposit at the foot of the road-cut, even building small cones.

e) Slides. Processes involving erosion of a great portion of T1 and T2. Their size ranges from 10-100 m². Slides leave a semicircular hole. At its foot, the slidied material is deposited, incorporating, in cases of a forest slope, trees and scrubs. This material also can reach the roadbed, blocking the traffic.

f) Incisions. On some roadsides, the overland flow has incised parallel rills and small shallow gullies, that have not been able to form hierarchical networks. If they are expanded, T1 and T2 acquire an aspect of high erosion.

g) Erosion microprocesses. Within this group, we include small processes that involve the mobilization of material package on T1 and T2. We refer mainly to creeping
and turf-falls. The first process is especially linked with the action of pipkrakes, which raise stones and soil aggregates, causing their further slow descent. Turf-falls affect especially the top sector of road-cuts. Here subsurface flows and root actions undermine the contact between soil and debris, while the former remain in unstable position. Under these conditions, the collapse and the descent along road-cuts of small packages of soil and scrub are usual.

3. Results

The relative importance of erosion processes is shown in Table 2. On T1, the most important erosion processes correspond to the group of erosion microprocesses, with an average extension of 44.1 % (88.2 cms). Secondly, rockfalls representing 23.5 % (47.1 cms) follow in importance. Finally, slides occupying 17.1 % (34.2 cms) set down the table at a certain distance from the other erosion processes. On T2, the distribution is more homogeneous: severe sheet wash (27.6 %) and null erosion (23.7 %) occupy a higher percentage of outline than the rest of the erosion processes. From these first results we can infer a different behaviour of T1 and T2 with relation to erosion processes. We must not forget that road-cut (T1) is a result of hillslope undercutting and T2 is a result of downslope accumulation of debris excavated during road building.

<table>
<thead>
<tr>
<th>Erosion Processes on Hill-Roads</th>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>cms %</td>
<td>cms %</td>
<td></td>
</tr>
<tr>
<td>Null erosion</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Sev. sheet wash eros.</td>
<td>24.3</td>
<td>12.1</td>
</tr>
<tr>
<td>Mild sheet wash ero.</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Incision</td>
<td>4.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Slides</td>
<td>34.2</td>
<td>17.1</td>
</tr>
<tr>
<td>Microprocesses</td>
<td>88.2</td>
<td>44.1</td>
</tr>
<tr>
<td>Rockfalls</td>
<td>47.1</td>
<td>23.5</td>
</tr>
</tbody>
</table>

The application of a discriminant analysis (DA) enables us to prove or reject this initial hypothesis. With the help of DA, we checked whether we are in presence of well-differentiated groups, whether a variable or variables discriminate groups and, finally, whether it is possible to reclassify cases-118 cases-in the groups. The result of the discriminant analysis is recorded in Table 3, which shows that a single factor gathers variables in two opposite blocks: on the one hand, erosion processes that involve slides of soil package or rocks and, on the other hand, erosion processes activated by overland flow (sheet wash erosion) or where erosion is null. These two opposite blocks explain geomorphological functioning of two sectors of hill-roads (T1 and T2). The matrix, which relates real values measured on T1 and T2 sectors to predicted values by discriminant analysis, indicates a correct classification of 88 % in T1 and 72.8 % in T2. Thus, the percentage of well-grouped cases is 80.5 %, an excellent result. These data
confirm a different functioning of T1 and T2 and enable us to go on working on these two sectors in an independent way.

Table 3. Discriminant Analysis

<table>
<thead>
<tr>
<th>Function</th>
<th>Eigenvalue</th>
<th>Relativ. Percent.</th>
<th>Canonical Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84</td>
<td>100</td>
<td>0.67</td>
</tr>
<tr>
<td>Wilks Lambda</td>
<td>Chi cuadrado</td>
<td>DF</td>
<td>Sign. level</td>
</tr>
<tr>
<td>0.54</td>
<td></td>
<td>68.89</td>
<td>7</td>
</tr>
</tbody>
</table>

Standardized Discriminant Funct. Coeff. Correl. between variab. and canon. factors

Null Erosion -0.315 Null Erosion -0.552
Sev. sheet wash 0.043 Sev. sheet wash -0.289
Mild sheet wash -0.188 Mild sheet wash -0.289
Incision 0.205 Incision -0.010
Slides 0.660 Slides 0.465
Microprocesses 0.832 Microprocesses 0.392
Rockfalls 0.695 Rockfalls 0.220

CLASSIFICATION TABLE

<table>
<thead>
<tr>
<th>Actual Group</th>
<th>n^2 cases</th>
<th>1</th>
<th>2</th>
<th>1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>59</td>
<td>52 (88.1 %)</td>
<td>7 (11.8 %)</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>59</td>
<td>16 (27.1 %)</td>
<td>43 (72.8 %)</td>
<td></td>
</tr>
</tbody>
</table>

Percent of "grouped" cases correctly classified: 80.5 %

To confirm the weight of environmental and topographical variables in the main erosion processes, we have grouped two types of variables: those of general character that explain the context where hill-roads run (altitude, lithology, exposure, type of vegetation and type of hillslope), and those directly related to the characteristics of hill-roads (see below). Having different information in both groups of variables, we have chosen to use several statistical techniques. Specifically, the first group, being integrated by categorical variables, has been studied using contingency tables, subjected subsequently to chi-square test; the second, with quantitative variables, has been analysed using correlations.

The utilization of chi-square test, determining a confidence level of 90 %, indicates us that, in T1, there is a good relation between the main erosion processes and the type of hillslope (p=0.04), lithology (p=0.09) and altitude (p=0.09). This does not happen in the case of vegetation and hillslope exposure factors, which must be rejected, since they do not reach the required confidence level. In T2, we must reject null hypothesis (distribution at random) in the case of lithology (p=0.005), altitude (p=0.04) and vegetation (p= 0.07).
Table 4. Cases with dominant erosion processes

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th></th>
<th>T1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n° cases</td>
<td>%</td>
<td>n° casos</td>
<td>%</td>
</tr>
<tr>
<td>Null Erosion</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td>32.2</td>
</tr>
<tr>
<td>Sev. sheet wash ero.</td>
<td>7</td>
<td>11.8</td>
<td>18</td>
<td>30.5</td>
</tr>
<tr>
<td>Mild sheet wash ero.</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>10.1</td>
</tr>
<tr>
<td>Incision</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Slides</td>
<td>6</td>
<td>10.1</td>
<td>2</td>
<td>3.3</td>
</tr>
<tr>
<td>Microprocesses</td>
<td>32</td>
<td>54.2</td>
<td>10</td>
<td>16.9</td>
</tr>
<tr>
<td>Rockfalls</td>
<td>14</td>
<td>23.7</td>
<td>4</td>
<td>6.7</td>
</tr>
</tbody>
</table>

This information facilitates the understanding of the spatial organization of geomorphological erosion processes on hill-roads in relation to general aspects. In T1, type of hillslope (concave, convex or straight) is especially important in the distribution of erosion microprocesses and slides. The former has been detected on road-cuts situated on concave slopes (58.3 %). The slides, in 50 % of the studied cases, are located on straight hillslopes. The lithology is also an important factor in the three main erosion processes of T1. Erosion microprocesses are activated in clays and shales (47 %), the same as with slides (67 %). Rockfalls, naturally, manifest their preference for road-cuts, where bedrocks outcrop with a tendency to physical weathering (quartzsandstone and limestone). Finally, the altitude enables us to determine differences in the distribution of some erosion processes. To be more precise, 83.3 % of all cases with slides are found between 600-1000 m; unlikely erosion microprocesses are preferably located between 1000-1400 m. If we draw a regression straight line (Figure 2) for both cases, relating the percentages of surface occupied by the erosion process and the altitude, we deduce that the higher the altitude, the more important the erosion microprocesses (r=0.35, significant at the 99 confidence level-Student's t test). However, slides decrease with the altitude (r= -0.38, significant at the 99 % confidence level-Student's t test).

Table 5. Chi-square test of environmental variables

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th></th>
<th>T1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>10.70</td>
<td>0.41</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Lithology</td>
<td>18.73</td>
<td>0.51</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Exposur.</td>
<td>6.44</td>
<td>0.33</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Vegetation</td>
<td>5.95</td>
<td>0.32</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Type of hills.</td>
<td>9.57</td>
<td>0.42</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

On T2 the most important process is severe sheet wash erosion, which appears in conditions opposite to null erosion. Taking into account the three most influential variables in this process, the severe sheet wash erosion shows preference for action on silty materials (33.3 %), on slope scrub cover (50 %) and in altitudes that range between 600 and 1400 mts (88 %). If we draw a straight regression line, following the same
Fig. 2. Regressions between erosion processes and altitude
viewpoint indicated previously, we will observe that, as happens with the slides in T1, severe sheet wash decreases with altitude (r= -0.40, significant at the 99% confidence level-Student's t test).

The study of morphometric characteristics of hill-roads has been carried out in order to find out whether we can find relationships between these characteristics and erosion processes. On T1, we have worked with variables such as road-cut height, road-cut angle and percentage of vegetation cover. On T2, we have collected data of T2 length, T2 angle and percentage of vegetation cover. Finally, we have recorded slope angle upslope and downslope of hill-roads. In Table 6 we summarize these data for all hill-roads and those affected by dominant erosion processes. The average slope angle is 10.5°. The installation of a hill-road involves a slope breaking resulting in a road-cut (T1) of 23.5° and a downslope side (T2) of 18.7°. If we analyse the data of hill-roads characterized by specific erosion processes, we will see that slides require higher values: 13° of slope angle, 27° of road-side angle and 2.80 m of height. Severe sheet wash erosion appears in hill-roads with a T2 length longer than the average one. As for the percentage of vegetation, we must point out that it is very reduced in road-side with rockfalls, slides and severe sheet wash. Consequently, those sites where plant cover is very dense (85%), erosion processes do not occur, prevailing null erosion.

Table 5. Hill-road characteristics and erosion processes

<table>
<thead>
<tr>
<th>a) T1 (road-cut)</th>
<th>slope angle</th>
<th>T1 angle</th>
<th>T1 height</th>
<th>% veget. cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>All hill-roads</td>
<td>10.5°</td>
<td>23.5°</td>
<td>2.05 m</td>
<td>19.8</td>
</tr>
<tr>
<td>With Microprocesses</td>
<td>10°</td>
<td>23.5°</td>
<td>2.01 m</td>
<td>28.4</td>
</tr>
<tr>
<td>With Rockfalls</td>
<td>12.4°</td>
<td>24.2°</td>
<td>2.10 m</td>
<td>11.1</td>
</tr>
<tr>
<td>With Slides</td>
<td>13.50°</td>
<td>27°</td>
<td>2.80 m</td>
<td>3.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>b) T2 (downslope side of the road)</th>
<th>slope angle</th>
<th>T2 angle</th>
<th>T2 length</th>
<th>% veget. cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>All hill-roads</td>
<td>10.5°</td>
<td>18.7°</td>
<td>449 cms</td>
<td>53.4</td>
</tr>
<tr>
<td>With Null erosion</td>
<td>11°</td>
<td>18.7°</td>
<td>328 cms</td>
<td>85.8</td>
</tr>
<tr>
<td>With sev. sheet wash</td>
<td>10°</td>
<td>18.2°</td>
<td>653 cms</td>
<td>18.9</td>
</tr>
</tbody>
</table>

A correlation matrix allows us to know which variables of hill-roads are related to erosion processes. To make the interpretation of the results easier we have designed Figure 3. There, the coefficients with significance levels lower than 99% (r=0.33) have been eliminated. The results of the matrix are not representative enough to justify cause-effect relationships, although they can be discussed, because a certain relationship between the variables and the frequency of erosion processes is observed.
Fig. 3. Correlation coefficients between erosion processes and hill-road characteristics

We verify correlations between the various characteristics of hill-roads. In T1, there is a positive correlation between slope angle, road-cut angle and road-cut height. This is not surprising, as a cut in the hillslope for hill-road building gets deeper as the slope increase. This fact also explains the correlations in T2. A high angle slope, with a deep cut, forces a lot of material to be deposited downslope of the hill-road, resulting in an increase of the T2 length and T2 angle.

With relation to erosion processes on T1, slides show positive correlations with hill-road characteristics, such as road-cut angle and road-cut height, and also with slope angle. We cannot say the same about the other dominant erosion processes of T1: rockfalls and erosion microprocesses. In both cases, other variables help their activity. On T2, severe sheet wash erosion is correlated positively with length and negatively with plant cover. Therefore, this type of erosion process requires a certain length to act upon, allowing runoffs to increase speed and erosion capacity, as well as areas without vegetation. Null erosion shows negative correlations with T2 length and positive ones with plant cover.
4. Discussion

Hill-road building in mountains involves the alteration of the hillside profile, leaving bare road-side, with strong slopes, at the mercy of some erosion processes. The activity of these processes is more intensive in mountains with a large geomorphological activity and in those mountains where the hill-road design is inappropriate or where the works of maintenance and protection have been insufficient. Under these conditions, large-size erosion processes, which endanger the utility of the road, occur. If these circumstances do not combine, geomorphological evolution of the hill-road will be slower and less catastrophic. Only small-size erosion processes are responsible for the erosion and the transport of sediments. Mainly the latter have been mainly studied in this paper.

Hill-road building in mountains also modifies hydromorphological functioning of the hillslope. Both the overland flow and the subsurface flow are interrupted. On road-cut (T1), subsurface flows originate areas with high concentration of moisture where small erosion processes, such as turf-fall or creep, take place. Besides the moisture, thermic contrasts are also necessary for these processes to occur; this is why this type of erosion processes are more frequent in higher altitude (see Figure 2). If the hill-road crosses a sector of concave hillslopes, the possibilities of stock of flows and, consequently, those of evolution of these small erosion processes, are larger. Slides are more related to characteristics of road-cuts and hillslope angles. To be more precise they appear in hillslopes with angle stronger than the average. Nevertheless, the influence of lithology and altitude must not be discharged. A large number of slides have been detected on slaty and clayey materials. We have also located them below 1000 m, in unsteady sectors where different anthropic actions previous to the hill-road building have been concentrated: deforestation, abandoned bench-terrace and fire. A fractured lithology seems to be the most important factor explaining rockfalls.

The downslope side of the road (T2) is frequently a loose scree that has been partially recolonized by vegetation, although in some examples T2 looks totally bare. Here, if a good drainage system has not been built, rain and flows coming from saturated areas of road-cut (some hill-roads have intercepted pipes) generates overland flow. In the hill-roads that we have studied the dominant process is severe sheet wash erosion which has been seen on T2 of important length, with little vegetation cover and clayey materials. In some cases, this severe sheet wash envolves rectilinear rills and gullies. In T2, sectors with null erosion are also important on road-side with dense plant cover and in high altitude areas. There are two reasons for this: first of all, mid and upper sections of hill-roads circulate through forest areas with fewer problems of erosion, and secondly, hillslopes are gentler and with a minor slope angle, owing to the special geological evolution of our study area. This second reason causes a smaller cut to be made in the hillslope for hill-road building, with a decrease of the road-cut angle (T1), the road-cut height (T1) and the length of downslope side of hill-road (T2).

To sum up, hidrogeomorphological functioning of hillsides, interrupted by hill-road building, and environmental-topographical variables combine to expedite and
diversify erosion processes. In our study area, small mass movement (turf-fall, for example), pipkrakes with creep of particulates and aggregates, rockfalls and slides are the most important erosion processes on road-cuts (T1); on downslope side of the road (T2), overland flow prevail, generating sheet wash erosion. The erosive capacity of these, with an evaluation of sediment yield is the present purpose for further study on hill-roads.

Acknowledgements. This research has been financed by Instituto de Estudios Riojanos (Autonomous Community of La Rioja)

References


EROSION PATTERNS IN RILL AND INTRERRILL AREAS IN BADLAND ZONES OF THE MIDDLE EBRO BASIN, (NE-SPAIN).

G. BENITO (1), M. GUTIERREZ (2) & C. SANCHO (2)

(1) Department of Geosciences, University of Arizona, Tucson, Az. 85721, USA.
(2) Departamento de Geología, Facultad de Ciencias, Universidad de Zaragoza, 50009 Zaragoza, Spain.

ABSTRACT

Erosion rates were estimated for two plots in badland areas on: a) a recently incised infilled valley (225 m², 4-6° slope), and b) a slope of exposed Tertiary clay (100 m², 25-30° slope). Erosion pins and microtopographic profiles were measured every six months. Average ground lowering of 3-9 mm/year in the infilled valley and 8-17 mm/year in the slope were recorded. These erosion rates are directly related to the cumulative rainfall during each measurement period. Erosion records indicate that 87-92% of the total sediment production in the infilled valley and 73-82% in the slope was produced by runoff processes operating in interrill areas. On the steeper clay slope, similar erosion rates were observed in both rill and interrill areas, indicating a dynamic equilibrium between the rills and the adjacent interrill areas.

Key Words: erosion, rills, interrill areas, badlands, erosion pins, microtopographic profiles, infilled valleys, Middle Ebro Basin, NE Spain.

RESUMEN

En este trabajo se presentan los resultados de las tasas de erosión medidas en dos áreas de badland localizadas en: a) un valle de fondo plano del Holoceno, actualmente incidido (225 m², 4-6° de pendiente), y b) una ladera donde afloran arcillas del Mioceno (100 m², 25-30° de pendiente). Los métodos utilizados han sido tanto de medida directa (varillas de erosión y perfílador microtopográfico), como de análisis comparativo de formas en el tiempo y el espacio (cartografía morfológica y fotografías de detalle). Las varillas de erosión se colocaron cada 1.5 m, formando una retícula, y en puntos singulares como fondos de regueros y áreas de interruegulos. Los perfiles microtopográficos fueron situados principalmente en secciones transversales a los regueros. Las medidas se iniciaron en noviembre de 1987 y se repitieron aproximadamente cada 6 meses hasta diciembre de 1990. Las tasas de rebajamiento del suelo estimadas mediante las varillas de erosión varían entre 3-9 mm/año en el valle Holoceno y 8-17 mm/año en la ladera. Por su parte, los valores de denudación registrados mediante el perfílador microtopográfico varían entre 7-17 mm/año en el relleno Holoceno y 12-19 mm/año en la ladera. Los datos obtenidos mediante las varillas de erosión reflejan la
denudación media de las parcelas, mientras que los perfiladores muestran únicamente la erosión de los regueros. Esto explicaría las diferencias en las tasas de erosión registradas con ambos métodos. Se ha observado que los valores medios de erosión aparecen directamente relacionados con la lluvia total para cada uno de los periodos medidos. La relación de las tasas de rebajamiento en las zonas de regueros/interregueros aparece determinada por la intensidad de las precipitaciones. Los métodos de medida utilizados ponen de manifiesto el elevado porcentaje de producción de sedimentos de las zonas de interregueros. En la estación de El Barranco, el 87-92 % de la pérdida de suelo es debido a procesos de arroyada que actúan en las zonas de interregueros, mientras que en la estación de La Charca estos procesos producen el 73-82%. En cuanto al rebajamiento superficial, en la estación de El Barranco se ha observado un distribución irregular, siendo mayor alrededor de los regueros principales. Por su parte, en la estación de La Charca, se observan tasas similares para las zonas de regueros e interregueros, indicando la existencia de un equilibrio dinámico entre los principales componentes del sistema badland.

Most erosion studies in Spain have concentrated on the southeastern semiarid areas where high intensity rainfall and fine-grained materials produce extensive badlands areas. The Ebro Basin is one of the northernmost semiarid areas in Europe, exhibiting high erosion rates controlled by unique climatic and lithologic characteristics. The climate is continental Mediterranean, and the geology consists of continental Tertiary sediments, with conglomerates and sandstones near the margins and clays, marls, limestones and gypsum in the center. The climate and the erodibility of materials like clays, marls and gypsum make the Ebro Basin a suitable area for the study of geomorphic and erosion processes.

The erosion features in the Ebro Basin occur at different scales and rates. Piping has been the subject of most past studies (GUTIERREZ & RODRIGUEZ, 1984; LASANTA, 1985; GARCIA-RUIZ et al., 1986; GRACIA, 1986; MAIRE & PERNETTE, 1986; and GUTIERREZ et al., 1988). These studies analyzed the genesis and evolution of pipes and their linkage with gullying and rilling processes. Apart from these descriptive works, some attempts have been made to estimate soil erosion. For example, erosion assessments from the Universal Soil-Loss Equation (U.S.L.E.) were mapped by LOPEZ-CADENAS et al. (1987). Actual measurements of erosion rates and their relationships with soil properties and geomorphic processes were obtained by BENITO (1989) and BENITO et al. (1989; 1990).

The measured erosion rates in Mediterranean badlands vary widely, ranging from 0.45 mm/year (YAIR et al., 1982) to 20-30 mm/year (ALEXANDER, 1982). Apart from lithological and climatical variability the erosion values depend on the measurement techniques used. Erosion values recorded by means of direct ground-lowering records are usually higher than the sediment yield data obtained from the measurement of the material conveyed outside the catchment (Gerlach troughs type methods). Here we compile the results from two erosion plots during a three-year measurement period beginning in November 1987. Meter- to centimeter-scale geomorphological mapping, repeat photography, and direct measurements with erosion pins and a microtopographic profile gauge were used. Erosion measurements were taken twice a year (usually in July and December). The results show a direct relationship
Figure 1: Location of erosion pins and microtopographic profiles of the El Barranco (A) and La Charca (B) experimental plots. The sites are 100 meters apart on Holocene sediments and Tertiary clays, respectively.
between erosion rates and cumulative seasonal precipitation, and the seasonal variability of erosion in the rill and interrill areas is established.

1. The study area

The sites are located in the central-northern part of the Ebro Basin, Spain (Fig. 1). Average annual temperature at Almudévar (6 km to the SW) is 13°C, ranging between 23°C in July and 3°C in January. Mean annual precipitation in Lupiñén (10 km to the NW) is 650 mm, occurring primarily in spring and autumn. During intense storms, rainfall may exceed 30 mm in a few hours.

The erosion study was carried out at two plots. The El Barranco plot is in Holocene valley-fill sediments, and the La Charca plot is on a slope of exposed Tertiary clay (Fig. 1). The El Barranco site covers a 225 m² area, devoid of vegetation, and was mapped using a 1.5 m grid (Fig. 1A). The site has low relief and gentle slopes (4°-6°), with locally steeper gradients produced by a dendritic network of rills and collapsed pipes (Fig. 1A). The site is divided into eleven microcatchments, between 1 and 60 m² in surface area, with a meandering channel that terminates in a collapsed pipe. The La Charca site is 100 m east of the El Barranco plot on a NW-facing slope (25-30°) of exposed Tertiary clay, covering an area of about 100 m² which is devoid of vegetation. The site is underlain by 9-m thick Miocene shales except for the top of the slope where there is a 30-cm thick limestone layer. The La Charca plot is incised by a parallel network of rills which are discontinuous at some locations because of pipes (Fig. 1B). The soils sampled in both plots have A/C horizons with relatively low percentages of organic matter, high pH values, low electrical conductivities (EC), high sodium absorption ratios (SAR), high dispersion indices (DI of particles < 2μ is higher than 0.7), and a general absence of expansive clays.

2. Methodology

Comparative study methods and direct measurement techniques were used to determine erosion rates. The comparative measurements utilized mapping of the micromorphology and analysis of repeated photographs. Direct measurements of ground lowering and surface changes were carried out with erosion pins and a microtopographic profile gauge.

The erosion pins are steel rods 4 mm in diameter and long enough (60 cm) to be permanently fixed in place. The pins were installed at 273 points on the El Barranco plot and at 199 points on the La Charca plot. The pins were placed at the intersections of the grid pattern (1.5 m between pins) and along rills and interrill areas where maximum or minimum erosion was expected (Fig. 1).

Surface changes can be monitored using profilometers without disturbing the surface form or processes (CAMPBELL, 1981). The microtopographic profile gauge used (BENITO et al. 1988 AND 1989) is based on CURTIS & COLE (1972) and MOSLEY (1975) profilometers. The device has a 110-cm wide and 90-cm high
RILL AND INTERRILL AREAS

aluminium frame that acts as a background to a black panel with white horizontal lines 2 cm apart on its front face. Along the lower horizontal edge of the frame, a 104-cm long hollow aluminium bar with holes drilled 2 cm apart is fixed. Through these holes, 51 rods 4 mm in diameter slide up and down in response to microtopographic variations. The profilometer was maintained in a horizontal position by adjustable vertical tubes mounted on fixed erosion pins. The results were recorded photographically.

![Diagram showing erosion measurements](image)

Figure 2: Average variations in ground lowering in rill and interrill areas measured by erosion pins in the El Barranco (A) and the La Charca (B) plots and by the microtopographic profile gauge (C). Rainfall distribution (mm/day) between November 1987 and December 1990 (D). J: January; F: February; M: March; A: April; M: May; J: June; J: July; A: August; S: September; N: November; D: December.

Data analysis was carried out by assigning x and y values to each rod and using a cubic spline interpolation that fits a series of cubic functions, S_j, in each subinterval [x_j,x_{j+1}] for j=0,1,...,n-1. The cubic spline interpolation allows integration between several measurements on one profile, obtaining the ground variation for each profile in mm. At the El Barranco and La Charca plots 33 and 22 microtopographic profiles, respectively, were measured in December 1987, July 1988, February, July and December of 1989, and July and December of 1990. The data from the first three measurement periods have been processed completely. Only 8 profiles for each plot have been processed for the other periods.

Erosion measurements from the erosion pins and the microtopographic profilometer have different meanings. Data from the erosion pins reflect the average soil loss from a plot and the relative distribution of soil loss from rill and interrill areas. The microtopographic profiles record rill changes and the response of the immediately adjacent interrill areas to these variations. The potential measurement errors are 1 mm for the erosion pins and up to 2 mm for the profilometer.
Figure 3: Ground lowering contours recorded by erosion pins in the El Barranco plot. Note that the greatest ground lowering is in the central-southern part of the plot and around major rills (compare the contours with the distribution of rill and interrill areas in figure 1).
Figure 4: Selected microtopographic profiles from the El Barranco (A and B) and La Charca (C and D) plots. Profile 2 of the El Barranco plot shows deposition until December 1989, after which a downstream pipe collapse in this rill triggered high ground lowering rates in the measurement periods December 1989-July 1990 and July 1990-December 1990. In Figures B, C, and D note the parallel retreat of the ground surface in both rill and interrill areas.
3. Results

In the El Barranco plot, the average erosion rates measured by erosion pins range between 6 and 2 mm in rill areas (160 and 55 ton/hectare/year soil-loss rates, respectively) and 5 and 3 mm in interrill areas (135 and 80 t/ha/year, soil loss) (Fig. 2A). In the periods November 1987-July 1988, July 1988-February 1989, and February 1989-July 1989, the greatest amount of ground lowering occurred in the south-central area, where the incision of major rills produce the steepest slopes (Figs. 3A,3B,3C). During the periods July 1989-December 1989 and December 1989 and July 1990 the highest erosion rates occurred in the southern part of the plot (Figs. 3D,3E). In the last measurement period (July 1990-December 1990) the erosion spread into the southwestern and northern parts of the plot (Fig. 3F). During this period the average erosion rates were increased as a result of two intense storms of 32 and 46 mm rainfall. In this site, with a low slope angle and scarce vegetation, erosion rates are strongly related to the total amount of precipitation occurring during each measurement period (Fig. 5). The sediment detachment and the sediment transport capacity are directly related to the cumulative rainfall within a period of measurement.

![Relationship between average ground lowering (mm) and cumulative rainfall (mm) for each measurement period in the El Barranco plot. The total erosion fits to a simple regression. The average ground lowering in interrill areas is above this line for rainfall lower than 300 mm, whereas the ground lowering is equal to or above the total erosion for precipitation higher than 300 mm.](image)

In the El Barranco plot, the data obtained with the microtopographic profiles show higher erosion rates than those recorded by the erosion pins, although the erosion follows a similar pattern (Fig. 2A, 2C). The higher erosion rates recorded by the profilometer are due to the location of most of the profilometer measurements across major rills, where ground lowering is usually greater, as well as local processes operating in rills. For example, after December 1989 a new pipe in a major rill increased the erosion rate measured by the microtopographic profile up to 17 mm/year, whereas the average erosion rate determined with the erosion pins was 8 mm/year. Along this rill (Fig. 4A), the erosion rates measured by the profilometer were 60 mm/year in profile 2
Figure 6: Ground lowering contours recorded by erosion pins in the La Charca plot. Contours show higher erosion rates in the south-central part of the plot.
BENITO, GUTIERREZ & SANCHO

(near the pipe), 40 mm/year in profile 8 (upstream), and 5-10 mm/year in the head of the basin (profiles 5-10) (Fig. 1A).

In the La Charca plot, erosion ranged between 15 and 5 mm in rill areas (500 and 170 t/ha/year soil loss) and between 12 and 4 mm in interrill areas (400 and 170 t/ha/year soil loss) (Fig. 2.B). The isopleth maps show that the higher erosion values are in the middle northern part (topographically lower area) of the plot (Fig. 6). However, during the periods July 1988-February 1989, December 1989-July 1990 and July 1990-December 1990, the erosion reached the southern area (higher part) of the plot, especially in pins positioned where headcut retreat of the rills has taken place. In the periods July-February 1989 and July 1989-December 1989, the ground lowering measured with the profilometer was 10 and 12 mm, whereas the average denudation measured with the erosion pins was 5 mm during both periods (Fig. 2.B). In the La Charca site, the soil erosion in rill and interrill areas determined by both methods follows similar patterns (Fig. 2.B;C & 6). In this site, the relationship between rainfall and erosion is not as strong as in the El Barranco plot (Fig. 7), suggesting that processes other than surface runoff are operating. These processes include small mass movements and piping collapses. The piping is concentrated in the lower part of the slope and may collect runoff and produce collapses, affecting the average erosion rates.

![Figure 7: Relationship between average ground lowering (mm) and cumulative rainfall (mm), in the La Charca plot for each measurement period. The average ground lowering tends to increase with the total rainfall.](image)

4. Discussion

4.1. El Barranco plot

In the El Barranco plot the erosion rates follow an irregular pattern, although the highest values are located around rill areas in the south-central part of the plot (Fig. 3). In this site, where the dominant processes are overland flow and rilling, the exposed materials have low sodium absorption ratios (SAR) and low dispersion indices (0.70-0.75) (BENITO et al. 1991). In the underlying materials, with SAR up to 46 and
RILL AND INTERRILL AREAS

dispersion indices close to 1, the piping processes are very active and produce collapses on the plot surface (BENITO, 1989). These collapse structures trigger a positive feedback in the surface, encouraging rill incision and increasing denudation rates in rill and interrill areas (profile 2 in Figure 4).

The rill/interrill erosion rates depend on the sediment production in interrill areas and the flow transport capacity of the rills. When the sediment production in the interrill areas approximates or exceeds the transport capacity of the rills, the incision rates in the rill areas decrease. In this case, the soil loss in rill areas is below the average soil erosion of the plot and local depositon may result (Figs. 3 and 4A&B). However, in times of high intensity rainfall, the flow in the rills is sufficient to transport the sediment production of the interrill areas and even to produce erosion in the rills. The inferred boundary between these two situations for the El Barranco plot is shown in figure 5. Erosion rates in interrill areas are equal or higher than rill areas below 300 mm of rainfall. In contrast, in the November 1987-July 1988 measurements, with a cumulative precipitation of 514 mm (six storms above 20 mm rainfall), the average erosion in rill areas was higher than the average soil loss of interrill areas (Fig.5).

In addition to the overall erosion rates, the data reflect significant spatial and temporal variability in the geomorphic processes across the plots. In summer, strong temperature contrasts produce desiccation cracks, softening and weathering the surface cover and enhancing the sediment availability. However, the relatively short-duration rainfall events transport the sediment for short distances, filling rills and smoothing the surface. Similar effects are produced by frost heaving in the winter. In constrast, during spring and autumn, the sediment stored in rills and interrill areas is flushed out by runoff and the rills are incised or infilled depending on the rill position within the system and on the amount and intensity of the rainfall (Fig. 4A&B).

4.2. La Charca plot

In the La Charca plot, the data show similar rates of ground lowering for adjacent rill and interrill areas. The comparable average erosion for rills and interrills indicates that overland flow and rill processes are acting at similar rates, resulting in a regular retreat of the slopes within the plot (Fig.4).

In the entire plot, the isopleth maps show that the contours are perpendicular to the slope (Fig. 6). In the upper part of the site (southern areas), where overland flow and rilling are the dominant processes, the erosion rates are below the average. The analysis performed in these levels (BENITO, 1989) indicates SAR lower than 15, dispersion indices between 0.71 and 0.9 (D.I. of particles lower than 2μ). In contrast, in the lower part (northern area in Fig. 6) where piping, rilling and overland flow are the dominant processes, the erosion rates are greater. The chemical analysis of the northern levels show high SAR (>40) and dispersion indices higher than 0.95 (BENITO et al. 1991). Therefore in the La Charca plot, erosion rates appear to depend on slope angle, distance from the upper part of the slope, and lithologic variability, with only small differences between rill and interrill areas.
The amounts of ground lowering calculated from the July measurements (after spring rainfall) are greater than those recorded in December (after autumn rainfall) (Fig. 2.B&C). This observation indicates a strong seasonality variability in the geomorphic processes. In summer and winter, the material is detached, and the sediments are flushed away by runoff during spring and summer storms. The higher erosion rates in the July measurements (Fig. 2B) indicate the greater effectiveness of the geomorphic processes that are operating in winter (frost heaving) and spring (overland flow).

4.3. Erosion patterns in the Ebro Basin badlands

In general, average ground lowering based on erosion pin data is a good estimation of average soil loss, while the microtopographic profiles record rill changes and the response of the immediately adjacent interrill areas to these variations. Likewise, erosion increases in major rills due to local phenomena (Fig. 4A) were recorded by the microtopographic profiler, whereas the erosion pin method only indicated a slight increase in erosion rates.

The relationship between the erosion rates and the total precipitation is direct in the El Barranco plot (Figs. 5), whereas a more random distribution was found in the La Charca site (Fig. 7). The high slope gradient in the La Charca plot produces high shear stress flow values even during low intensity rainfalls. In this plot, the runoff transport capacity is able to flush away the sediment produced in summer and winter almost independently of the rainfall intensity. However, in El Barranco, with a lower slope, the rill transport capacity is only capable of removing the stored sediments during high intensity storms (Figs. 4&5).

In both plots, erosion pins and profilometer methods show that the highest sediment yield is produced in the interrill areas. In the El Barranco plot, where 90% of the plot is composed of interrill areas (Fig. 1A), both methods indicate that 87-92% of the total denudation is due to interrill processes. In the La Charca plot, interrill areas comprise 80% of the total surface and produce 73-82% of the total erosion (Fig. 1B). Similar results are obtained by LEOPOLD et al. (1966) in Arroyo Coyote, New Mexico, where the 98% of the total sediment yield is produced by overland flow in interrill areas. Likewise, EMMETT (1970) and DUNNE & DIETRICH (1980), using rainfall simulation techniques, found higher activity in overland flow processes than rill processes.

The percentage of sediment production in interrill areas is higher because the area covered by interrill zones is significantly higher (Fig. 1). In terms of ground surface lowering, consistent seasonal variations between rill and interrill areas can be observed in both experimental plots. However, for the total period measured, similar rates of ground lowering were observed on rill and interrill areas at the La Charca plot without significant changes in morphology (Fig. 4). These observations in the La Charca plot indicate that a dynamic equilibrium occurs between the main components of the badland system (SCHUMM & LICHTY, 1965), suggesting that over small periods of time and in small areas, a state close to “steady state” may be maintained. Dynamic equilibrium
RILL AND INTERRILL AREAS

may be interrupted when extrinsic and intrinsic changes, such as piping collapse, cause the system to cross a threshold.

5. Conclusions

Erosion measurements in a recently incised infilled valley and a slope of exposed Tertiary clay were recorded by erosion pins and microtopographic techniques. Erosion rates obtained with the microtopographic profiler were greater than those recorded by the erosion pins, although they both followed a similar pattern. These measurements indicate an average ground lowering of 3-9 mm/year in the infilled valley and 8-17 mm/year in the slope. There is a direct relationship between the erosion rate and the total rainfall during each measurement period in the infilled valley, whereas a more random distribution was observed in the slope. In the infilled valley the detachment and the sediment transport capacity are directly related to the amount and the intensity of the rainfall. In contrast, the steeper slope produced high shear stress flow values even during low intensity rainfalls. Erosion measurements indicate that 87-92% of the total sediment production in the infilled valley and 73-92% in the slope is produced by interrill processes. The spatial pattern of the ground lowering in the infilled valley is irregular, although erosion was greater around rill areas. However, for the three-year measurement period similar rates of ground lowering were recorded in rill and interrill areas in the slope, indicating a dynamic equilibrium between rills and adjacent interrill areas. This equilibrium may be broken when extrinsic and intrinsic changes, such as piping collapse and rill captures, cause the system to cross a threshold.

Acknowledgements

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References


54
SOIL EROSION STUDIES IN NW SPAIN

E. BENITO, B. SOTO & F. DIAZ-FIERROS

Departamento de Edafología e Química Agrícola. Universidade de Santiago de Compostela. 15706-Santiago de Compostela (Spain).

ABSTRACT
The knowledge of the history of erosive processes from the beginning of the Holocene is presented, as well as the values of current erosion, determined from the suspended sediment carried out by the rivers. An evaluation of the factors determining soil erodibility is made, showing the great importance of parent material and land-uses. The importance of forest fires is pointed out, as processes triggering erosion. The use of several measurement methods allows us to evaluate soil erosion, ranging from 20-150 t/m²a using erosion pins and 5-13 t/m²a per year using erosion plots USDA-type. The different factors involved are discussed, concluding the difficulties of applying the USLE to predict soil erosion in burnt areas. Finally, the importance of erosion in cultivated slopes in springtime is pointed out.

Key-words: soil erosion, soil erodibility, forest fires, experimental plots, U.S.L.E., Galicia.

RESUMEN
Se plantea inicialmente el conocimiento actual sobre la historia de los procesos erosivos en Galicia, señalando los datos paleoecológicos la existencia de un período rexistásico, generalizable a numerosos suelos, en los comienzos del período Subatlántico (1000 a 2500 BP) y otro en los comienzos del Holoceno (9500 a 10500 BP). Se considera asimismo probable, de acuerdo con la hipótesis de FOLSTER (1972) la existencia de otro episodio erosivo importante al final del período Atlántico.
Las pérdidas de sedimentos por los ríos aportan información sobre los ritmos actuales de denudación de los suelos, estimados para la zona en 0.8-1.6 t/m²a/año, reflejando una situación de relativa protección de los suelos por bosques y matorrales.
Se han realizado estudios sobre la erosionabilidad de los suelos con simulador de lluvia, encontrándose que los suelos cultivados son siempre más sensibles a la erosión que los de prado, bosque o matorral, y asimismo que los suelos derivados de esquistos pelíticos, anfibolitas y gabros, son siempre los más erosionables.
Se destaca la importancia de los incendios forestales en relación con la erosión, al destruir total o parcialmente la protección derivada de la cubierta vegetal. Estudios realizados con clavos de erosión ponen de manifiesto niveles altos de pérdida de suelo (de 20 a 150
BENITO, SOTO & DIAZ-FIERROS

Tm/Ha/año), que por otro lado tienen una evolución muy rápida en el tiempo, ya que normalmente el 80 % de la erosión originada se produce en los 3-4 primeros meses posteriores al fuego. Se ensayó la posibilidad de predecir la erosión con la Ecuación Universal de Pérdida de Suelo, encontrándose dificultades, sobre todo con la evaluación de los factores C y K que resultaban ser los más modificados por la acción del fuego.

En un estudio de laboratorio para demostrar la influencia del calentamiento del suelo sobre su estabilidad estructural, se encontró que ésta, después de un breve episodio de mejora de la estabilidad con temperaturas inferiores a los 200 °C, experimentaba un proceso creciente de degradación hasta los 450 °C, donde se estabilizaba. Asimismo se destacó la existencia de dos tipos de degradación estructural: seca, sin la intervención del agua y húmeda, como consecuencia de la acción de la lluvia.

Se completa el estudio de la influencia de los incendios forestales sobre la erosión con experiencias en parcelas experimentales, poniéndose de manifiesto la importancia de la intensidad y tipo de fuego como factor determinante y que puede hacer variar las pérdidas de suelo de las 13 Tm/Ha/año, con fuegos intensos que provocan combustión del suelo, a las 5 Tm/Ha/año, en incendios moderados o dèbiles, que afectan sólo a la vegetación. Asimismo se demuestra cómo la hidrofobia que se detoca después del fuego puede afectar sensiblemente a los incrementos de la escorrentía superficial.

Finalmente, se pone de manifiesto la importancia que pueden llegar a tener como zonas susceptibles a la erosión los terrenos de agricultura intensiva con cultivos de primavera, sobre todo en las parcelas que como consecuencia de la concentración parcelaria aumentaron mucho su longitud.

1. Erosion during the Holocene

Soil formation in Galicia (N.W. Spain) has experienced evident discontinuities, generally as a result of successive periods of biostaxia and resistaxia. Early studies (Mucher et al, 1972) based on soil descriptions and analysis of their sand and pollen content found that material belonging to a relatively recent period of soil formation associated with sub-Atlantic vegetation was separated discontinuously (often by a stone line) from material with considerably more ancient pedological and botanical characteristics. The recent 14C dating studies (DIAZ-FIERROS, 1991) confirmed this: all but one of the soils studied had a discontinuity between 1,000 and 2,500 B.P.; many also had another between 9,500 and 10,500 B.P.; and the exceptional soil had a discontinuity at about 4,000 B.P. (Fig.1).

There have therefore been two major periods of erosion, at the beginning and end of the Holocene, in keeping with VITA-FINZI's scheme (1969) for resistaxia in the Mediterranean area. Fööster's notion that in the Iberian Peninsula a sub-Atlantic episode was preceded by a period of erosion around 4,000-5,000 B.P. has only been confirmed in Galicia as regards the later event, but there are nevertheless some indications that he may not have been wrong. Not only is his hypothesis fitted by the 14C dating of the exceptional soil in Fig.1 (Colou 3); it is also in keeping with the abundant palynological evidence of deforestation in Galicia during the Atlantic period (SAA and DIAZ-FIERROS, 1986), since the periods of erosion at both the beginning and the end of the Holocene were triggered by deforestation (which in the former case was due
Fig. 1. Botanical, lithological and pedological discontinuities in Galician soils, with their absolute data. Numbers are depths (cm) at which the discontinuities are formed.
to intense cold and in the latter to the influence of man, possibly helped by climatic factors).

2. Current erosion

Current net soil loss from erosion can be estimated from measurements of material carried in suspension by Galician rivers. Gross soil loss is of course greater, since soil material is deposited as sediment at various points of a river's basin. Net loss data are nevertheless useful for comparison with other regions, since they are the most widely available worldwide. Table 1 shows that the intensity of soil transport by Galician rivers is in general currently 5-10 Tm/km²/year a figure similar to that of other Atlantic Zone rivers (FOURNIER, 1960). The last few years an increase of 30% in the material carried in suspension by Galician rivers has been recorded.

Table 1. Mean densities of suspended matter in Galician rivers, with corresponding values for net soil loss and ratio of gross soil loss to suspended matter density, and comparison with other European rivers

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miño-Lugo</td>
<td>2,303</td>
<td>1,433</td>
<td>622</td>
<td>7.6</td>
<td>5.0</td>
<td>4.7</td>
<td>0.94</td>
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<tr>
<td>Miño-Ourensa</td>
<td>12,962</td>
<td>9,465</td>
<td>732</td>
<td>6.7</td>
<td>5.0</td>
<td>4.9</td>
<td>0.98</td>
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<td>Sil-Barcena</td>
<td>860</td>
<td>833</td>
<td>1,032</td>
<td>7.6</td>
<td>7.0</td>
<td>7.8</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>Sil-S. Pedro</td>
<td>7,989</td>
<td>5,334</td>
<td>668</td>
<td>7.9</td>
<td>5.0</td>
<td>5.3</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>Cabreta-Pte DF</td>
<td>560</td>
<td>431</td>
<td>769</td>
<td>8.8</td>
<td>7.5</td>
<td>6.8</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Tambre-Portón</td>
<td>1,146</td>
<td>1,207</td>
<td>1,053</td>
<td>8.8</td>
<td>5.8</td>
<td>9.3</td>
<td>1.60</td>
<td></td>
</tr>
<tr>
<td>Navia-Doiras</td>
<td>2,289</td>
<td>2,246</td>
<td>981</td>
<td>6.3</td>
<td>5.0</td>
<td>6.2</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td>Eo-Tirso</td>
<td>712</td>
<td>732</td>
<td>1,028</td>
<td>5.5</td>
<td>6.5</td>
<td>5.6</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

Dnieper 4.0
Dvina 6.0
Volga 18.6
Onega 4.0
Yenisei 4.0
Ural 18.6
Don 18.3

1) Station; 2) Basin Km²; 3) Contribution mean (Hm³); Contribution specific (mm); 4) Suspended matter (mg l⁻¹); 5) Gross erosion suspended matter; 6) Net soil loss (T Km⁻²·y⁻¹); 7) Gross erosion (T ha⁻¹·y⁻¹)

Real soil loss in actively eroded areas can be estimated from net river-borne losses using the empirical delivery ratios established by the American Society of Civil Engineers (1975), which take basin size into account. The results for Galicia suggest real losses of 80-160 Tm/km²/year (0.8-1.6 Tm/Ha/year), i.e. an average of rate of soil denudation about 100 mm per 1,000 years for soils with a density of 1 g cm⁻³. As expected in view of Galician orography, this estimate is within the range mentioned
SOIL EROSION IN NW SPAIN

by YOUNG (1969): between 50 mm per 1,000 years for gentle slopes and 500 mm for very steep slopes.

The fact that erosion in Galicia is nearer the low end of Young's scale than the high end almost certainly reflects the high degree of protection afforded by the woodland or shrub covering 70% of the surface and the pasture and crops occupying a significant proportion of the rest. If this vegetation cover were to be lost—which is in some areas a real possibility in view of the current prevalence of summer forest fires—the great erosive potential of Galician rainfall would undoubtedly give rise to severe erosion (see below).

3. Soil erodibility

The resistance of Galician soils to erosion by water has been studied using a rain simulator whose main components are a sprinkler nozzle and a Morin-type interruptor (MORIN et al., 1967); soil samples were placed on a 250 μm mesh sieve 2 m below the sprinkler nozzle and were subjected to 30 minutes artificial rain with a flow rate of 45 mm/h and a kinetic energy of 13.6 joul/m² mm (BENITO et al., 1986). The numerical values of such measurements cannot be taken as representative of field conditions, because they only reflect one kind of erosive process (particle detachment) and because the elastic resistance and humidity of the soil on the sieve clearly differ from natural conditions, but they can nevertheless be accepted as showing the relative erodibilities of various soil types. In the study in question, simulated rain was applied to samples of the top 10 cm of 90 soils that were fairly representative of soil usages and parent rocks in N.W. Spain (Table 2). Since the influence of climate was assumed to be less than that of land-use and parent material, climatic variation was ignored.

Table 2. Number of soils studied for each type parent material, classified by land-use

<table>
<thead>
<tr>
<th>Parent rock</th>
<th>Crop</th>
<th>Pasture</th>
<th>Woodland</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Amphibolites and Gabbros</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Pelitic schists</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Clay sediments</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Schists and Micaschists</td>
<td>6</td>
<td>4</td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td>Granites-Granodiorites-Migmat</td>
<td>12</td>
<td>4</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Sandy sediment and sandstone</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>TOTAL</td>
<td>32</td>
<td>20</td>
<td>38</td>
<td>90</td>
</tr>
</tbody>
</table>

Soils under crops such as maize or potatoes were always more erodible than less intensively used soils under pasture, shrub or woodland. The erodibility of natural soils generally increased between four- and six-fold when they were brought under cultivation. This loss of resistance to erosion by water may be in part attributable to the customary loss of organic matter brought about by cultivation, but detailed analysis shows that some other factor or factors must also be involved. It is thought that the
improper management practices suffered by many cropped soils (especially the use of heavy machinery in very wet conditions) may deteriorate structural stability and with it resistance to the action of rain (BENITO & DIAZ-FIERROS, 1991).

![Graph showing soil loss vs % C](image)

Fig. 2. Soil loss (rate of loss under simulated rain in the laboratory)- % C plane, showing regions occupied by soils developed over three major classes of parent rock.

The nature of parent rock also appeared to influence soil erodibility, though the wide dispersion of the data meant that the differences had little statistical significance. When the preponderant influence of carbon content on this dispersion is taken into account, the major classes of parent rock are separated fairly well by the erodibility data (Fig.2). Since the organic matter content of Galician soils can be estimated, as a first approximation, from the use to which they are devoted (Table 3), especially if no distinction is made between pasture and untilled land, and since there are 1:50,000 scale maps of both land-uses and parent rocks for Galicia, then the above relationship allows Galicia to be mapped for erodibility, the seven erodibility levels indicated in Fig.2 being attributed on the basis of parent rock and land-use as in Table 4 (DIAZ-FIERROS & BENITO, 1990).

4. Erosion and forest fires

In recent times the incidence of forest fires in Galicia has reached alarming levels. Over the past 25 years some 871,248 ha have been affected, 45% of uncultivated
SOIL EROSION IN NW SPAIN

Galician land, and it has been shown by DIAZ-FIERROS et al (1982) and VEGA et al (1982) that in these areas the limits of tolerable soil loss are generally far exceeded, losses of over 50 Tm/yr having been recorded in extreme cases.

Table 3. Mean organic matter contents of soils of three land-use types

<table>
<thead>
<tr>
<th>Land use</th>
<th>% Organic matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop</td>
<td>7.27</td>
</tr>
<tr>
<td>Pasture</td>
<td>13.27</td>
</tr>
<tr>
<td>Woodland</td>
<td>15.81%</td>
</tr>
</tbody>
</table>

Table 4. Expected erodibility classes of soils of given parent material and land-use

<table>
<thead>
<tr>
<th>Parent rock</th>
<th>Crop</th>
<th>Pasture and woodland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone, Amphibolites, Gabbros and Pelitic schist</td>
<td>5±6</td>
<td>3</td>
</tr>
<tr>
<td>Clay sediments</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Granite, Granodiorites, Migmatites and Schists</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Sandy sediments and sandstone</td>
<td>3</td>
<td>0±1</td>
</tr>
</tbody>
</table>

4.1. Studies with erosion pins

The first studies of the effects of forest fires on erosion were carried out on twenty-nine plots in the neighbourhood of Santiago de Compostela. This area is climatically very homogeneous, but quite varied pedologically and topographically. All the soils involved have more than 10% of organic matter and unstable fine-to-medium granular structure. All the plots were affected by fires in the months July-September of the years 1978, 1979 or 1981 (in the exceptionally wet summer of 1980 no fires occurred in the area). Measurements were continued until the spring of 1982, so that a period of up to forty months is spanned for some plots.

Measurements of erosion were carried out using erosion pins (SCHUMM, 1967; LEOPOLOD & EMMETT, 1972; HAIGH, 1977, etc.). Nine pins were staked out as a T parallel to the slope of the plot, and the gain or loss of soil in the 20 m² area so defined was calculated from the mean variation in the exposed length of the pins and the bulk density of the 2 cm of burnt soil (whose average was 0.6 g cm⁻³). As Fig. 3 illustrates, soil erosion after forest fires occurs mainly during the six months following the beginning of the rainy season, when on average 80% of the total erosion suffered takes place. Table 5 which shows the means of accumulated loss and intensity of erosion for the twenty-nine plots over the periods 0-2, 2-6, 6-12 and 12 months after burning; it reflects the exponential decay of the erosion process, which virtually ceases after 12 months. It should nevertheless be borne in mind that, doubtless due to the topographical and pedological variety of the plots, these data exhibit a large dispersion, with interquartile differences of 40%.
Fig. 3. Accumulated loss of soils (Tm/ha) in various plots

Table 5. Soil losses during successive periods after burning (means of 29 plots).

<table>
<thead>
<tr>
<th>Months after burning</th>
<th>Accumulated loss (Tm/ha)</th>
<th>Intensity of erosion (Tm/ha month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 2</td>
<td>39.6</td>
<td>15.8</td>
</tr>
<tr>
<td>2 - 6</td>
<td>48.0</td>
<td>2.1</td>
</tr>
<tr>
<td>6 - 12</td>
<td>56.0</td>
<td>1.1</td>
</tr>
<tr>
<td>+ 12</td>
<td>-</td>
<td>0.2</td>
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</tbody>
</table>

The method used to measure soil loss in the individual plots fails to distinguish between rill erosion and inter-rill erosion. However, the great predominance of small pin recordings over large values implies that if the small values may be attributed to interrill erosion and the large values to rill erosion (ROELLS et al., 1983) then the latter have relatively little effect on the mean value for each plot, which is the most relevant parameter for the purposes of global soil losses from burnt woodland.

4.2. Applicability of the U.S.L.E. to burnt sites.

The LS factors of the plots, calculated BY WISCHMEIER et al (1978) with corrections for irregularity of slope, exhibit no correlation whatsoever with the gross
SOIL EROSION IN NW SPAIN

erosion suffered. Even when two sites were defined in the same slope, their erosion data were uncorrelated. This lack of relationship between the topographical factors of the U.S.L.E. and erosion measured on burnt hills has also been reported by IMESON (1970) and KINAKO et al (1979).

In the present case, the apparent predominance of interrill erosion may partly explain the lack of correlation with the LS factor, since this kind of erosion depends less on the length and inclination of the slope than does rill erosion (KIRKBY, 1980). Moreover, soils with "fast" and "moderately fast" hydraulic conductivities, which predominate among the plots studied tend to reduce runoff.

Fig. 4. Accumulated erosion in various plots (% of final value) together with vegetable cover curves after burning.

(-----): average vegetable cover in the plots whose erosion is shown;
(- - -): vegetable cover pre-August and post-August fires by Casal et al., 1984

As has been shown by DURGIN & TACKETT (1981), WALKER & POPE (1980), DISSMEYER & FOSTER (1984) and others, the determination of the U.S.L.E. C factor in forest soils is particularly difficult owing to a larger number of data being required than those originally specified by Wischmeier. In this study the C factor is calculated using the method devised for forest soils by WALKER & POPE (1980), which requires only the degree of initial protection of soil (roughly estimated for all the plots studied as 10%) and the evolution of the degree of vegetation cover (measured at four different times after burning in various plots). The results are shown in Fig. 4, together with plant cover curves determined in Galicia following pre-August and post-August fires under ecological conditions very similar to those of the present study (CASAL et al, 1984). These data agree well with our own, which differ mainly in the longer initial lag with zero cover, a critical period during which (as a Fig. 4 shows) some 50-80% of the total erosion suffered in the first three years after burning takes place.
The R factor for each period studied was calculated using the function 0.8 P2/P adapted for Galicia from that proposed by the FAO-UNESCO, 1977 (DIAZ-FIERROS & DIAZ BUSTAMANTE, 1981). Fig. 5 shows that there is fairly good correlation (r = 0.859) between the erosion measured and the product R x C. However, the fact that the regression line fails to pass through the origin, and that its slope is not unity as theoretically expected, suggests either that this linear relationship oversimplistic or that the factors R and C require more complicated formulae in order to adapt them to the soils studied.

![Graph showing correlation between measured erosion (Tm/Ha yr) and the product RxC (USLE)](image)

**Fig. 5.** Correlation between measured erosion (Tm/Ha yr) and the product RxC (USLE)

### 4.3. Effect of temperature on erodibility and soil degradation in the laboratory.

Another studies (BENITO, 1988) suggest that the structure and texture of Galician hill soils have little influence on their erodibility (K factor), perhaps due to their high organic matter content, which normally exceeds 10%. BARA (1981) found that immediately after burning the mean soil organic matter content of 42 Galician hill sites was still 16.2%. Burning, moreover, can produce substantial changes in soil properties invalidating the relationships which Wischmeier established basically for the prediction of erosion in agricultural soils. The effect of burning in soil structure is in fact far from clear, some authors claiming that structural stability is favoured (SCOTT & BURGY, 1956; TARRANT, 1956; LE BORGNE & MONNIER, 1959) while others have reported slightly diminished stability (GIOVANNINI & LUCCHESI, 1983) or frank degradation (FULLER et al, 1955; DE BANO et al, 1979).

The range of soil temperatures reached in forest fires is 25-900°C. Except below 200°C, the changes induced in soils by temperatures in this range are generally detrimental to their productivity. Those involving loss of material are undoubtedly the most serious, since they are irreversible; they include a) volatilization, b) heat-
Fig. 6. Soil loss due to volatilization (o), volatilization plus dry breakdown (*) and volatilization plus dry breakdown plus wet breakdown (Δ) in six soils subjected to various temperatures
BENITO, SOTO & DIAZ-FIERROS

induced dissolution, and c) the mobilization of fine material hither to retained in soil aggregates, which thereby becomes susceptible to removal in runoff.

On studied samples from the top 5 cm of six woodland Humic Cambisols developed over gabbros, amphibolites, schists, clay schists, granite and sandy deposits under Ulex and Pinus pinaster stands in Galicia (NW Spain). The samples were subjected to differential thermal analysis (DTA) to determine the thermal events involved in their degradation and hence the most appropriate temperatures for subsequent experiments. In view of the above results and the data reported by GIOVANNINI et al. (1988) heat-induced degradation experiments were carried out at temperatures of 25°C, 170°C, 380°C, 460°C and 700°C. after which we determined losses due to volatilization, dry breakdown (by sifting through a 250 μm sieve) and wet breakdown (after exposure to simulated rain), (SOTO et al., 1990).

Fig. 6 shows the losses from volatilization, volatilization plus dry breakdown and volatilization plus dry breakdown plus wet breakdown of the six soils studied as percentages of initial soil weight, together with the distribution of soil weight between the aggregate fraction and the sand fraction > 250 μm.

Losses due to volatilization were closely related to DTA events and exhibited the same pattern in all soils. A small loss due to dehydration below 170°C was followed by more considerable losses due to organic matter combustion between 170°C and 460°C; at higher temperatures, volatilization losses were negligible. In keeping with this pattern, volatilization losses were clearly related to soil carbon content, the soils with most carbon (soils 1 and 3) suffering greatest losses.

Dry breakdown did not occur in any soil below 170°C, and like volatilization was greatest over the range 170-460°C in which organic matter was burnt. Soils heated to 700°C suffered dry breakdown losses no greater than, and in most cases rather less than, those heated to 460°C.

Wet breakdown was slight in all soils. Resistance to wet breakdown was generally rather greater after heating at 170°C than at 25°C, in agreement with earlier results (DIAZ-FIERROS et al., 1987) and with ALMENDROS et al. (1984) finding that the organic matter of woodland soils is most stable after heating to 100-160°C. In most of our soils, wet breakdown was greatest after heating to between 170°C and 460°C; only in the soil developed over sandy deposits did heating to 700°C cause more wet breakdown than heating to 460°C. Since organic matter, the most important cementing agent in these soils (BENITO & DIAZ-FIERROS, 1989), is totally consumed at temperatures below 460°C, the fall in wet disintegrability between 460°C and 700°C suggests the initiation of sintering or laterization processes (GIOVANNINI et al., 1988).

Overall, the great majority of soil matter loss was due to volatilization or dry breakdown rather than wet breakdown. Most losses occurred in the range 170-460°C, very little aggregated sub-250 μm material remaining in soils heated to 460°C.
SOIL EROSION IN NW SPAIN

Most of the aggregate structure of the soils studied was lost as the result of volatilization and breakdown after heating to temperatures of 400-500°C. Degradation may therefore be attributed largely to the combustion of organic matter. The structureless soils produced by these temperatures may be assumed to suffer severe lack of aeration, making for great difficulty in recolonization by plants. Soils heated to below 200°C (as in certain pasture fires or controlled shrub burning) suffer very little degradation and may even be improved. Wet breakdown is of little account in the overall degradation process, most of which is caused, to roughly equal extents, by volatilization and dry breakdown.

4.4. Studies in U.S.D.A. plots

Finally a experimental plot study was preformed in 1988. The 2000 m2 experimental area faces west with a slope of 30% at an altitude of 320-350 m on Monte Pedroso (Santiago de Compostela, N.W. Spain). The soil is a humic cambisol (FAO-UNESCO, 1974), the parent rock granite, and vegetation cover 8 year old Ulex europaeus bushes. Mean annual rainfall at the site is 1700 mm.

Side by side for burning experiments, and two further plots of the same size defined at the ends of the series for general soil and vegetation sampling, each of the eight plots being surrounded by a safety fringe. At the lower end of each of the six central plots, runoff is channelized into a sediment collector with a 1/9 flow divisor.

Hydrological conditions following the fires shows the evolution of infiltration + evaporation, runoff and interception expressed as percentages of rainfall (Fig.7). Average interception on burnt plots was 10-14% as against 38% for the control plots. Runoff increased initially as the result of a corresponding increase in the intensity of rainfall, reaching 20% in the burnt plots; the subsequent progressive decrease is attributed to gradual loss of water repellency. There was practically no difference in runoff between the two kinds of burnt plot, which was always significantly greater than in the control plots.

Evaporation and transpiration figures were calculated using RITCHIE's model (1972). Transpiration by vegetation is assumed to be zero in burnt plots, in which burning destroyed all leaves, leaving only woody biomass. Direct evaporation from soil totalled 76 mm in burnt plots by the end of the period studied, during the rainy period from 10 October 1988 to 10 November 1988 evaporation accounted for 4% of rainfall, while in the dry period from 10 November 1988 to 31 January 1989 it accounted for 40%.

Fig.8 shows that infiltration was appreciably less for burnt soil than for control soil during the first 20 hours of laboratory experiments on saturated samples. This is attributed to fire induced water repellency. The fact that water repellency was maximum at a depth of 2 cm (Fig.9) can in principle be explained by the Debano's theory, but the negative correlation between repellency and water content suggests that it is the latter that determines the depthwise pattern of the former.
Fig. 7. Evolution of the infiltration, evaporation, runoff and interception expressed as a percentage against rainfall
SOIL EROSION IN NW SPAIN

This study was maintained for two years. The plots became stable after about 450 days (Fig.10), by which time cumulative soil loss was about 5 Tm/Ha on the burnt plots and about 2 Tm/Ha on the only control plot that survived the two years. The fate of the other control plot illustrates the degree to which the severity of erosion depends on the temperature reached during burning: it was burnt by accident during a period when the soil was very dry, and as a result suffered a soil loss of 13 Tm/Ha during the following year.

![Graph showing evolution of saturated hydraulic conductivity in control soil and burnt soil](image)

Fig. 8. Evolution of saturate hydraulic conductivity in control soil and burnt soil

Fig.10 also shows erosion-pin measurements taken in the same way as in the study discussed above in Section 4.1. The fact that the erosion-pin values are some five times greater than the estimates obtained using sediment collectors is in keeping with the results of other authors (KHANBILVARDI, 1983; VEGA et al, 1983; DIAZ-FIERROS et al, 1982) and suggests that the conclusions of the earlier study must be modified. The current best estimate of the soil loss that would be measured in U.S.D.A. plots on slopes affected by forest fires is 5-20 Tm/Ha/year, depending on the conditions of slope, etc.

5. Erosion of agricultural soil

The traditional practice of burn-and-slash may be largely responsible for the erosion suffered by many Galician soils in the course of their agricultural history (BOUHIER, 1979). This practice can mean soil temperatures of over 400°C being maintained for several days, with the resulting marked degradation of structural stability and consequent severe soil loss. During the second year of the U.S.D.A. study described above in Section 4.4, some of the plots were subjected to slash and burn using traditional local methods; soil losses from these plots totalled 51 Tm/Ha.
Fig. 9. Change of soil water repellency and water content with depth

Fig. 10. Measured pin erosion (-----) and losses sedimented from runoff (-----) on post-fire and control plots
Fig. 11. Rills in the lower part of the plot

Soil deposits in the lower part of the plot
BENITO, SOTO & DIAZ-FIERROS

Spring sowing of maize or potatoes, which removes plant cover during the months of April and May, leaves the soil vulnerable to erosion by heavy rains, which can create downfield rills (Fig. 11) carrying considerable quantities of soil (Fig. 12). Though there have as yet been no quantitative studies of this process, it appears that it is general on long slopes with a gradient of over 5%. Since field lengths have increased progressively as the result of the land ownership redistribution policy put into effect in Galicia since the 1960’s, it seems possible that steps may have to be taken to ensure that erosion control measures accompany redistribution in future.

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72
SOIL EROSION IN NW SPAIN


PROCESS INTERACTIONS AND BADLAND DEVELOPMENT IN SE SPAIN

A. CALVO-CASES (1), A. M. HARVEY (2) & J. PAYA-SERRANO (1)

(1) Departamento de Geografía, Universidad de Valencia. (2) Department of Geography, University of Liverpool

ABSTRACT
In the South-East of Spain badlands are frequent on softrock terrain. This paper studies badlands from different points of view. First, a map of the phenomena have been made for the area between Valencia and Almería. Secondly, we study geomorphic processes operating on badland surfaces, analyzing their interactions at different timescales, and the influence on the forms evolution.

RESUMEN
En el Sureste Español son frecuentes los abarrancamientos (Badlands) sobre litologías blandas. Este trabajo aborda su estudio desde varias perspectivas. Por una parte se ofrece una cartografía del fenómeno para la zona entre Valencia y Almería. Por otra parte se aborda el estudio de los procesos geomórficos que operan en las superficies de los badlands, analizando la interacción de estos en el tiempo, a diferentes escalas temporales, y su influencia en el modo de evolución de las formas.

Badlands are usually defined as zones of deeply dissected soft rock terrain with little or no vegetation on which rapid erosion, dominantly by surface processes, produces a rill and gully network of very high drainage density. Badland development may be initiated by the formation of small isolated linear gullies on hillslopes or valley floors, dissecting a previously stable surface. Gully extension, either from the base of the slope or in midslope progressively removes the former surfaces creating a landscape of partial badlands characterized by deep gully development into the hillslopes, but where the divides between individual gully systems are still intact. Further erosion removing all of the previous surface creates a landscape of total badlands.
Fig. 1. Distribution of badlands in SE spain
BADLAND DEVELOPMENT IN SE SPAIN

In this paper we examine the distribution of badland types in southeast Spain, and discuss how the processes on badland slopes progressively change during badland development. It is based on a synthesis of some of our previous work (HARVEY & CALVO, 1989; HARVEY & CALVO, in press; CALVO & HARVEY, in press) together with some new data.

In addition to the regional survey, four badland areas in the southeast have been studied in some detail, at Tabernas and Vera in Almeria, and at Monnegre and Petrer in Alicante (Figure 1). At Tabernas and Vera we have monitored the morphological development of badland surfaces over a ten year period (CALVO & HARVEY, in press), and in addition have carried out short term process studies, including rainfall simulation experiments (HARVEY, 1982; ALEXANDER & CALVO, 1990; CALVO et al, under review). At Monnegre and Petrer we have monitored the morphological development over a three-year period but at a more intensive scale (HARVEY & CALVO, in press) currently with work undertaken on short-term processes, including rainfall simulation (CALVO et al, under review). Other rainfall simulation and infiltration experiments have been undertaken at a number of other sites within the southeast (HARVEY, 1982; ALEXANDER & CALVO, 1990; CALVO et al, under review). Rainfall simulation experiments, have been carried out with the equipment described in CALVO et al (1988), morphological changes on selected plots have been recorded photographically and evaluated as it is described in HARVEY & CALVO (in press) and CALVO & HARVEY (in press).

1. The distribution of badlands

Badlands are particularly associated with dry climates (BRYAN & YAIR, 1982). In Spain they are well developed in the semiarid climates of the southeast. In a previous study (HARVEY & CALVO, 1989) we mapped their extent in the area between Valencia and Almeria, distinguishing between total and partial badlands, and linear gullies (Figure 1). We identified five sets of factor controlling the distribution. (i) Most important is the underlying lithology: easily erodible marls clays and shales are particularly prone to badland development. (ii) High available relief is important, allowing deep dissection of softrock terrain. (iii) These two factors are primarily controlled by Neogene tectonic patterns, with differences in style of badland development between the folded sediments of the Prebetic ranges and the uplifted sedimentary basins of the Betic ranges being partly due to different tectonic styles. (iv) Climate appears also to be important: in that badland development consistently greatest in the drier areas. (v) Partly dependent on the climate and partly on human activity, vegetation cover appears to be significant: badlands are common in areas of least vegetation cover, both at regional and at local, aspect-controlled scales.

These factors combine to produce a strong contrast between northern and southern parts of the region, with many large areas of total and partial badlands in Murcia and Almeria, but fewer and smaller badland zones in Alicante and Valencia. Furthermore we have identified areas which, though not characterized by badlands at present, on the basis of the controlling factors, could be susceptible to future badland
initiation. The implications are that badland development represents a continuum from initiation to the total badland stage. Badland location and rate of development are influenced by the factors outlined above.

As a major type of eroding slopes, badlands have an important role in the long term evolution of hillslopes. The total badland stage is unlikely to be the end product of badland erosion, in that continued erosion may ultimately lead to slope decline, reduction of eroding area, or to some other mechanism through which erosion rates decline allowing stabilization to take place. This may result in a slope and pediment hillslope system. Alternatively badland process are reactivated leading to a multiple-stage badland system.

2. Processes and process interactions

Although erosion on badlands surfaces may be dominated by overland flow processes (BRYAN & YAIR, 1982), many badlands show evidence for a variety of processes. Weathering processes include not only the primary breakdown of the underlaying material, but also swelling and shrinking and associated cracking, resulting both from wetting and drying and from chemical changes (IMeson & Verstraten, 1988). Where a thick weathering layer develops the material can be prone to mass movement (La Roca & Calvo, 1988). Surface processes resulting from overland flow include splash and wash on interrill areas as well as rill erosion in the rill network itself (Bryan, 1987). Where concentrated flow occurs below the surface piping may be important (e.g. Bryan & Yair, 1982).

In many cases more than one of these process groups my operate leading to complex process interactions (Harvey & Calvo, in press). Some of these vary spatially and some temporally, over timescales from the short term to the seasonal (e.g. Schumm, 1956; 1964) to the medium and long term. Longer term changes include both cyclic and progressive changes; the latter are of particular importance to the evolution of badland systems.

3. Temporal and spatial variations

3.1. Long term progressive changes

At Tabernas large areas of multiple-age complex badlands have evolved during and since the Quaternary, in the context of deep dissection induced by tectonic uplift, (Harvey, 1987). These badlands illustrate the long term progressive changes. These badlands are cut in Upper Miocene (Tortonian) turbidite marls, with local sandstone bands forming caprock escarpments.

Six evolutionary stages can be identified in the present morphology in some parts of the Tabernas badlands. The first three (A, B, C, Figure 2) are represented by
successive scarp retreat and pediment development and the younger three (D, E, F, Figure 2) by episodic dissection of the pediment surfaces along present drainage lines.

At each stage, slope recession appears to have taken place by badland processes, with stabilization of the pediment surfaces and basal slopes occurring as a result of their burial by coarse debris, modifying infiltration behavior (POESEN, 1986; POESEN et al., 1990), reducing erosion and stimulating vegetation colonization and soil development.

Stage A is represented by debris mantled triangular slope facets (SANCHO et al., 1988); stage B and C by extensive pediments. Stage B appears to grade into an extensive (late Pleistocene ?) fluvial terrace of the Rambla de Tabernas. Each phase of successive pediment dissection and renewed badland development appears to be base-level controlled and related to episodic incision by the Rambla de tabernas.

A different style of development follows the dissection of stage C whereby linear incision along the present drainage lines with only limited pediment development associated with only shallow incision. The causes of this change in evolutionary style
are uncertain, but appear to be related to base level changes and therefore represent a lagged response to differential rates of incision by the Rambla de Tabernas and its tributaries. This may be themselves governed by changes in the relative importance of long term, tectonically induced and climatically controlled stream and slope processes from late Pleistocene to Holocene times (HARVEY, 1987).

Tabernas is not the only site where Holocene linear development has replaced the Pleistocene pediment formation. All four study sites show evidence of deep Holocene incision below the late Pleistocene pediment or terrace surfaces. At Tabernas and Monnegre incision still appears to dominate badland development, but at Vera and Petrer Holocene incision has been followed by the recent development of pediments (CALVO & HARVEY, in press).

In the switch from a pediment dominated to a linear system at Tabernas between stages C and D (Fig. 2), the detailed controls of the stabilization mechanism have also changed. There has been a reduction in the availability of coarse debris derived from scarp retreat, restricting the amount of stone cover on the small incipient pediment slopes. There has been also an increase of the importance of fluvial dynamics as the result of variable rates of basal incision. With the development of north and south facing slopes, aspect has become an important local control of surface processes and influences stabilization through lichen and vegetation colonization (ALEXANDER & CALVO, 1990).

Figure 3. Runoff hydrographs and sediment concentration for rainfall simulation experiments at Tabernas
BADLAND DEVELOPMENT IN SE SPAIN

The influence of the stabilization processes on short-term erosional dynamics can be illustrated by reference to the results of rainfall simulation experiments (Figure 3). On bare, generally south-facing plots both runoff and especially erosion rates tend to be high (TA20). On plots with a stone cover or a lichen cover (TA34, TA13), preferentially developed on north-facing slopes (ALEXANDER & CALVO, 1990), erosion rates are reduced. On vegetated plots with a higher plant cover, in excess of c20% (TA50), both runoff and erosion rates tend to be reduced (CALVO et al., under review). Rates of erosion therefore appears to slow down with increasing stone, lichen or vegetation cover, thus accelerating stabilization. Furthermore there are indications of variations in the style of process, which may be partially aspect controlled, in that surface processes dominate on south-facing bare slopes, whereas a thicker regolith, locally prone to mass movement may develop on lichen covered or vegetated north-facing slopes (ALEXANDER & CALVO, 1990).

3.2. Medium term cyclic changes

At Vera on badlands cut in upper Miocene (Messinian) gypsiferous marls, a progressive change in the relative importance of various processes also seems to operate, with piping as a temporary phase in the medium to long term evolution of the badland slopes (HARVEY, 1982). Stages in this development exhibit strong aspect controlled spatial characteristics (see below). Even on south-facing slopes, where piping is no longer important, other process interactions illustrate medium term cyclic changes over timescales of several years to decades (CALVO & HARVEY, in press).

For a south facing slope at Vera the morphological changes have been recorded photographically between 1978 and 1988, usually in spring. The identification of processes (Figure 4) shows two complete sequences of destruction and regeneration of the rill network. These morphological changes relate to rainfall characteristics. Rill generation is important in the more humid period which started in 1986. The destruction of rills by swelling/shrinking and mass movement occurs during drier periods.

In addition to the climatic characteristics, intrinsic geomorphological factors also seem to be responsible for the morphological changes observed. A developed rill network produces instability in the inter-rill areas. This can produce slow mass movements, as a consequence of swelling/shrinking, that close the tributary rills and increase the surface roughness (Figure 4, from 1980 to 1982). After that, during a drier period with some storms, there were failures and the removal of regolith cover. The rill network had virtually disappeared in April 1983, but following rainfall that month had reappeared by May. During 1984 some increase in rill density occurred and surface roughness increased in a period with moderate rains and presumably changing soil moisture content. Heavy rains in 1985-86 produced mudflows that removed surface material and filled up the main rill bottoms. Subsequent rains (October 1986) started to generate new tributary rills and completed the sequence of morphological change.
Figure 4. Morphological changes at Vera site
BADLAND DEVELOPMENT IN SE SPAIN

The importance of regolith thickness in determining the style of process interactions is also well explained by the infiltration characteristics measured during rainfall simulation experiments (CALVO et al., under review). At Vera, plots with a deep regolith cover produce lower rates of runoff and high sediment concentrations, and plots with a reduced regolith cover have higher runoff rates with lower sediment concentrations. Under natural rains, on slopes with a deep regolith high infiltration rates would lead to mass movements, whereas slopes with a reduced regolith and low infiltration rates would have a tendency for rill generation.

3.3. Short term and seasonal changes

At Monnegre (Figure 1) badlands cut in Upper Cretaceous (Sennonian) marls exhibit process interactions in response to rainfall sequences which illustrate short term and seasonal changes (Figure 5). Longer term development is base-level controlled in response to deep Holocene incision of the Río Monnegre and its tributaries, creating temporal and spatial variable process interactions between piping and surface processes (HARVEY & CALVO, in press). In the short term these interactions are also variable in response to rainfall events and wetting and drying cycles.

From the eight plots studied there, we have selected three as representative of the different behavior. Morphological properties (Figure 5) have been evaluated from sequential photography taken at 2 or 3 months.

Monnegre 2-3 is located on a low gradient slope, with vertical pipes related to tension cracks and a thin regolith cover. The clarity and development of the rills vary inversely with piping. As the pipe inlets open, rills develop better. Surface roughness behavior shows a similar temporal change, but on this plot it is more closely related to erosional pinnacles and splash processes than to swelling/shrinking.

Monnegre 7 (Figure 5) represents conditions on steep slopes with rills and rill-pipes and a deeper regolith cover. The pattern of morphological change is sometimes opposite to that in plot 2-3. Rills and pipes are well developed during winter (after September-October rains), but are destroyed or reduced during the summer months by the higher swelling/shrinking rates, causing increases in surface roughness. Monnegre 8 (Figure 5) is at the base of Monnegre 7 slope, but on a lower gradient conditions and with a shallower regolith cover, this produces a smaller magnitude in the oscillations, but in a pattern similar to that in plot 7. High magnitude rains in 1989 produce a decrease of the regolith cover.

In Monnegre plots, seasonality is commanded by two groups of process interactions. Autumn and winter, if there are rains of some intensity, The dominant process seems to be rilling, controlled by piping, as the regulator of the base level. In contrast, with shorter amounts of rain, during the warmer months of the year, swelling/shrinking processes determine the morphology. This behavior is merely modified by the magnitude of the rainfall that in rainy years amplifies the seasonal pattern.
Figure 5. Morphological changes and rainfall at Monnegre plots.
BADLAND DEVELOPMENT IN SE SPAIN

3.4. Spatial variations

Badland surfaces may exhibit marked spatial as well as temporal variability in the processes and process interactions operating on them. This can be caused by (i) differential rates of long term progressive development, (ii) lack of synchronicity of cyclic changes, (iii) differential lag times to various climatic events and (iv) spatial variability in the factors affecting different processes. We have presented some evidence of this already, especially in relation to the experimental plots at Monnegre (see above). Two other cases, at Vera and Petrer, serve as examples of spatial variations effective over long and short timescales respectively.

At Vera (HARVEY, 1982), badlands developed on north, west and south-facing slopes exhibit contrasting morphologies which express different styles of process interaction, related to aspect differences in the rates of progressive development, (Fig. 6).

The north-facing slope is dissected only by isolated, discontinuous, shallow, linear gullies. The rest of the slope is fairly well vegetated. Depths of weathered regolith exceed 0.5 m and the soil surface carries a well developed lichen crust. Although runoff rates on this slope are fairly high (ALEXANDER & CALVO, 1990), sediment yield is low indicating that long term erosion rates are only slow. On the west-facing slope much less of the original surface remains intact, and the vegetation cover is less dense. Linear gullies are more closely spaced, deeper and are intimately related to a sub-surface pipe system. Pipe erosion is important and on collapse increases the gullied area at the expense of the non- gullied surface. Erosion rates on this slope are clearly higher than north-facing slope. On the south-facing slope all the original surface has been removed and the whole surface is subject to high rates of erosion, involving the cyclic interaction of rilling and mass movement described above. Here the simulated erosion rates are much higher (ALEXANDER & CALVO, 1990). The implication is that the erosional development of badlands on the south-facing slope has progressed further than on the north facing slope. The piping evident on the intermediate, west-facing slope, is merely a temporal phase in the long term progressive development of these badlands.

At Petrer, on the same lithology as Monnegre, the badlands studied are in a maximum aspect contrast. South facing slopes have a total badland development with no vegetation cover except in some parts, where a small stone cover has favored some vegetation development. North facing slopes are partial badlands systems, most of the surface is covered by plants on a well developed soil, but some of the slope toes are badland surfaces. The slopes are also dissected by linear gullies.

Plots 1 and 6 (Figure 7) are representative of different regolith thickness at the south facing slope, and plot 8 represents a pure badland surface on the north facing slope. In these three plots rilling is the dominant process, with some differences reflecting morphological position, degree of evolution and regolith characteristics. Plot 1 has a well developed dendritic rill network, and the other two are dominated by a parallel
Figure 6. Morphological map of the Vera Site
BADLAND DEVELOPMENT IN SE SPAIN

Figure 7. Morphological changes and rainfall at Petrer plots.
rill network. In all cases the rill network has been permanent since the beginning of the monitoring. Changes are only related to the small tributaries, that appear and disappear in response to swelling and shrinking sequences.

The style of temporal changes varies according to both regolith characteristics and aspect. On the south facing plots morphological changes occur with a high frequency according to the high number of drying and wetting cycles. Differences between plots 1 and 6 are related to material properties. The lower swelling capacity of the material in plot 6 results in morphological changes of a lower magnitude. On the north facing plot 8 the number of cycles of change decreases reflecting the persistence of soil moisture for a longer time after each rainfall event. This behavior contrasts, expressed in sequential photography, is also confirmed by the response of the plots to rainfall simulation experiments. Plots on the north and south facing slopes show a great contrast in both runoff and sediment production. Figure 8 shows the extreme conditions. In PT11, a north facing plot with thin regolith cover and dense network of very small cracks (equivalent to plot 8), infiltration capacity is very low and runoff is generated quickly. The network of small cracks closes only minutes after the runoff initiation and begins to work as a microrills system that increases erosion rates. In contrast, south facing plots like PT12 or PT13 have a thicker regolith cover with deep and wide crack systems that in some cases do not close during rainfall simulation experiments. As a consequence, in the south facing plots, infiltration capacity is very high and sediment concentration of runoff is also very high, although total soil loss during the experiment is low due to the lower runoff rates. Under natural rainstorms mass movements in the form of mudflows appear to be the most important process on such plots.

4. Conclusions

Badlands are widespread in southeast of Spain, but there is a contrast between the extreme southeast (Murcia and Almería), with large areas of total badlands, and the Levant region (Valencia-Alicante), characterized by small isolated badland areas.

On badland surfaces although overland flow related processes are the most efficient in removing material from slopes, swelling and shrinking related processes and mass movement have an important role.

Spatial and temporal variations in the interaction between these processes determine the style of slope. Changes on the evolution may relate to intrinsic processes, or in some cases, to extrinsic causes (e.g. tectonic or land use changes).

Spatially and in the short term, the style of the evolution is controlled by site characteristics and material properties. Some seasonal patterns can be found, but modified by the magnitude rainfall events.

In the medium term cyclic behavior is dependent on spatial factors. Controls vary in relation to morphology and to the balance between weathering and removal rates.
Finally, in the long term forms change absolutely with time. Ultimately stabilization mechanisms may cause the natural cessation of badland processes as a consequence of intrinsic mechanisms in the evolution of the system. Thresholds initiate renewed badland development. There may be intrinsic but in most cases are related to extrinsic causes (e.g. tectonic or Pleistocene/Holocene climatic control are responsible for the switch from pediment to linear development at Tabernas).

The variety of styles in the processes interactions along time implies that research on process and erosion rates on badland has to take into account the timescale. Short term must be put into the context of the long term progressive development. Also, the variety of styles of process interactions spatially and in medium timescale, implies that studies of erosion rates have to pay attention to the processes that are dominant at the time of study.

Acknowledgements

We are grateful to the Acciones Integradas /British Council Programme for a grant towards the costs of cooperative research. To the drawing office of the Department of Geography, University of Liverpool for assistance with the cartography. To Mario Payá and his family for their help in field work at Petrer and to the Comisión Interministerial de Ciencia y Tecnología for the financial support to the project NAT89-1072-C06-04.
References


LAND CONSERVATION AND HYDROLOGICAL STUDIES IN THE HIGH LLOBREGAT BASIN (BARCELONA)

F. GALLART

Institut de Ciències de la Terra Jaume Almera CSIC, 08080 Barcelona, Spain.

Since early 1981 a maintained research work has been devoted to the present-day geomorphic processes and hydrology of the headwaters of the Llobregat basin. The early research team was formed by J. Calvet, N. Clotet and F. Gallart in the Departament de Geomorfologia of the Universitat de Barcelona, but from late 1992 the team moved to the Institute of Geology (later Earth Sciences) Jaume Almera (CSIC). In September 1990 N. Clotet died in a traffic accident in the study area, but at this moment the team had grown enough to be able to continue the main research guidelines.

This research started with the scientific influences from L. Solé-Sabaris (Barcelona), J. Tricart (Strasbourg) and Polish geomorphologists (A. Kotarba, T. Gerlach, L. Starkel). Since 1984, the scientific relationships were enlarged with the help from M. Sala (Barcelona) who introduced the team to the Commission on Field Experiments (later Comm. on Measurement, Theory and Application in Geomorphology), I.G.U.

1. Main Characteristics of the study area

The high Llobregat basin has an area of nearly 500 Km2, with elevations between 2 500 and 600 m a.s.l., and lies in the Eastern Pyrenees, 120 km to the north of Barcelona.

The climate of this area is of montane Mediterranean type, the mean annual temperature is about 10° with minima of -20° and maxima of 30°. The annual precipitation varies between 800 and nearly 1 500, with two main rainy seasons in autumn and spring, and with a secondary peak in late summer which corresponds to
convective short-lived but very intense downpours. Snow falls on about 22 days at year, and frost occurs on about 100 days per year.

The geology is complex because this basin is located along the eastern margin of the allochthonous tectonics units of the Prepyrenees, in contact with the autochthonous northern (Axial zone and its cover) and southern (Ebro Depression) units. The main peaks are on limestones, while nonmarine mudstones and marine marls, with gentler slopes, outcrop in valleys and depressions. The nonmarine smectite-rich mudstones of the late Cretaceous (Garumnian facies), and the flyschoid grey marine marls of the Eocene are the lithologic units which show the most active geomorphic processes.

On account of the mountainous character of the basin, the population density is low. This was formerly one of the areas with more scattered rural population in Catalonia; late in the last century the growth in industrial activity resulted in an early but selective abandonment of traditional land uses. Only the mining and industry activities counteract the depopulation tendency. Deforestation for agricultural or underground coal mining activities in the past and surface mining in the present, are the main human activities which modify the natural geomorphic processes, and which seem to be among the main factors for the degraded areas and the sediment supply. (For a wider description see 24).

2. Main research items and works

The preliminary works dealt with Geomorphologic mapping, Quaternary evolution and application of the geomorphic maps. This work showed mainly the relevance of mass movements of diverse sizes and ages in the Garumnian mudrocks, and the evidence of Pleistocene glaciers in the area (6,16,17).

The main work on present-day geomorphic processes was made in order to know what were the main aspects of sediment response of the basin: to characterize the geomorphic activity of the different sub-basins and lithologic units, to identify the sediment sources, to assess the sediment yielded from them, and to estimate a first approach of the sediment budget of the whole basin. Some of the methods used were an analysis of the drainage net and some detailed studies on the erosion rates in selected areas (badland areas and surface coal mines, both on Garumnian mudrocks) (see 5, 10, 11, 13, 14, 22).

During this work the basin suffered the extreme rainfall event of November 1982, which produced 912 landslides of different kinds, 939 small failures of slopes of agricultural terraces, and relevant changes in the main drainage net. This event deserved a special study, which showed, among other results, a good relationship between rainfall amounts and landslide occurrence, that all the big mass movements took place in old unstable sites, and the uncertain role of trees in triggering landslides (7, 8, 9, 18, 20, 21, 23).
The last work within this first period, characterized by the scarcity of instrumentation, was the sediment budget for the Vallcebre basin (18 km²), which offered also a medium term erosion rate for badland areas on Garumnian mudrocks (1, 2, 12).

In 1988 the present period started with two main research projects which deal respectively with the analysis of the whole High Llobregat basin and the small basin of Cal Parisa, located within the sub-basin of Vallcebre.

The aim of the first project, leaded first by N. Clotet and by L. Solé after her decease, was to study the badland areas in relation to the different aspects of the environment of the basin (lithology, climate, geomorphology, vegetation, landuse) and their hydrological and sediment behaviour and contribution (3, 4, 25, 29).

The second project, lead by the author, was concerned with the hydrological and sediment response of a small basin on Garumnian mudstones, free of badlands but representative of areas strongly modified by farming in the past and recently abandoned; prediction of future behaviour being the long term purpose (26, 27, 28, 31).

Since 1990 a new project deals with the processes and evolution of badlands, to be compared with badlands from other eastern Spanish locations (Almería, Murcia, Valencia, Jaca). This project was designed and started by N. Clotet and now continued by the author.

A schedule of the main research items and researchers involved is presented on the adjacent table.

Acknowledgements

The present paper is dedicated to the memory of Nuria Clotet, who started and made possible the present state of research work presented here.

Funding for this work has been obtained from several institutions: Omnium Cultural, a private association, as well as CIRIT and the Servei Geològic de Catalunya, both depending on the Generalitat de Catalunya, and a Research Project of the CSIC financed the first studies. The LUCDEME project (Fight against desertification of the Mediterranean) of ICONA, by the agreement CSIC-ICONA, funds the main research projects since 1988, which afforded most of the instrumentation. Fellowships from the Departament d'Ensenyament of the Generalitat de Catalunya and the Ministerio de Educación y Ciencia finance some of the Ph. D. works. Funding from the Programa Nacional de Conservación del Patrimonio Natural, CICYT (Project NAT89-1072-C06-01) is supporting the work since May, 1990.
<table>
<thead>
<tr>
<th>period</th>
<th>researchers</th>
<th>main research item</th>
<th>relevant papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981-84</td>
<td>N. Clotet, J. Calvet, F. Gallart</td>
<td>detection and assessment of sediment sources.</td>
<td>5, 6, 10, 11, 13, 14, 22, 24, 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>geomorphic consequences</td>
<td>7, 8, 9, 18, 20, 21, 23</td>
</tr>
<tr>
<td>1986-87</td>
<td>C. Balasch, N. Clotet, F. Gallart</td>
<td>geomorphological sediment budget</td>
<td>1, 2, 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vallcebre Basin (20 Km²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vegetation: abandoned fields and badlands</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>P. Llorens, F. Gallart</td>
<td>Climate and precipitation</td>
<td>29</td>
</tr>
<tr>
<td>1989</td>
<td>C. Llasat (2), J. Martin (3), D. Sempere, R. Solé (2)</td>
<td>Soil and sediment characteristics and relationships with geomorphic processes.</td>
<td>31</td>
</tr>
</tbody>
</table>
1990
C. Balasch
X. Castelltort
D. Sempere
P. Llorens
F. Gallart

1: Dep. de Botànica, Universitat de Barcelona.
2: Dep. Astronomia i Meteorologia, Universitat de Barcelona.
3: Dep. Geografia Física, Universitat de Barcelona.
4: Estación Experimental de Zonas Aridas, CSIC, Almería.
5: Esc. Superior Agricultura de Barcelona.

References


95


EROSION IN ABANDONED FIELDS, WHAT IS THE PROBLEM?

José M. GARCIA-RUIZ (1), Purificación RUIZ-FLAÑO (1),
Teodoro LASANTA (1), Gabriel MONTSERRAT (1),
Juan P. MARTINEZ-RICA (1), Giovanni PARDINI (2)

(1) Instituto Pirenaico de Ecología (C.S.I.C.), Zaragoza, Spain.
(2) Institut Jaume Almera de Ciencias de la Tierra (C.S.I.C.), Barcelona, Spain.

ABSTRACT
Abandoned fields constitute a very important part of the landscape in the middle mountains of the Central Spanish Pyrenees, mainly in sunny hillsides. In such areas a great heterogeneity exists from a biogeographical and geomorphological point of view: some abandoned fields show dense scrub cover and a very limited sediment yield, but in other cases soil has been almost completely eroded, with prevailing severe sheet wash erosion, rills, stone pavement and stone flows. The age of abandonment and the shape of the hillslope control this heterogeneity to a great extent. The available information -both from experimental plots and geomorphic transects- allows us to distinguish two different ways of evolution: If plant succession is not interrupted by fires or overgrazing, then scrub cover communities protect the soil and no-erosion areas prevail on the slope. But if plant colonization is periodically disturbed, then the open scrub cover is not able to prevent sheet wash erosion and undermining. The last stage of this evolution is the predominance of stone pavement, when sediment yield logically decreases. Stones are very difficult to move in interrill areas.

Key-words: land abandonment, plant colonization, erosion, sediment yield, Pyrenees.

RESUMEN
El Pirineo Central español, como otras regiones de montaña, ha experimentado una fuerte contracción de la superficie cultivada durante el siglo XX. Con el fin de asegurar el abastecimiento alimentario de la población local, la mayoría de las laderas solanas situadas por debajo de 1.600 m.s.n.m. fueron roturadas, convertidas en campos pendientes o abancalados y cultivadas con cereales, a veces en condiciones topográficas muy difíciles. El descenso de la presión demográfica desde finales del siglo XIX y el cambio de las relaciones de mercado explican el progresivo abandono de las laderas más pendientes y de los sectores
Land abandonment has been the most outstanding geocological characteristic in Spanish mountainous areas during the 20th Century. This phenomenon involves changes in the landscape physionomy and dynamics, and changes in the spatial organization of land-uses. In mountains the process of abandonment has almost stopped since 1970-75, owing to the intense depopulation that took place between 1940 and 1970. At present, only the best plots -those with deep soil in flat and accessible areas- are cultivated. But the problem has been recently transferred to other marginal lands: The European Community encourages the abandonment of the less productive plots in the poor and semiarid areas of Spain. Many fields will be abandoned in the near future and the ecological and geomorphological consequences of this generalized process are not well known.

What happens in an abandoned field? After many years of cultivation, an abandoned field is a natural, uncommonly complex laboratory, in which three factors act together:

a) On one hand, plant colonization takes place in successive stages. The features of plant colonization depend not only on the general climatic context, but also on the quality of the soils.

b) Secondly, upon the abandoned plot, which is scarcely protected by plant cover at the beginning, several geomorphic processes whose intensity and frequency vary over time occur, depending on the characteristics of plant colonization and on soil erodibility.

c) Finally, abandoned fields, though they are not cultivated, still continue to be integrated in the general spatial organization of mountainous areas. Normally, hillslopes with abandoned fields are grazed by sheep. Grazing management has a great deal of influence on plant colonization and also, therefore, on the hydromorphological
ABANDONED FIELDS

functioning of the soils. The conclusion is that abandoned areas enter into new
dynamics controlled by the predominant land-uses before and after the abandonment, and
by the characteristics of plant colonization, both factors explaining the temporal and
spatial variability of sediment yield.

In mountain areas, cultivation of marginal steep slopes has a negative effect on
soil conservation (see, for example, IVES, 1985), which is sometimes countered by
means of the construction of bench terraces and of complex drainage systems. In
sloping, non-terracing fields, one could expect that the abandonment would mean a
decrease in sediment outputs: both the volume of precipitations as well as, in general,
soil characterisatics encourage a quick plant colonization and a restoration of natural
conditions (see also the results obtained by FRANCIS, 1986, in SE Spain). Nevertheless, many plots, abandoned several years ago, show high soil losses and the
old cultivated areas show a great geomorphological heterogeneity. What is the problem?

Since 1987 a research team of the Instituto Pirenaico de Ecología (Pyrenean
Institute of Ecology), Zaragoza, and of the Instituto Jaume Almera de Ciencias de la
Tierra , Barcelona, has been studying the evolution that mountain abandoned areas
undergo. The basic question is: why do some plots appear extremely degraded and
others, on the other hand, are well protected by plant cover and in advanced stages of
plant succession? But there are also other questions: What are the processes that act in
the abandoned fields and what is their spatial and temporal variability? How is the
interrelation between plant colonization and erosion expressed? What are the thresholds
in soil quality and in land-uses that block or encourage plant succession? What is the
role of land-uses?

In the following pages the authors present the methodological scheme they are
using and some of the results obtained. These partially answer the previous questions
and confirm the complexity of a phenomenon situated in the interphase between both
physical and human processes.

1. The study area

The study is performed in the domaine of the Southern-Pyrenean eocen flysch,
which is very homogeneous from a topographical and lithological point of view. In this
area some of the most important Pyrenean villages are located, and a great part of the
hillslopes have been deforested and cultivated in the past. Relief is characterized by
smooth divides and regularized versants (between 20 and 40 %). Mass movements
(slumps and debris flows) and ravines have a great capacity to carry sediments as for as
the rivers, which show the typical braided pattern (GARCIA-RUIZ &
PUIGDELABREGAS, 1982; GARCIA RUIZ et al, 1988).

This region enjoys a Mediterranean mountain climate, somewhat continentalized, with annual rainfalls ranging from 800 to more than 2,000 mm in the
highest parts. Precipitations are concentrated mainly in spring and winter, with
relatively dry summers. However, the most intense rainstorms fall in Autumn.
Pinus sylvestris woods dominate the northern exposures, while in the sunny ones abandoned fields alternate with small Quercus gr. faginea woods and with submediterranean bushes (Buxus sempervirens, Genista scorpius, Echinospartum horridum, Rosa gr. canina and Juniperus oxycedrus).

In the old cultivated areas, shallow brown, loamy soils prevail, with high stoniness on the surface. They are poor in organic matter (less than 1.5 %) and in nutrients, rich in carbonates (30-40 %) and with a pH between 8 and 8.5. The high content of carbonates plays an important role because, on one hand, it tends to prevent the clay dispersion and, on the other hand, it contributes to the structural stability by
means of recrystallizations under the form of micritic cement. The stability of aggregates, tested by the drop test, has produced satisfactory results.

2. Methods

First of all, a delimitation of the areas of abandoned fields was carried out in several Pyrencean valleys, with the aim of finding out the extent of the problem and to study in detail the process of abandonment. From the aerial photographs of 1956 and 1981 different patterns of plots were distinguished, in such a manner that we know the more important stages of abandonment and the changes in land-use. Parallely, information about the systems of soil conservation and about the livestock management systems was obtained.

Afterwards, the study concentrated on three groups of problems: geomorphic functioning, soil characteristics and plant colonization. By means of geomorphic transects (see RUIZ FLANO et al., 1990 and in press) the relative importance of geomorphic processes and their variability according to the age of abandonment and the shape of the hillslope (concave, convex and straight) was discovered. Different geomorphic micro-environments, whose capacity to yield water and sediments was controlled by means of small plots, were defined with the transects. The mobility of stones was studied in rills (with small sediment traps) as well as in interrill areas (with signs of paint in stones of different sizes). Also detailed geomorphological maps at a scale of 1: 125) were elaborated in several selected plots, with the aim of studying the spatial organization of geomorphic processes and the neighbouring relationships established between them.

The study of soils included grain size analysis, nutrient content, porosity and stability of aggregates. Fortnightly, soil samples were taken in 13 plots to study the seasonal variability of the water reserve. The capacity and velocity of infiltration was measured by means of different rain-simulator tests, that allowed us to complete the available information on sediment and water yield.

Plant colonization was studied by means of plant relevés in plots of different age of abandonment. At the same time, both in the field and in the laboratory, tests of seed dispersion and germination were carried out, especially of Genista scorpius, the most widespread plant in abandoned fields.

Previous information -a part of which has been already recorded and elaborated- must serve to establish hydrological patterns.

3. The process of abandonment and the posterior land-uses

In the valleys of the Central Pyrenees the maximum cultivated surface under 1,600 m a.s.l. was at least 28 % (LASANTA, 1988 and 1989), sometimes in very difficult topographical conditions. In the Aísa Valley the main frequency of cultivation was on slopes of between 20 and 40 %, especially between 1.000 and 1.200 m a.s.l. in
sunny exposures. The majority of the fields were sloping fields -only very few were true bench terraces- and some were integrated into a nomadic agriculture. The maximal extent of the cultivated space was probably reached in the middle of the XIXth Century, coinciding with the moment of greatest demographic density. Since then a process of land abandonment has taken place, affecting first the steepest slopes, on straight and convex, sunny slopes and, posteriorly, to other flatter, more unaccesible plots (LASANTA, 1988; GARCIA-RUIZ & LASANTA, 1990). In 1957, 63 % of the cultivated space had already been abandoned. At present farming represents less than 3 % of the majority of the Pyrenean valleys.

Once abandoned, these fields were grazed by sheep and, therefore, they are perceived as forming part of the livestock space. In these conditions the progress of plant colonization and the massive growth of spiny bushes are perceived as negative facts, that reduce the profitable surface. This is why fire has been used frequently to interrupt plant succession and to allow the sprouting of young grass in spring. This phenomenon, well known in Pyrenean land-uses, is confirmed by the presence of abundant ashes in the edaphic profile.

Nevertheless, two sources of heterogeneity in the use of fire exist:

- When the first plots were abandoned (at the end of the XIXth and at the beginning of the XXth centuries) demographic pressure was still very strong. Many flocks grazed in the abandoned fields, which were burnt frequently. After 1960 the number of flocks greatly diminished and the use of fire was less necessary and even forbidden. The consequence is that in the last 20 years abandoned fields have suffered very few or even no fires.

- The grazing system is now completely individual and each stock-farmer carries its sheep flock to his own abandoned fields only. This system explain why some fields have suffered a strong livestock pressure and have been burnt frequently, whilst others -those belonging to owners that have migrated from the valley- have had a normal plant succession and account for a dense scrub cover. In some cases this diversity is explained also by the greater or lesser proximity to villages, since in the last 30 years the least accessible abandoned fields are almost no used as grazing land.

4. Some features of the plant colonization

Plant colonization in abandoned fields is a process of secondary succession upon fairly unfertile, almost without plant cover soils. Plant colonization is very quick, mainly for annual plants (weeds). Many of them have easily scattered seeds, which are able to resist for a long time in the seed-bank of the soil. Shortly after abandonment some biennial plants appear, at the same time as others of longer life. After 10-15 years a generalized expansion of Genista scorpius is produced, practically colonizing the whole surface. Afterwards some shrubs penetrate, such as Buxus sempervirens , Rosa gr. canina and Juniperus communis . After 50 years of abandonment, Genista scorpius enter in a regressive stage, whilst Buxus sempervirens occupy more and more of the
ABANDONED FIELDS

surface. With more than 100 years of abandonment, plots have junipers and pines, next to thorny shrubs such as *Prunus spinosa* and *Crataegus monogyna*, with the first oaks (*Quercus gr. faginea*) finally appearing.

The previous scheme advances in more or less rapid stages, according to soil quality and to land-uses. If the plot is frequently grazed or burnt, the progression towards mature stages of plant succession is very slow and even occasional regressions are produced, with soil losses that restrain the recuperation capacity of natural plants. Precisely the soil poverty (lacking nutrients, especially Nitrogen) and the use of fire explain the great importance that *Genista scorpius* reaches, resprouting easily after a fire.

5. Temporal and spatial variability of geomorphic processes in abandoned fields

By means of 75 geomorphic transects the presence and frequency of different geomorphic microenvironments were discovered (see RUIZ-FLAÑO et al., 1991). The areas with severe sheet wash erosion appear in the largest proportion (over 28.5%), followed by areas with mild sheet wash erosion (20.4%), accumulations (small deposits located uphill bushes), areas of no-erosion, rills, small mass movements (including tongue-shaped landforms, scars and creeping) and stone flows and stone pavement. This means that the processes of unconcentrated overland flow represent the most extensive geomorphological activity, because accumulation processes also detect the presence of sheet wash erosion.

The distribution of geomorphic microenvironments is greatly conditioned by the age of abandonment. Table 1 shows that the plots of more recent abandonment are fundamentally affected by sheet wash erosion (almost 95%). But as the age of abandonment increases, so the importance of accumulations (that pass from 0.7 to 30%), rills and stone flows enlarges. Sheet wash erosion progressively loses importance (21% in the more than 50 years old fields) and areas of no erosion increase their extent, though in an irregular manner. Plant colonization explains a part of this evolution: Once abandoned, the plots have sparse herbaceous cover, favouring the predominance of sheet wash erosion processes. As scrub cover penetrates, the presence of sheet wash erosion decreases and moderate or no-erosion increases; at the same time accumulations enlarge, as they are closely related to bushes. In a recent paper, RUIZ-FLAÑO et al. (1990) point out that the mean length of each microenvironment suggests that erosion processes settle upon a base in which initially erosion hardly acts: such base will diminish in extent as the deterioration of the plot advances, but it will always constitute continuous patches more widespread than those occupied by other microenvironments.

In view of Table 1, it seems evident that as the years go by a process of deterioration of abandoned fields takes place, as the increasing presence of rills and stone flows proves. From that one can deduce that the abandonment of cultivated areas is a very negative phenomenon for soil conservation, but this is a very simple conclusion.
GARCIA RUIZ et al.

Table 1. Presence of geomorphic environments (%) in abandoned fields, according to the age of abandonment

<table>
<thead>
<tr>
<th>Age of abandonment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10 years</td>
<td>1.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7</td>
<td>60.0</td>
<td>34.3</td>
<td>3.5</td>
</tr>
<tr>
<td>10-25 years</td>
<td>4.1</td>
<td>1.8</td>
<td>9.4</td>
<td>11.9</td>
<td>19.9</td>
<td>36.1</td>
<td>16.5</td>
</tr>
<tr>
<td>25-50 years</td>
<td>7.7</td>
<td>3.0</td>
<td>2.6</td>
<td>19.2</td>
<td>29.6</td>
<td>16.2</td>
<td>21.4</td>
</tr>
<tr>
<td>&gt; 50 years</td>
<td>13.6</td>
<td>8.1</td>
<td>7.7</td>
<td>30.0</td>
<td>15.2</td>
<td>5.6</td>
<td>19.4</td>
</tr>
</tbody>
</table>


The shape of the hillslope has also a great importance in explaining the distribution of geomorphic microenvironments. Convex hillslopes have the greatest proportion of rills, mass movements and stone flows. Straight and concave hillslopes show a higher predominance of sheet wash erosion, while no-erosion areas are only important on the concave hillside.

6. Sediment yield in abandoned fields

In order to obtain comparable information about water and sediment yield in different geomorphic microenvironments, 19 small plots (2.5-3.5 sq. meters) were installed, 3 with no-erosion (dense shrub cover), 6 with mild sheet wash erosion (meadows and more open bushes), 4 with severe sheet wash erosion, 3 with stone pavement and 3 with undermining. The transport capacity of rills was studied by means of sediment traps. The control of the plots has been followed since April, 1, 1990, with some precipitations of heavy intensity: 80 litres in October, 22, and 93 litres in October, 30.

Runoff coefficient ranges between 0 and 75 %. The majority of coefficients are lower than 15 %. Sediment concentration, in mg.l⁻¹ has also a great variability, from less than 10 to more than 60.000. Tables 2 and 3 include information about runoff coefficients and sediment concentration in the different micro-morphological patterns.

The greatest runoff is yielded in the plots with severe sheet wash erosion (19 %), and with undermining (18 %). In the first case plant cover is very poor, whilst in the second one, though plant cover is quite dense, the microtopography encourages runoff concentration, which tends to erode the margins of the sectors occupied by bushes. The lowest runoff is yielded in the no-erosion plots.

Sediment concentration shows a similar trend. The lowest figures are recorded in the no-erosion plots, followed at a great distance by plots of mild sheet wash erosion, stone pavement, severe sheet wash erosion and undermining. If the results are analyzed in soil loss per square meter during the studied period, the no-erosion plots show remarkably moderate behaviour, with losses close to 50.5 gr. m⁻². Plots with
ABANDONED FIELDS

Mild sheet wash erosion have yielded 663 gr.m\(^{-2}\), that is, about 12 times more. Plots with stone pavement have yielded 1,400 gr.m\(^{-2}\), that is, 28 times more. Plots with severe sheet wash erosion have lost around 3,800 gr.m\(^{-2}\). And finally, plots with undermining have exported a figure close to 4,600 gr.m\(^{-2}\).

Table 2. Runoff coefficients in different geomorphic micro-environments of the abandoned fields. Signification level is 0.0

<table>
<thead>
<tr>
<th>Geomorphic microenvironment</th>
<th>Runoff coefficient</th>
<th>Standard deviation</th>
<th>Monitored cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>No erosion</td>
<td>1.51</td>
<td>5.32</td>
<td>83</td>
</tr>
<tr>
<td>Mild sheet wash erosion</td>
<td>11.94</td>
<td>16.71</td>
<td>153</td>
</tr>
<tr>
<td>Severe sheet wash erosion</td>
<td>19.00</td>
<td>15.06</td>
<td>118</td>
</tr>
<tr>
<td>Stone pavement</td>
<td>7.73</td>
<td>10.83</td>
<td>82</td>
</tr>
<tr>
<td>Plots with undermining</td>
<td>18.04</td>
<td>21.48</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 3. ANOVA of sediment concentration (mg.l\(^{-1}\)) in runoff yielded by different geomorphic microenvironments of abandoned fields. Signification level is 0.002

<table>
<thead>
<tr>
<th>Geomorphic microenvironment</th>
<th>Sediment concentration mg.l(^{-1})</th>
<th>Standard deviation</th>
<th>Monitored cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>No erosion</td>
<td>1.66</td>
<td>1.92</td>
<td>83</td>
</tr>
<tr>
<td>Mild sheet wash erosion</td>
<td>3.00</td>
<td>5.79</td>
<td>153</td>
</tr>
<tr>
<td>Severe sheet wash erosion</td>
<td>3.99</td>
<td>4.17</td>
<td>118</td>
</tr>
<tr>
<td>Stone pavement</td>
<td>3.71</td>
<td>5.24</td>
<td>82</td>
</tr>
<tr>
<td>Plots with undermining</td>
<td>4.28</td>
<td>5.51</td>
<td>88</td>
</tr>
</tbody>
</table>

It is evident that the different processes - all of them related to plant cover density and to stoniness - explain the differences in water and sediment yield. With little stoniness, deep soil and dense plant cover the main part of rainstorms remain controlled by the plot itself. The importance of plant cover is so great that a small decrease in its density (passing, for example from 100% to 90 or 95%) is quite enough for sheet wash erosion to act and for the sediment yield to multiply by twelve.

Plots with severe sheet wash erosion and with undermining represent a very advanced stage of deterioration, in which the presence of soil - above all in the undermining- produces high sediment yields recordings. On the other hand, stone pavement constitutes the final stage: the bedrock appears covered by stones, avoiding the direct impact of raindrops on the soil and favouring infiltration (POESEN et al., 1990; POESEN, 1990), thus decreasing the sediment yield owing to the exhaustion of the sediment source.
7. Rills and stone movement in abandoned fields

Some features of the behaviour of interrill areas have been controlled by means of microplots. But rills have been worked in a special manner, because they represent a very advanced stage in the deterioration of abandoned fields and because they have a greater capacity to carry out sediments. Their study was carried out by means of detailed geomorphological maps to observe the characteristics of the drainage network and by means of three small sediment traps located in a plot abandoned 80 years ago.

Geomorphological maps show that incisions start at a short distance from the upper part of the plot. They have little sinuosity and are hardly integrated. In many cases in the middle-lowest part of the plots, incisions either disappear—sometimes substituted by stone flows— or they undergo diffusions, with flow loss. The rill network structure proves that this is still an immature, little organized system. The sizes of the channels are not related to the distance or to the surface of the basins, demonstrating intermediate losses of discharge. The lack of organization of the system is due surely to the important role that scrub plays in the structure of overland flow and to the high stoniness. The substitution of rills by stone flows shows the progressive loss of transport capacity in the last stretch and is explained because scrub contributes to the dispersal of the water flows and to slowing them down (RUIZ-FLAÑO & GARCIA-RUIZ, 1990).

According to the available information, the displacement of stones in abandoned fields is only possible in the rills. In interrill areas painted stones of different sizes have been located, but no movement has been recorded, even during heavy rainstorms. In the rills, stones have reached the sediment trap during intense storm events, in wet periods with saturated soil. The weight of the stones displaced keeps a very close relation to the size of the basin, that is, to the discharge. In all cases it has been proved that the volume of coarse sediments (more than 2 mm Ø) has little importance in carried sediments as a whole (sometimes, less than 5 %) in comparison to suspended sediments. These results prove that the rills of abandoned fields constitute very limited systems for moving coarse material, even of small size (RUIZ-FLAÑO & GARCIA-RUIZ, 1990).

8. Conclusions

The studies realized up to now show that the environment of abandoned fields in Central Pyrenees have, in general, acceptable conditions for quick plant recovering. The soils, though quite eroded, show a remarkable resistance to raindrops splash; the annual volume of precipitations is quite enough—more than 800 mm in the study area—to allow a quick plant succession towards mature stages; and the erosivity of rainstorms is much lesser than in other Spanish regions (see for example, DAVY, 1978).

Nevertheless, in spite of these favourable conditions, one can find a great heterogeneity in the landscape. Some plots have a very dense plant cover and suffer extraordinarily low erosion taxes. But many other plots show a great degradation, with
ABANDONED FIELDS

great soil losses, stoniness in surface, very active geomorphic processes and an open, degraded submediterranean scrub cover. The reasons for this heterogeneity are complex, but at the bottom of the problem is human management. Fields abandoned more than 100 years ago endured a heavy livestock pressure and were probably -as it has been demonstrated in many cases- burnt several times to interrupt the plant succession towards a spiny shrub. On the other hand, other fields, abandoned posteriorly, were able to develop a normal succession, hardly influenced by livestock or by fire.

Human management is of great importance in the evolution of abandoned fields, because in controlling plant structure and density, it also controls water and sediment yield. Plots with a dense scrub cover have a very moderate hydromorphological functioning and their erosion taxes show that they are in a constructive stage, towards more mature stages. This fact is very important since it shows that when bushes cover the whole plot it is not necessary to reforest to reduce soil losses (see also FRANCIS & THORNES, 1990).

When plant cover is more cleared, different processes act in the plot, ranging from mild sheet wash erosion to rill and stone flows formation and stone pavement, that represent the most advanced stage of degradation. The available information allows us to conclude that the greatest soil losses are produced when severe sheet wash erosion and undermminings prevail. Afterwards, once most of the soil has been eroded, sediment output diminishes, as in the case of the plots with stone pavement.

Probably, if plant succession is frequently interrupted and if, moreover, there is a strong livestock pressure, soil losses reduce the productive potential and plant cover recuperates with difficulties, until a threshold is reached from which the destructive processes are more important than the constructive ones: That is the moment in which the greatest erosion taxes are yielded (severe sheet wash erosion and undermminings), with a progressive increase in stoniness. All the results point the same way: the process of field abandonment in mountain areas is only negative depending on the human management system. The problem is surely different in semiarid environments, with scarce and irregular, much more erosive precipitations, and with very poor soils, making plant colonization difficult.

Acknowledgements

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GARCIA RUIZ et al.


CHANNEL DEGRADATION AS A RESPONSE TO EROSION CONTROL WORKS: A CASE STUDY

A. GOMEZ-VILLAR (1) & R. MARTINEZ-CASTROVIEJO (2)

(1) Departamento de Geografía. Colegio Universitario de La Rioja. 26001-Logroño, Spain
(2) Instituto Pirenaico de Ecología, CSIC, Apartado 202, 50080-Zaragoza

ABSTRACT
This paper shows some geomorphological effects on the fluvial system triggered by erosion control works. Several basins draining the eocen flysch band in the Central Pyrenees have been selected. The authors emphasize the effects on braided channels and the alluvial fans originated at the outlet of three of the basins. The observations prove that the decrease in sediment supply promoted by afforestation and check dams has caused degradation of the channel. Such an effect means the recover of the equilibrium in the balance sediment availability/stream power. The degrading state is revealed by two processes very active nowadays: incision and lateral migration of the channel. Ultimately, these processes imply the securing of deposits now available for plant colonization. In turn, this provides greater stability to the system.

Keywords: channel degradation, alluvial fan degradation, erosion control, Central Pyrenees.

RESUMEN
El presente trabajo muesta algunos efectos geomorfológicos que sobre el sistema fluvial han desencadenado ciertas actuaciones destinadas al control de la erosión. Para ello se han seleccionado varias cuencas inscritas en la banda de flysch eoceno surpirenico, área especialmente afectada por cursos de carácter torrencial. Los autores destacan aquellos efectos ocasionados sobre canales de modelo trenzado y sobre abanicos aluviales formados a la salida de tres de las cuencas. Se comprueba que el descenso de los aportes sedimentarios provocado por las re poblaciónes forestales y los diques de retención ha iniciado una fase generalizada de degradación en los canales dirigida a la restauración del equilibrio en el balance disponibilidad de sedimentos/capacidad de transporte. Ello se manifiesta en dos procesos muy activos en nuestros días: incisión y migración lateral del canal. En última instancia, estos
River channels are the result of the different processes (hydrological and geomorphological) occurring in their basins. Thus, the morphology and stage of any given river keep a close relationship with the necessity to evacuate water and sediments produced in the basin. The way in which such equilibrium is maintained contains a set of mechanisms that ultimately establish the river state. If stable, channel has adjusted slope and morphology in order to get the best equilibrium of the balance sediment supply/stream power. If not, the former equilibrium is unbalanced towards one of the extremes; so, channel erodes bed and banks (greater stream power than that required to transport the sediment load coming from slopes and upstream) or deposits the excess of sediment load (larger sediment supply than the available stream power). These processes are known as degradation and aggradation, respectively.

Time scale plays an important role in river state, in such a way that one river in equilibrium may degrade or aggrade throughout several years without altering the general balance (dynamic equilibrium, SCHUMM, 1977). The reason is the non-uniform character of sediment supply and sediment transport. Man-induced changes in the conditions of the basin also promote these adjustments. The time required by the fluvial system to recover the balance is still unknown and it depends on many variables. In the same way, it is very difficult to state river conditions through short periods of survey, especially in mountain rivers where most of the morphological work is made in a few number of events. However, changes in structural factors of the basin (e.g. vegetation cover) trigger rapid responses of the channel. This paper deals with mountain rivers whose basins have been afforested in the last 40 years; our aim is to look for some evidences of the channel adjustments promoted by human erosion control activities.

1. Study area

The rivers Ijuez and Aurin and the alluvial fans of Escuer, Oros and Olivan are in the eocen flysch band that extends on the south side of the Sierras Interiores, Central Pyrenees (Fig. 1). Marls and sandstones alternate in very tight layers, which encouraged the formation of folds and fractures by means a very active tectonics throughout the Cenozoic Period. Such a complex structure ranges between 900 and 2000 m a.s.l. The weak cohesion of the material has caused a large number of erosion processes to take place, so sediment yield is very high. This results in braided rivers at the bottom of the main valleys. On the slopes, three levels can be found (MARTINEZ CASTROVIEJO et al, 1990):

a) Above tree line slopes, with active headwaters, solifluction lobes and slides on deep soils; locally, gully systems occur.
CHANNEL DEGRADATION

Fig. 1. Study area

b) Pine wood slopes, dominated by infiltration and soil creep.
c) Submediterranean slopes, very altered by human activities (abandoned fields and scrub on sunny slopes). Rockfalls and debris flows take place here.

The latter is the most active level in sediment yield (GARCIA RUIZ & PUIGDEFABREGAS, 1984) through a wide range of mass movements.

The torrential nature of the rivers draining the flysch band has forced the organs of government to attempt measures both biological -afforestation with Pinus nigra- and hydraulic -check dams- to ensure a more moderate behaviour of the channels.

Climate is submediterranean with a tendency towards oceanic mountain in the upper parts of the watersheds. Mean annual rainfall is 900 mm at the outlet of the basins and 2000 mm for the higher parts of the flysch band. There is a clear gradient that equals annual rainfall in mm and altitude in m (GARCIA RUIZ & PUIGDEFABREGAS, 1982). The seasonal distribution of rainfall determines a greater risk of floods in the autumn: maximum values of rainfall in 24 hours are registered between September and November.
2. Erosion control works

There are three types of erosion control works (ASHIDA, 1987):

a) Hillside works, such as restoration of vegetation on bare slopes, which are effective measures for reducing sediment supply.
b) Dam constructed on a channel for controlling erosion or checking sediment yield.
c) Channel works constructed along the river course on an alluvial fan where a considerable amount of sediment is produced.

The first two are the main causes of degradation in the channels of our study area.

Restoration of vegetation aims to improve the hydromorphic functioning on the slopes by reducing the runoff. Their geomorphological and hydrological effects have been largely discussed (TRIMBLE & WEIRICH, 1987; ORTIGOSA, 1991). On the other hand, check dams stop the sediment load and reduce the tractive force of the stream by decreasing channel slope, which inhibits further erosion. In our study area, there are three check dams in the Ijuez river, one in the Aurin river and several more along the reach upstream from the apex of the Escuer, Oros and Oliván alluvial fans. Moreover, the former two have been channelized downstream from the apex by means of longitudinal walls.

Better vegetation conditions of a basin imply a real control of sediment yield, but some sediment supply is still maintained through the material stored in tributaries (delayed input) and main stream (immediate input)

3. Degradation evidences

Channel degradation has been a very common topic in recent literature. GREGORY & MADEW (1982) and KELLERHALS (1982) have studied that caused by changes in land management and by river regulation, respectively. In our study area, the process exhibit similar features both in braided rivers and alluvial fans.

3.1. Degradation in braided rivers

Several channel adjustments have been found in the Ijuez and Aurin river since the first available air photo (1956). By that time, most of rivers crossing the flysch band received a sediment input much greater than their capacity to entrain it. It resulted in a braided channel where riffles and pools alternate throughout. Active alluvial plain reached 200 m width near the mouth in the Aurin river (an 88 km² drained basin, 25 km long) and 150 m in the Ijuez one (46 km², 14 km). In the upper part of the latter river, a valley-confined debris flow (BRUNSDEN, 1979) is developed.

The torrentiality of these rivers was corrected by means the mentioned biological and hydraulic works. The three check dams completed in the Ijuez river date
Fig. 2. Channel morphology before and after the Aurin's dam completion in 1966.
1) Channel boundaries; 2) Channel and active area at bankfull; 3) Recent deposits with no vegetation; 4) Recent deposits with sparse scrub; 5) Deposits colonized by scrub between sparse and close; 6) Deposits with close scrub; 7) Very old level supporting meadow fields; 8) Man-altered zone
from 1958, 1966 and 1983, while the Aurin dates from 1966. This one was selected to
detect downstream effects of dams in a former paper (MARTINEZ-CASTROVIEJO et
al., 1990). Fig. 2 shows the evolution of channel pattern before and after dam
completion. The most remarkable effect is the removal of the braiding, substituted by a
single channel which extends to 850 m downstream by 1988.

All the bedload and an undetermined part of the suspended load is trapped
upstream from the dam, at least before the filling of the reservoir, in such a way that the
parameters that control sediment transport dynamics are disturbed. To recover the
sediment load once the water is released, the stream proceeds to erode bed and banks.

Selective erosion, rather than massive, increased mean grain size from ca. 120
mm up to 250 mm just below the dam, so an armour layer progressing downstream in
time was created. The fine material is washed out and particles below 100 mm in
diameter only represent 20% of the bed material, while they accounted for the 60% of
the ancient deposits. In Fig. 3 the location and date of completion of the three dams on
Ijuez river is presented related to mean grain size. It can be seen how the oldest dam
promotes the most outstanding alterations on the tendency of mean grain size, all three
being very similar in trap efficiency. This proves the progressive character of the
process. However, pre-dam bed material size distribution also plays a decisive role in
grain size changes.

![Graph showing mean grain size evolution](image)

Fig. 3. Mean grain size evolution along the Ijuez river and location of the dams

In reaches not altered by dams degradation is also present. Surveys carried out
recently show that scouring and streambank erosion are the main sediment supply on
the valley-confined debris flow deposit existing in the upper reaches of the Ijuez river.
Here, the original configuration of the deposit is being fluvially reworked (MARTINEZ-
3.2. Degradation in alluvial fans

Studies carried out on alluvial fans have shown that their aggradation processes represent an equilibrium condition between the sediment supplied and the sediment eroded (BULL, 1977). When an environmental change occurs in the basin, the alluvial fan adjusts its size and sedimentary patterns (HARVEY, 1987). Thus, the stage of the alluvial fans is a good reference of the dynamics of their drainage basins, according to the amount and sorting of the sediment supply.

Three alluvial fans developed at the outlet of afforested basins draining the flysch band have been studied (Table 1). As in the rivers, the survey of the air photos corresponding to 1956, 1977 and 1988 shows a reduction of the active zone, with changes in the aggradation and deposition stage towards degradation and incision. This trend has been accelerated throughout the last decades, being related to a decrease in the sediment availability.

Table 1. Some characteristics of alluvial fans and their drainage basins

<table>
<thead>
<tr>
<th></th>
<th>ESCUER</th>
<th>OROS</th>
<th>OLIVAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin area (Km²)</td>
<td>6.0</td>
<td>12.25</td>
<td>32.25</td>
</tr>
<tr>
<td>Ravine slope (%)</td>
<td>15.8</td>
<td>15.40</td>
<td>6.70</td>
</tr>
<tr>
<td>Fan area (Km²)</td>
<td>0.39</td>
<td>0.69</td>
<td>1.54</td>
</tr>
<tr>
<td>Basin mean altitude (m)</td>
<td>1283</td>
<td>1403</td>
<td>1389</td>
</tr>
<tr>
<td>Basin mean slope (%)</td>
<td>35.78</td>
<td>37.31</td>
<td>40.29</td>
</tr>
<tr>
<td>Fields area (%)</td>
<td>43.30</td>
<td>41.50</td>
<td>25.00</td>
</tr>
<tr>
<td>Abandoned fields in 1956 (%)</td>
<td>66.0</td>
<td>51.5</td>
<td>62.0</td>
</tr>
<tr>
<td>Active channel slope (%)</td>
<td>13.0</td>
<td>8.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

A great part of the surface of the studied fans was active at least until 1956 (see Fig. 4 and 5). Almost one third of the Escuer alluvial fan surface was active by that time (29.6%, Table 2). The channel, very steep (over 25%), erodes the lateral moraine where it entrenches entraining very coarse gravel and even boulders. The available fine material encourages the formation of visco-plastic flows after heavy rainfalls, which allows the transport of large boulders far away from the apex. The debris flows, with a lobed tongue shape, well-developed in the proximal zone, have reached the distal zone where they occupy a maximum width of 360 m. In fact, there is a good relationship between the active zone of the fan and the volume of sediments supplied by the moraine. In this fan, the area recently abandoned occupies 33.7% of the total surface, being formed by debris flows. This shows the torrential behaviour of the basin.

By 1956, the active zone on the Oros and Olivan alluvial fans was less representative than in the Escuer one (9.22 and 9.8%, respectively). The material reaching the fan is better sorted, due to the larger distance travelled and the transport mechanics: the channel pattern, a braided one, encourages the selection of the transported
Fig. 4. The different areas of each alluvial fan by 1956 (same legend as in Figure 5).
Fig. 5. The different areas of each alluvial fan by 1977
material. The active zone is formed by a single channel at the apex, then diverging in more unstable channels that change on every flood.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escuer</td>
<td>31.11</td>
<td>39.72</td>
<td>29.6</td>
<td></td>
</tr>
<tr>
<td>Oros</td>
<td>41.73</td>
<td>40.15</td>
<td>8.65</td>
<td>9.22</td>
</tr>
<tr>
<td>Olivan</td>
<td>30.07</td>
<td>30.11</td>
<td>30.02</td>
<td>9.8</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escuer</td>
<td>31.05</td>
<td>39.07</td>
<td>23.9</td>
<td>3.01</td>
<td>2.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oros</td>
<td>41.73</td>
<td>37.9</td>
<td>7.26</td>
<td>7.1</td>
<td>3.76</td>
<td>2.25</td>
<td></td>
</tr>
<tr>
<td>Olivan</td>
<td>34.06</td>
<td>23.9</td>
<td>21.09</td>
<td>8.37</td>
<td>2.65</td>
<td>3.43</td>
<td>6.5</td>
</tr>
</tbody>
</table>

1) Cultivated area; 2) The oldest area; 3) Very old area; 4) Old area; 5) Recently abandoned area; 6) Active area; 7) Works

Maximum width of the active zone at the distal zone is almost 200 m in Oros and more than 400 m in Olivan. Moreover, the near absence of moraine deposits reduces the heterogeneity of the material and the generation of debris flows.

It must be pointed out the significant extent occupied by the recently abandoned levels in Olivan (30.02%). In these areas, there is some evidence of similar dynamics to that of the active zone. In Oros, where the braiding is clearly less marked, the high stage of plant colonization on the fan shows the limited activity of the basin in the last thirty years.

The most spectacular changes triggered by the erosion control works are found in the alluvial fan of Escuer, whose basin, in turn, has been the most affected by such works: more than one third of the basin was afforested; in the channel, 15 check dams and two longitudinal walls were built up since 1956. So, the active area is restricted to 3.01% of the total surface in less than twenty years. In Oros and Olivan the restriction has been up to 3.76 and 3.42% of the total surface, respectively.

4. Discussion

Some evidences shown by Ijuez and Aurin rivers and Escuer, Oros and Olivan alluvial fans allow us to describe the evolution of their channel pattern. The former situation, previous to 1956, was characterized by a large sediment input to the streams, which promote steep and very wide channels. Such conditions encourage the formation of braided patterns even on the alluvial fans. Since then until today, several changes affecting the vegetation conditions have altered the overall functioning of the basins.
CHANNEL DEGRADATION

which has been reflected by changing in fluvial dynamics. Two processes have led the
new one both in braided rivers and alluvial fans: incision and lateral migration.

Incision takes place by selective erosion, induced both by the sediment storage
upstream from the check dams and the limited sediment supply from the slopes. It is a
very extended process along braided rivers, but located only at the proximal zone of
alluvial fans. The first consequence of incision is the restriction of the active area of the
channel, up to 75% of the former alluvial plain in an extraordinary case registered on a
braided reach of the Ijuez river. Incision has progressed up to 2.5 m in alluvial reaches,
though that caused by downstream effects of dams may reach 3 m. In these cases,
degradation is faster and more locally extended than that triggered by structural measures
in the basin. In alluvial fans, on the other hand, a 4 m cut has been registered at the
apex of Escuer. However, the erosion processes in the proximal zone becomes
deposition in the distal zone through intersection points (HOOKE, 1967). The channel
spreads out and a secondary alluvial fan is formed. Escuer is also a good example of
that.

When incision by selective erosion results in an armour layer, the stream
cannot entrain additional sediments from the bed and it migrates laterally to erode banks
where old deposits are dismantled by cutting and undermining. Such a migration implies
a slight increase of the restricted active area. Nevertheless, an exceptional bank retreat of
15 m has been observed for the eleven years following the check dam construction in
the Aurin river (1.5 m/y of bank retreat); the rate had diminished up to 0.5 m/y for the
last 11-year period.

All these processes have not been gradual, as indicated by several levels of
deposits which reflect different moments in channel evolution. Changes seem to occur
during floods, so degradation processes can be unnoticed between two floods. This
agrees with the idea that aggradation also takes place during extraordinary events.

Plant colonization reflects contrasts within the different deposits from a
sedimentological and hydrological point of view (DRURY, 1956). Three floristic
sampling (GOMEZ VILLAR et al, in press) allowed us to establish a classification of
the vegetation communities (box zone, willow zone and channel) according to their
distribution both in the proximal and distal zones (Tables 3 and 4). Logically, riverbank
wood shows a preference of location near the active channel, while it is little represented
in the box zone, that is to say, there is a decreasing tendency towards drier zones.
Pastureland and grasslands, though less abundant, are present in the box and willow
zones of the distal zone, while they are located near the channel on the proximal one. It
must be taken into account that this type of vegetation is associated with well-developed
soils found in the more stable areas of the fan. The rest of the vegetation types behave
in a similar way, according to the age of the deposits.

Channel dynamics is a consequence of the hydrological regime and the sediment
supply. Thus, effective measures controlling both variables should not result in a
broken equilibrium. Once proved the effectiveness of afforestation in reducing flood
GOMEZ-VILLAR & MARTINEZ-CASTROVIEJO

magnitude and frequency (BINNS, 1979), there must be a stronger control of the sediment yield. If this hypothesis were true, it should mean that the channel itself has become the main sediment source of the fluvial system. To state that, further research about runoff generation and slope dynamics in afforested basins is required.

Table 3. Distribution of vegetation groups according to different alluvial fans (number of individuals)

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Box woods</th>
<th>Willow-Grove</th>
<th>Channel</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riverbank wood</td>
<td>21</td>
<td>113</td>
<td>192</td>
<td>8.9</td>
</tr>
<tr>
<td>Pastureland/grassland</td>
<td>36</td>
<td>41</td>
<td>31</td>
<td>2.9</td>
</tr>
<tr>
<td>Stony land</td>
<td>173</td>
<td>338</td>
<td>166</td>
<td>18.4</td>
</tr>
<tr>
<td>Diverse woodland</td>
<td>205</td>
<td>149</td>
<td>27</td>
<td>10.4</td>
</tr>
<tr>
<td>Dry environment species</td>
<td>1321</td>
<td>770</td>
<td>95</td>
<td>59.4</td>
</tr>
</tbody>
</table>

Table 4. Distribution of vegetation groups according to the different zones of the alluvial fans (number of individuals)

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Proximal zone</th>
<th>Distal zone</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riverbank wood</td>
<td>206</td>
<td>120</td>
<td>8.9</td>
</tr>
<tr>
<td>Pastureland/grassland</td>
<td>41</td>
<td>67</td>
<td>2.9</td>
</tr>
<tr>
<td>Stony land</td>
<td>359</td>
<td>318</td>
<td>18.4</td>
</tr>
<tr>
<td>Diverse woodland</td>
<td>172</td>
<td>209</td>
<td>10.4</td>
</tr>
<tr>
<td>Dry environment species</td>
<td>916</td>
<td>1270</td>
<td>59.4</td>
</tr>
</tbody>
</table>

GOMEZ-VILLAR et al. (in press)

Degradation does not imply necessarily an increase in flow competence. Moreover, present-day stream power seems to be very similar to that previous to afforestation, a few decades ago. This has been deduced analyzing the morphometric indices of deposits belonging to both periods. Channel scouring with similar stream power constitutes one more proof of the sediment lack occurring in basins recently restored and, as a consequence, of their more moderate behaviour.

5. Conclusions

To state that the rivers draining the afforested basins of the flysch band have lost the equilibrium condition, a detailed sediment budget is required. A given river "in regime" (HENDERSON, 1966) may aggrade or degrade through short lived changes. Once again, time scale appears to be the overriding factor in determining the distinction between short lived changes and long term effects. Most of authors agree that the adjusting mechanisms of long term effects may take several years (MACKIN, 1948; LEOPOLD et al., 1964; GRAF, 1988).

If present-day channel erosion is due to the afforestation of the basin, the triggered processes must be long term effects. Moreover, the vegetation restoration has been put on the same level as a climatic change with regard to flood peak and sediment
CHANNEL DEGRADATION

yield reduction. Nevertheless, degradation is not constant and short stages of aggradation occur, especially when dams fill their trap capacity and sediments removed from the older deposits are deposited downstream. In any case, the consequences of these erosion control works are very difficult to predict and they even counteract in the medium-term the control effects that they attempted.

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121
GOMEZ-VILLAR & MARTINEZ-CASTROVIEJO


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EROSION AND ECOLOGY IN THE MIDDLE EBRO BASIN. SLOPE ASPECT AS A FACTOR OF EROSIONAL PROCESSES. AN INTRODUCTION APPROACH

José C. GONZALEZ HIDALGO, María T. ECHEVERRIA ARNEDO, Francisco PELLICER CORELLANO

Departamento de Geografía y Ordenación del Territorio. Universidad de Zaragoza, 50009- Zaragoza

ABSTRACT
During the summer of 1989, the Department of Geography at Zaragoza University (Spain), started up a research focussed on erosion processes under semi-arid environment in the Ebro River Basin (NE Spain). The aims of this paper is to present a brief global note about the principal investigation lines, techniques used and advances of results.

Key-words: erosion, runoff yield, natural plant cover, slope aspect, Ebro basin.

RESUMEN
En el verano de 1989 el Departamento de Geografía de la Universidad de Zaragoza (España), comenzó una línea de investigación centrada en los procesos de erosión bajo condiciones ambientales semiáridas en la Depresión del Ebro (NE de España). El propósito de estas notas es presentar una breve descripción global de las principales líneas de actuación, técnicas empleadas y resultados iniciales.

Erosion process studies in Spain during recent years have increased. The reason is very simple: it is said that over 2/3 of national land is suffering problems of soil erosion. The factors which control the mechanisms are very well known, particularly rainfall characteristics, hydric stress and the paucity of plant cover, and human activities, often not accordingly to the natural dynamic.

123
Although such conditions, except in the north Atlantic sector, are spread over peninsular and Baleares Island areas, the majority of studies and Research Programs have been developed along the Mediterranean littoral area, where catastrophic events, coupled with human and economic loss, have demanded the need for knowledge to preview and control them. The Spanish inland has received little attention, and few studies have been carried out until present. Rural land abandonment processes since the fifties and less intense erosion processes compared to those of the littoral area could be the reason for this situation. In the first case, because erosion processes, as a social problem, have an economic interpretation (erosion produces a decrease in land productive capacity. And secondly, we must take into account that rainfall aggressiveness is lower in Spanish inland areas than in littoral ones, where coast relief barriers play an important role.

The central part of the Ebro River Basin is one of the most significant sectors in this area, where erosion processes have high potentialities. Paucity of rainfall, caused by a sheltered position among the peripheral mountains, produces arid conditions only comparable with those of SE of Spain. As a consequence, plant cover is scarce, and has been modified by human intervention for centuries. Lithologically, gypsum and marls, as dominant materials, have a high erodibility. Finally, rainfall aggressiveness is an important factor, often related to convective storms because of the inland location.

Under such conditions, the Department of Geography at Zaragoza University (Spain) has considered the need to start up an investigation focussed on erosion processes in the Ebro Basin since 1988. In this paper we will develop the conceptual framework and the methodology, the main investigations that are being carried out and some initials results.

1. The study area

The project is being carried out in the Violada Area, located in the north of the Ebro River (Huesca province, Spain). Topographically, it is an area of gentle slopes that ranges in relief from 480 m to 380 m a.s.l.

From north to south the areas has a series of infilled valleys oriented west-east. They are excavated in the loamy and gypsum materials that make up the central part of the Miocenic basin. The cross section of these valleys shows some asymmetry between slopes facing north and south.

Morphoclimatic conditions are semiarid. Annual rainfall is circa 500 mm but there is a high interannual variation. The mean annual rainfall is uniformly distributed throughout the year, and seasonal percentages are higher than 20 % of the mean total rainfall. Intensities expressed as concentration higher than 10 mm/day show that more than 50 % of monthly rainfall falls in such events. Springs and Autumn have the highest values (GONZALEZ HIDALGO 1989).
EROSION IN THE EBRO BASIN

Plant cover abundance-dominance, sociability class and dynamics in the area indicate an environment with a low natural productivity, although there is a great variation between slope azimuth.


2. The problem

The need to simplify at the beginning of any investigation has allowed us to reduce the general aims (erosion processes), focussing the study on the conditions which control runoff production under natural plant cover. This choice -and we understand that choice dominates all the research processes-, is based on a commonly accepted rule that runoff is the principal agent in erosion processes under semiarid environments, at least in the spatial dimension. The conceptual scheme, with this assumption, has been designed reducing aims to the maximum, and considering runoff as a response to precipitation. The second line has been concentrated on the spatial variability of runoff production, with special emphasis in the slope aspect effects.

Reasoning is as follows. Given an azimuth in any slope, short wave radiation varies according to the following equation:

\[ S = S_1 \cos \varnothing \]

where \( S_1 \) is the value of normal short wave radiation and \( \varnothing \) the angle between solar beam and normal.

Because short wave radiation is considered in any case as the most important factor which controls potential demands on hydrological balances, and given the variability between different azimuths, soil water evolution can be modified according to aspect. By this reasoning, an initial hypothesis in which temporal rhythms and magnitudes in soil available water could be different, according to aspect, would seem appropriate.

Although high annual potential demands produce an homogeneity, empirical evaluations have demonstrated that there are monthly variations between aspects, both soil water and ETa (Fig. 1). Finally, according to aspect, the setting up and the maintenance conditions of plant cover could be variables. As a consequence, and as a hypothesis, not only can plant cover be modified by aspect, but also the mechanism and magnitudes of runoff, under the well known ratio plant cover-runoff (erosion).

All the concepts that have been stated above have been developed methodologically trying to control the three main variables included in a hydrological balance. For that reason, final aims have been focussed not on getting extrapolable
Fig. 1. ETA and soil water evolution. Net precipitation 300 mm (calculations have been done by Specht's model -1972- in which principal assumption is that evergreen communities under water restriction develop adaptative mechanism to survival. Under such conditions ETA/Eo = K*W, and water never reaches cero level or, in any case, at the end of the dry season. In the opposite case, plant communities would have disappeared. K coefficient is an indicator of adaptation (about 0.4 in the area).

magnitudes, but on finding out operation processes. We have consistently preferred to build up boundary plots, after a period of six months working on open plots. The results of this experience were intractable because there wasn't a reference area.

Field work is carried out by two parallel approaches. First focussed on controlling hydrological balance, with especial emphasis on runoff yield under different conditions. Second, focused on plant cover conditions (hydric stress and biomass productions).

3. First approach

3.1. Input Records

A total of 18 pluviometers in both aspects, have been installed. Some of them are inclined, perpendicular to slope gradient. This was done to observe differences in rainfall amounts by aspects (wind dominant effect for example). Another set of pluviometer was installed under a canopy, to find out rainfall interception. Finally a monthly automatic rain gauge station (from July 1990) and weekly (June 1989-July 1990) was installed.

Experience acquired shows us the limited utility of weekly raingauge in the environments as studied. The hourly width in chart paper record is so reduced that time evaluation errors are very high in case of short, but intense, rainfall.
3.2. Soil Water Evolution Records

Soil water evolution is being studied by the gypsum blocks method for several reasons. First of all the range of values, between 0.1 and 15 bars, indicates a range between field capacity and hygroscopy water (more or less air dryness conditions). The water retained between both values has been accepted as soil water available for natural plant communities, not taken into account wilting point. The reasoning is that communities in the study are suffering hydric stress, and necessarily have developed physiological and morphological adaptations that protect them against dryness. In this case the wilting point is not a useful value because plant communities are able to suction water held at higher tension than 15-16 atm. SPECHT's model has been used, proving this situation in mediterranean sclerophylyus communities.

On the other hand, values lesser than 0.1 bar (saturation or gravity water) are being recorded sampling the superficial layer (<2 cm) and accepting that such a situation never reaches the deep layer. Gypsum blocks, finally, is a non destructive method, because after installation there are no more more modifications in the soil. The main problem is the hysteresis effect at >15 bars.

The recording mechanism is very easy. An electrode is put into a gypsum block connected with a cable. Inserted in the soil at a selected depth, the block will reach an equilibrium with the boundary, i.e., if the environment is moister than the block, the block will take water, and viceversa. When the cable is connected with the conductimeter, the value shows us the capacity of electricity to pass through the electrode. More conductivity indicates more humidity.

Results transformation to water volumetric content needs two further calculus. First the calibration curve between tension forces and conductivity, and second, soil water potential curves, both made by pressures valves.

The blocks were put at different depths to find out moisture profiles. Because of soil thickness, blocks are not installed at normal depths. In any case 2cm and 15 cm are recorded. The other points are referred to as the deepening of soil contact with parent material.

The duration of block is not infinite, because they will be dissolved. In any case, the time passed (18 months) after installations indicates the convenience of using them in environments where rainfall is scarce.

3.3. Output Records

Overland flow and eroded soil are recorded by traps (Gerlach type) 1 m width. Traps have been constructed by PVC tubes 18 cm in diameter covered by aluminium sheets to prevent direct rainfall. The collectors are connected to tanks (25-50 liters) placed in a hole. Overland flow and soil both pass from traps to tanks. The first time we put a net (2mm) to select gross material, but the results were overflowing traps, and a
waste of data. Finally we preferred to let overland flow and soil pass, and later, at the field, select the gross material with a net. Although input areas are not big (4 x 1 m), during some events traps were systematically overflowed, because of a high runoff coefficient.

The plots

The general structure of sampling records was repeated in different situations, with similar dimension and slope values of the plots. In every case a pluviometer was installed near the plot, and some gypsum blocks at different depths inside the plot area. Each plot has two traps for finding variations in the same situation. Plots are boundary by aluminium metal sheets (0.8 mm width). A more detailed description about construction and installation is given by GONZALEZ HIDALGO & ECHEVERRIA (1991).

Plot location

Different locations according to previous ideas, have been monitorized, trying to control:

- Aspect general effects.
- Position slope effects (top-bottom)
- Plant cover effects.

To do this, general distribution of plots was as follows:

- Plot at the top of slope.
- Plot at the bottom, with natural plant cover.
- Plot at the bottom without natural plant cover.

The general scheme is duplicated (two aspects).

Differences between slope position are given by, first, different plant cover, and, second, variations in soil depth, parent material on the surface, being more common at the top. Plant cover effects were studied comparing plots at the bottom. Finally, as the general scheme is coupled by two aspects, each situation is compared with its equivalent in the other aspect.

Temporal sampling design

Given that the time evolution of different variables involved in the hydrological balances does not have the same temporal patterns, sampling was focussed in two ways: input and output records and soil moisture evolution.

Precipitation and runoff do not offer any problems, being recorded after production. The problem arises with soil water evolution, because it is a continuous
variable, and there are differences in response to precipitation according to time season and sampling depth.

To achieve maximum accuracy, because continuous record facilities do not exist, we have adopted a weekly sampling design during the first year, complemented with sampling records after rainfall events. We think that after a year we have reached a global pattern of soil water evolution, not only as a response to rainfall (at the depth of 2 cm) but temporal patterns at different depths.

After a year we have changed the strategy and at present we are sampling after events and two weeks after the last rainfall. The new sampling started in February, 1991, and it is too early to know if we have made a good choice.

4. Second approach

Global sampling shown up to now is a black-box model in which we assume that outputs are a direct response to inputs. Only soil water evolution clears the scheme, but it is so poor. Runoff is not only produced as a response of rainfall and previous soil water. And moreover the above mentioned scheme does not solve the second question (the aspect effect influencing plant cover by soil moisture evolution).

Plot locations help us to clarify, via plant cover and lithological differences, but not verify if plant cover depends on soil water evolution, and then on slope aspect. To find out this effect, a second line of research has been implemented focussed on the knowledge of hydric stress of plant communities in different aspects, and on the spatial variations of biomass production also.

4.1. Hydric Stress Records

Water retained in plant communities, quite an important component of hydrological balance, is a good indicator of the stage at which such communities are; in others words hydric stress.

Sampling is being done cutting twigs of about 3-4 mm in diameter, drying and weighing. The amount of water lost over the maximum water content which is able to retain the specie under consideration, is reported. Sampling is made weekly in Rosmarinus and Ononis.

The central point of this study is the calculus of maximum water content, which has been evaluated as follows. Three individual plants were sampled with roots. After being washed in the laboratory, they were put in a bottle with distilled water for 48 hours. After this time they were weighed and dried at a constant weight (110°C). Lost water over the initial saturated weight was accepted as a maximum water content.

The water lost in the individual sampling in each twig is compared with the saturated water content calculated over the dry weight (in Rosmarinus the coeff. is about
2 over dry weight). The results can be reported as Saturated Water Content or Water Saturated Deficit.

4.2. Biomass production

The second way was approached by collecting biomass because previous records of elongations and diameter records were lost after 6 months. In three plots per aspect, 2 x 2 m, all the biomass was collected by cutting the stems of shrubs and measuring basal diameter, and harvesting herbaceous. Biomass is selected by species and weight, taking an aliquota carried to the laboratory to estimate water content. By dimensional analysis total biomass of twigs and stems is determined in shrubs.

Depending on the ecological conditions of each site, individual developing could be better or worse, reflected in the basal diameter. In this case frequency distribution would be able to show such conditions, and given that after a time lap, the communities move from low mean value to high one, it is possible to compare two population records. Under this assumption, the community basal diameter study can be an estimator of ecological conditions induced by aspect.

The main methodological problem arises because it is necessary to know the age of both communities, and only with the same age is the comparison possible.

A second approach was made by studying growth rings, although there are many problems derived from hydric stress conditions under which the communities are developed, and it is not possible to assume that a ring in basal diameter represents one plant year, because the paucity of rainfall and ecological conditions in soil moisture have forced the communities to adapt their physiology, which produces a particular situation in which during a year a ring may or may not be produced.

Although we know the difficulties, we hope that ring analysis from different aspects will allow us to establish relative differences.

Methodologically we operated cutting laminar sheets of rings in different shoots and measuring ring widths with a micrometric lens.

5. Results

At present, general results allow us to show global patterns which corroborate global ideas and hypothesis:

1. Empirical evaluations of short wave radiations, Potential ET, Actual ET, and Soil Moisture Evolution show differences between aspects. These evaluations correlate qualitatively well with the soil moisture records presented here (Fig. 1 and 2). Principal controls on temporal evolution seem to be rainfall distribution, and soil water maximum storage.
EROSION IN THE EBRO BASIN

Fig. 2. Soil water evolution (15 cm deep). Moving average (5 weeks) plots vegetated (Value from plots under natural plant cover -c. 60% south and 100% north-. Moving average clear the chart, although it does not show rainfall response at the deep of 15 cm. Logarithmic scale is need because of low values at summer time -between 150 and 225 days-. The results are well-correlated to empirical data: water stays longer and at a higher level in north than in south, never reaching zero values. It is interesting to realize the homogeneity during spring time, when maximum demand from communities are satisfied by a high water content in soil) (------ North aspect; ...... South aspect)

Fig 3. Rainfall interception. Throughflow under Rosmarinus officinalis. The values show (as percentages of total rainfall) the amount of water that reaches the soil. As one can see, there is an upper limit, which is an indicator of the maximum water storing capacity by canopy. The inverse of this relationship is the water intercepted by cover and evaporated from leaves).

2. Plant Cover in a hydrological balance yet again plays an important role: As an interceptor of rainfall with a known asymptotical relationship (Fig. 3), as a water consumer (with differences in soil water depletion during spring season between plots
with and without plant cover) and as an improver of infiltration conditions as low runoff coefficient shows (Fig. 4).

Fig. 4. Rainfall and overlandflow. Bare and vegetated north slopes. The figure shows the effect of plan cover between plots in the same aspect. Total rainfall does not take into account intensity. It is interesting to note the rainfall threshold from which runoff starts

( Vegetated north slope;  Bare north slope)

Fig. 5. Runoff production under different conditions. Three rainfall events. Differences between rainfall must be take carefully, because rainfall data do not reflect intensity. There is a clear classification between different plots according to conditions of plant cover and aspects. Note how the value ca. 30 % of plant cover represents a critical threshold.

( Bare south side;  Bare north side;  x South cov. c. 30 %;  South cov. c. 60 %;  ∆ North cov. c. 75 %;  x North cov. c. 100 %)

3. Overland flow production shows differences according to plots, showing the role of different factors involved in the present study (Fig. 5). Plant cover seems to be the most important factor, but time previous to rainfall, and previous soil moisture at a depth of 15 cm are also important.
4. Soil moisture evolution reflects both slope aspect and depth. It is interesting to note that during less potential demands on soil moisture evolutions, at least in the northern aspect, there is internal drainage. In Fig. 6 soil moisture profiles in bottom vegetated conditions are shown. Fig. 7 shows soil water evolution at three depths under plant cover.

Fig. 6. Soil water content evolution (at 15 cm in depth). Bare both north and south sides. Slope aspects is shown in this figure under bare conditions. General trend shows differences in soil water content evolution -measured by electrical conductivity- according to aspect. Compare with Figure 2 to observe plant cover effects. (——Bare north side; ..... Bare south side)

Fig. 7. Soil water content evolution. North facing, plant cover 100%. Same 15 cm values as in Fig. 2. Soil water evolution at different depths shows a decreasing influence of rainfall -not in chart- and a dramatic inversion profile during the summer. We consider this plot as a major source of ETa data compared with the bare one. Note how during spring soil water at 50 cm decreases faster than upper layers, although rainfall is abundant. It is obvious that internal drainage is inhibited by high water demands. (—— 15 cm; .....30 cm; - - - - 50 cm).
5. Hydric stress in plant communities reflects, more than differences in mean value, differences in standard deviation by aspect. It implies a greater homogeneity in one aspect than in other. Fig. 8 shows mean values of soil water content evolution in *Rosmarinus officinalis*.

Until present the data from eroded soil has not been analyzed, although time duration and intensity of rainfall seems to be the greatest control.

![Graph showing soil water content evolution](image)

Fig. 8. Plant water content evolution (m.a.v.5 W) *Rosmarinus officinalis*. Values show plant water content over dry weight. The moving average let us to know general trend throughout the time record. It is interesting to observe how water content is higher in south aspect from the late spring, probably reflecting a mechanism of rapid use of water. Values are the mean of 4 samples per week. (—— North aspect; ....... South aspect).

The global planning presented is firstly complemented by the physical analysis of soil (grain size, porosity, bulk density etc) made by transect from top to bottom of slopes. The aim is to find out soil structure variations along slopes and between slopes. Secondly, by the study of infiltration conditions made by rainfall simulation. Both are being implemented at present.

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EROSION IN THE EBRO BASIN

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Publications of the research team about this subject

1. Papers (in chronological order)


2.- Congress Communications (not included above)


SOIL EROSION IN A SEMI-ARID MEDITERRANEAN ENVIRONMENT.
EL ARDAL EXPERIMENTAL FIELD
(MURCIA, SPAIN)

Francisco LOPEZ-BERMUDEZ, Mº. Asunción ROMERO-DIAZ &
José MARTINEZ-FERNANDEZ

Departamento de Geografía Física. Universidad de Murcia, Spain.

ABSTRACT
In the El Ardal Experimental Field (Cuenca de Mula, SE Spain), studies on soil erosion have been carried out since 1989. These are taken from two automatic stations, one meteorological and another hydrological, 17 erosion plots and 6 plots for plant study.
Up to now the results have shown, on the whole, a low rate of erosion. This is due to the relatively large quantity of plant cover (about 60%), limestone substratum, fairly permeable soil (calcic xerosol) and lack of energy in the recorded rains.
A minimum rainfall threshold (3-5 mm) has been noted. Below this figure overland flow is not registered. Erosion and flow rates are related more to intensity than to quantity of rain.

Key words: Mediterranean, semi-arid, hydric erosion, experimental plots, overland flow, infiltration, soil moisture, sediment production, erosion rates, fertility loss.

RESUMEN
El Campo Experimental de El Ardal está instalado en una ladera, con pendiente media del 20%, donde se incluye una microcuenca de drenaje de 2 ha de superficie. En ella se controlan parámetros climáticos, mediante una estación meteorológica automática y una red de 18 pluviómetros; parámetros hidrológicos, a través de una estación de aforo; pérdidas de suelo y escorrentía, mediante 17 parcelas (12 de 8x2 m y 5 de 10x2), con diferentes orientaciones, pendientes y usos del suelo; biomasa, composición florística, índice de protección de la cubierta vegetal y hojarasca caída; también se mide la evolución de la humedad del suelo y se realizan análisis químicos de pérdida de fertilidad.
Los resultados obtenidos hasta ahora corresponden a un breve período de tiempo, los años 1989 y 1990, en los cuales las lluvias han tenido un comportamiento muy irregular. Parece existir una estrecha correlación entre el tipo de tormenta causante de la lluvia y la cantidad de agua recogida en los distintos sectores de la cuenca experimental. Además, se ha detectado un
umbral mínimo de precipitación (3-5 mm), por debajo del cual no se registra esorrentía, aunque se pueden producir situaciones particulares en función del manejo del suelo de las parcelas y sus condiciones ambientales.

Las tasas obtenidas de pérdidas de suelo han sido bajas, hecho que se explica por la abundancia relativa de cubierta vegetal (en torno al 60%), el sustrato calizo, un suelo (Xerosol calcico) bastante permeable y las características de la precipitación. Es de destacar que esorrentía y pérdidas de suelo están muy relacionadas con la intensidad de las precipitaciones; en 1990 tan sólo un episodio de lluvia produjo el 50% de toda la esorrentía anual y el 90% de las pérdidas de suelo totales. Estas pérdidas, en general, son bajas y los valores más altos se registran en las parcelas sin vegetación.

La humedad del suelo es mayor bajo la vegetación, pero es aquí donde también se registran las mayores oscilaciones (30%) entre periodo húmedo y seco.

De los estudios de vegetación se deduce que en el Campo de El Ardal el 59% corresponde a cubierta vegetal, el 30% a cubierta de piedras, el 6% a hojarasca y plantas muertas y el 5% a suelo desnudo, no existiendo grandes diferencias entre estaciones. El mayor crecimiento de las plantas se registra de abril a junio, y el suelo recibe la mayor cantidad de materia orgánica de mayo a octubre.

1. The Problem

Erosion is one of gravest processes of soil degradation in the semi-arid mediterranean areas of South-East Spain mainly because of its serious agronomic and environmental implications. In this region, which is the driest in Europe, soil erosion is both an endemic problem and at the same time a complex and dynamic process. From an agronomic point of view, hydric erosion affects the physio-chemical properties of the soil and its productivity by structural deterioration, decapitation of humerific horizons, nutrient carry-off, reduction of useful water reserve capacity and downhill sedimentation (LOPEZ-BERMUDEZ & ALBALDEJO, 1990). In sensitive areas soil loss can be extremely heavy, rates often reaching 200 tm ha\(^{-1}\) year\(^{-1}\) which is equivalent to 12 mm/year\(^{-1}\) (LOPEZ-BERMUDEZ, 1990). These high erosion values are, however, easily surpassed during the sort, but intense, periods of heavy rain with over 200 mm in 24 hours, such as recent episodes in Oct. 1973 and 1986, Nov. 1987 and Sept. 1977 and 1989 (LOPEZ-BERMUDEZ & ROMERO-DIAZ, 1991). This kind of high energy rain (18/19 Oct. 1973) produced soil losses of between 2000 and 4200 m\(^3\)/ha\(^{-1}\), equivalent to average soil thickness of between 200 and 420 mm (RUIZ DE LA TORRE, 1973), on dry farmland on the steep slopes of the Almanzora and Guadalfeso basins, and the Albuñol and Guarea river beds.

Soil erosion in the south-eastern region of the Iberian Peninsula also helps to create problems of turbidity and surface water deterioration due to the heavy load of sediment, salts, nutrient substances and phytosanitaria products in quantities which are excessive for this environment with its strong tendency towards aridity and sharp seasonal and annual contrasts. In this mediterranean region, the erosion of the soil resource (which is with water the most important), represents a serious threat to agrarian and forest activities and to the environment, causing on the one hand a sharp decrease in biological or productive potential and on the other hand the introduction of poor and
SOIL EROSION IN MURCIA

fragile ecosystems. In fact, the loss or deterioration of soil could cause a breakdown in the ecological balance and lead inexorably to the land becoming desert.

2. Experimental areas

2.1. Gracia river-bed

To find out and quantify spatial and temporal variations of hydric erosion processes, rhythms and importance in the semi-arid soil/plant/atmosphere system of South-East Spain in 1982, the basin of the Gracia water-course was chosen (Campos del Río, Murcia). A 60x50 m rectangular plot, at 30% slope, was set out with a 2x2 m square network placed over it. Properties such as plant density, plant species frequency, heights, slopes, topographical contours, overland flow feeding areas, soil moisture and infiltration rates were measured for each square of the network, as well as the importance of erosive processes and correlative sediment production for the whole (LOPEZ-BERMUDEZ et al, 1984; FRANCIS et al, 1986; ROMERO-DIAZ et al, 1988).

2.2. El Ardal

In 1988 a new area was chosen, one which reunited the semi-arid environmental conditions of the south-eastern region of Spain and the experimental device was designed. In 1989 the Campo de Ardal Experimental Station (Mula, Murcia) was created, and here a microbasin and several experimental plots were laid out while instrumentation began.

The experimental field of "El Ardal" is located on the northern flank of the Mula Basin at 550 m height, on a slope covered with mediterranean scrub above limestone substratum.

2.2.1. Location

The Mula Basin, situated in the centre of Murcia Region, of neogene-quaternary age, is surrounded by limestone reliefs which reach up over 1000 m height and is filled with neogene materials, particularly loam and sandstone.

The present-day climatic conditions in the Mula Basin are semi-arid; about 300 mm average rainfall; wide variability with intense and prolonged dry periods; heavy rainfall particularly in the autumn, with over 50 mm/h of intensity; a lot of sunlight, 2870 sunhours per year; average temperature of 18° C; global radiation of about 20 mega-jules/m²; and, as a result of this, serious evaporation and potential evaportranspiration of about 1100-1200 mm/year. Vegetation is physionomically made up of low, discontinuous scrub. The predominant botanical species are Thymus, Sıpa tenacissima, Sideritis leucantha, Salsola genistoides, Rhamnus lycioides, Brachypodium and other xeric species. The predominant tree species is Pinus halepensis to be found in small copses and as individuals.

139
Fig. 1. Location of experimental areas. Mula Basin (Murcia)

- Experimental site El Ardal
- Experimental site Rambla de Gracia
SOIL EROSION IN MURCIA

The area chosen for El Ardal, because of its height (550 m) limestone lithology, vegetation (mediterranean scrub), soils (calcic xerosol), slopes and so on, shows representative features of the mediterranean environment.

2.2.2. Design

The experimental area is situated on a 20% slope, where there is also a drainage microbasin of 1 ha area. Climatic parameters were recorded at an automatic meteorological station, and a network of 18 rain-gauges placed throughout the whole experimental field. The whole system was under manual and automatic control.

Hydrological parameters were recorded at a gauging station which was also automatic; 17 plots of erosion/overland flow; periodic measuring of soil moisture and infiltration capacity tests on the soil.

Both the physical and chemical erosion of soil is known for 17 plots (12 at 8x2 m and 5 at 10x2 m). Four of these were situated in the microbasin, all with similar slopes but different facings (NE and NW), and the others were placed outside, facing north. The plots are bordered by rubblework; water and sediments are at first poured into a trapezoidal collector with a lid, and later into a small pool. Finally, for some plant studies, 6 plots of 16x16 m were set out (Fig. 2).

3. Instrumentation, Methods and Techniques

3.1. Climate

3.1.1. Meteorological station

An automatic meteorological station, at the top of the slope, recorded most of the climatic information. It is made up of the following sensors:

- Anemometer
- Thermometer
- Rain-gauge
- Albedometer
- Wind-vane
- Hygrometer
- Radiometer

Apart from the specific variables recorded by each sensor, dew and net radiation were obtained. All this information was put into a data logger unit, at 10 minute intervals, with monthly autonomy. This unit transfers all the information into a computer for transport and manipulation.

3.1.2. Rain-gauge network

Together with the basic climatic data, a network of rain gauges was placed throughout the experimental field. This network consists of 8 Hellman rain-gauges, two
Fig. 2. Simplified model of variables in the atmosphere/plant/lithology/soil system, recorded in El Ardal experimental field (Mula, Murcia)
SOIL EROSION IN MURCIA

on each side of each set of plots, one vertical and the other at the same angle as the slope of the hillside. The aim was to determine the possible influence of this topographical factor.

Ten wedge-shaped rain-gauges were also used and placed under various plant species (fir, rosemary, thorn, etc...) over the whole hillside, with the aim of measuring interception.

3.2. Hydrology

3.2.1. Gauging station

To measure overland flow in the microbasin a gauging station was used which had a flow concentration deposit and a calming well for measuring water level. The station possessed sensors which could record rainfall, flow and solid loads:

- Rain-gauge
- Level measure
- Turbidimeter

All the data were gathered into a data logger unit at one minute intervals and with eight day autonomy. In such a way that only the information relative to the rainfall occurrence was kept. This unit transfers all the data to a computer.

3.2.2. Soil moisture

The moisture of the soil and its spatial and temporal variations are recorded. The process consists of soil moisture state control under various conditions:

- soil under vegetation
- soil under stones
- bare soil

Two control levels are also differentiated for each case:

- on the surface
- at the bottom of the cross-section

Because this is a method of "destructive" measurement (gravimetric), the sampling was done arbitrarily on a section of the hillside outside but near to the microbasin environment. The sampling was done fortnightly and after every rainfall occurrence.

The method used was gravimetric and by means of this soil moisture was obtained from the difference in weight between the moist sample and after it had been dried out at 105° C for 24-36 hours. It is expressed in percentage of dry sample.
With the study of soil moisture state the incidence of this factor in certain aspects such as hydric balance, overland flow generation, plant cover behaviour etc., can be checked.

3.3. Soil loss

Soil loss evaluation was carried out on erosion and overland flow plots, and was measured by a turbidity sensor installed in the gauging station at the end of the microbasin.

The experimental area consisted of 17 plots. Twelve at 8x2 m and five at 10x2 m. The former were distributed in the following way:

- 4 in the microbasin, facing in different directions and with scrub vegetation;
- 2 on the northern slope with similar vegetation;
- 6 in an area given over to fallow land/cultivation.

The first six, arranged in pairs, are placed on different slopes and facing in different directions. Three of them were cleared of vegetation so as to observe and evaluate comparatively the effect of afforestation on soil loss with the natural existant vegetation.

The remaining plots were placed in a set with the same slope and direction, but with different soil uses: barley, fallowland with colluvions and without colluvions, ploughed in the same direction as the overland flow, treated with polymer, and sowed with wheat. The study which was carried out on these plots consisted of: measuring the quantity of overland flow generated by each rainfall; sampling so that later, in the laboratory, the quantity of eroded soil could be discovered and, in the same way, by taking another sample, undertake various chemical analyses to find out nutrient loss.

3.4. Fertility loss

The study of nutrient loss in the plots is done from the overland flow waters and sediments. After each rainfall event an analysis of the following components and properties is carried out:

- pH
- CE
- Na
- K
- NH4
- Mg

- Ca
- Cl
- NO3
- PO4
- SO4
- RAS

When rain produces sediments, a complementary analysis is made so as to determine the nutrients carried off:
SOIL EROSION IN MURCIA

- C
- N
- K
- P
- Fe
- Cu
- Mn
- Zn

A check on these same soil constituents is undertaken seasonally in order to study evolution as well as a mineralogical analysis of clay in the sediments.

3.5. Vegetation

Studies relating to vegetation in El Ardal are centred on:

- Density of plant cover variations,
- Plant growth,
- Leaf fall from some species,
- Seasonal increase in scrub biomass,
- Protection of soil by scrub index,
- Calculation of total rosemary scrub biomass.

3.5.1. Density of plant cover variations

To study this aspect six plots of 16x16 m were used, facing different directions (west, northwest, east), on different slopes and with marked differences in plant cover (although the predominant botanical species in all of them was rosemary). The kind of plant cover and species at each point of the plots was identified by means of a grid with side measuring 0.5 m. The total number of sampled points per plot is 931; the measurements were taken monthly.

3.5.2. Plant growth

This research has until now only been carried out on rosemary, because of its large quantities and its being easy to measure. Having selected 8 plants from each of the vegetation plots (about 5% of the total), the following monthly measurements are taken: total height of plant and maximum outline, total number of stems and total number of visible stems. The number of checked stems, varies between 5 and 20 depending on the size of the plant; they were identified by means of numbered labels and their growth was followed.

3.5.3. Leaf-fall from various species

Having chosen rosemary (*Rosmarinus officinalis*) and juniper (*Juniperus oxycedrus*), plastic meshes were placed around them in order to gather up leaves and twigs which had fallen from the plants. This leaf-fall was gathered up and weighed once a month, and in this way the quantity which would have been left on the ground could be discovered.
3.5.4.- Seasonal increase in scrub biomass

In order to calculate biomass increase it is necessary to identify the number of growing branches within the plant. Then the average biomass increase measured from the stems is multiplied by the total number of growing stems. These can be easily identified in the spring.

In the plants outside the plots, however, the whorls (segments between knots) are cut and their length measured. They are then weighed separately and put into an oven at 60° C for 48 hours so as to calibrate the weight.

3.5.5. Scrub soil protection index

This method consists of the use of a screen with 10x10 cm squares, places over the upper part of several rosemary plants. Soil protection is measured by estimating the percentage of plant cover over each square on the screen. Using a metal graph-sheet to determine its position, a sprout is introduced and the number of leaves or stems touched is counted. About 150 points were recorded for each plant, the screen having been moved over it several times.

3.5.6. Total rosemary scrub biomass calculation

In order to find out the total biomass of a plant it is necessary to use destructive methods; the percentage corresponding to the part above ground (composed of leaves and stems) and the part below ground (roots) are thus pulled up and evaluated. Several rosemary plants of different sizes were, therefore, cut and pulled up and their leaves, stems and roots separated. This material was dried in an oven at 60° C for 48 hours so as to determine its dry biomass.

4. Results and Discussion

4.1. Climate

Although only little more that a year’s climatic records is available, there are certain points of interest such as the greater quantity of rainfall recorded by the rain-gauges placed in the concavity of the microbasin, compared to those on the periphery. There also seem to be different patterns in the recorded rainfall depending on orientation. Quantities vary widely, sometimes extremely so, depending on the topographical situation. There would seem to be a close relationship between storm type (convective, frontallogical, high or low in energy ...) and topographical shape of the experimental basin.

A minimum rainfall threshold can, however, be detected about 3-5 mm and below this overland flow is not recorded, although particular situations depending on soil use, slope, soil moisture can occur.
SOIL EROSION IN MURCIA

4.2. Soil loss and overland flow

In the short two year period for which we have data, 1989 and 1990 (Table 1), soil loss rates were low. This was due to the relatively high quantity of plant cover (about 60%) and rainfall features. 1989 was extremely wet (713 l/m²) compared to 1990 which was fairly normal (374 l/m²), causing the wide differences in recorded values, both for overland flow and soil loss (Fig. 3).

It is important to note that overland flow and soil loss are not always related to rainfall quantity but they are related to the intensity and sensibility of the ecosystems. One example is that of the rainfall on 13/09/90 when one single storm of 40 l/m² produced over 50% of all the overland flow and 90% of all soil loss for one year on all the plots.

Table 1. Soil loss and overland flow on experimental plots

<table>
<thead>
<tr>
<th>Plot no</th>
<th>Year</th>
<th>Runoff l/m²</th>
<th>Soil loss gr/m²</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1989</td>
<td>25.35</td>
<td>104.39</td>
<td>Barley</td>
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<tr>
<td></td>
<td>1990</td>
<td>11.20</td>
<td>19.31</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1989</td>
<td>7.05</td>
<td>2.06</td>
<td>Fallow on colluvions</td>
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<td></td>
<td>1990</td>
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<td>0.69</td>
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</tr>
<tr>
<td>3</td>
<td>1989</td>
<td>7.03</td>
<td>7.51</td>
<td>Fallow without colluvions</td>
</tr>
<tr>
<td></td>
<td>1990</td>
<td>3.67</td>
<td>6.04</td>
<td></td>
</tr>
<tr>
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<td>1989</td>
<td>31.38</td>
<td>184.94</td>
<td>Plot ploughed</td>
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<tr>
<td></td>
<td>1990</td>
<td>2.04</td>
<td>3.14</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1989</td>
<td>25.81</td>
<td>202.33</td>
<td>Wasted scrub (Eastern hillslope)</td>
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<td>27.18</td>
<td>50.64</td>
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<td></td>
<td>1990</td>
<td>5.50</td>
<td>5.32</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1989</td>
<td>17.03</td>
<td>5.91</td>
<td>Natural scrub (Western hillslope)</td>
</tr>
<tr>
<td></td>
<td>1990</td>
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<td>0.47</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1989</td>
<td>26.73</td>
<td>365.15</td>
<td>Wasted scrub (Western hillslope)</td>
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<td>1990</td>
<td>8.53</td>
<td>33.28</td>
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</tr>
<tr>
<td>9</td>
<td>1989</td>
<td>12.78</td>
<td>13.25</td>
<td>Natural scrub (Northern hillslope)</td>
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<td>2.92</td>
<td>0.61</td>
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</tr>
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<td>26.57</td>
<td>106.70</td>
<td>Wasted scrub (Northern hillslope)</td>
</tr>
<tr>
<td></td>
<td>1990</td>
<td>6.28</td>
<td>12.32</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1989</td>
<td></td>
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<td>Treated with polymers (40 gr/m²)</td>
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<td>1990</td>
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<td>14.77</td>
<td></td>
</tr>
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<tr>
<td></td>
<td>1990</td>
<td>8.58</td>
<td>45.39</td>
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</table>
Experimental Site "El Ardal"
Soil losses (gr/m²)

![Bar chart showing soil losses in grams per square meter for plots 1 to 12, with data from 1989 and 1990.](image)

Experimental Site "El Ardal"
Runoff (l/m²)

![Bar chart showing runoff in liters per square meter for plots 1 to 12, with data from 1989 and 1990.](image)

Fig. 3. Soil loss (g/m²) and overland flow (l/m²) in 1990
4.3. Fertility loss

On the whole losses are slight. The highest values, however, are found in plot
where scrub had been cut down and in the cultivated one, whereas the plot with scrub
showed the lowest values. Even when only the results of one year’s study are available,
it is evident that the greatest losses occur in spring and summer when the volume of
runoff is higher.

Clay minerals are carried off by overland flow at the same proportion that they
are found in the soil, or, at any rate, there is a slightly higher chlorite loss without there
being a differential esmectica loss.

4.4. Soil moisture

Various aspects of the study of soil moisture variations (Fig. 4), in the different
situations and edaphic levels which are controlled, are particularly notable. Due to its
constant high moisture content, soil under plant cover is of special interest. However,
the wide oscillations (30%) between wet and dry periods take place in this situation and,
above all, on the surface.

When the soil is completely uncovered, an extraordinary decrease takes place
during the dry months, July and August, with values of about 2-3% on the surface and
5-6% at the base of the soil profile. These values indicate an extreme situation in the
survival of plant cover.

Among these extreme cases, there is that of soil protected by the stoniness of
the surface. The softening effect of the stones on moisture variations can be thus
deduced, and it is in this situation that the least oscillations occur. Moreover, when the
soil is at its driest (August), soil under stones retains more moisture than under plant
cover and, obviously, than when it is bare.

There is also a notable difference in the moisture content between surface and
cross-section base, depending on the wetness or dryness of the period under analysis.
This difference is wider in the case of soil under plant cover.

4.5. Vegetation

Results obtained from variations in plant cover density studies (Fig. 5) show
that, on the whole, three main types of plant cover predominate: loose stones, rosemary
and forbs. The area occupied by bare ground is negligible. This indicates the importance
of including the total quantity of vegetation in erosion models (THORNES et al, 1990).
Taking the different types of cover together it is possible to state that in "El Ardal",
59% is plant covered; 30%, stone covered, 6% leaf-fall and dead plants and 5% bare
ground. It is also important to note that there are no great differences in plant cover from
season to season. As for plant growth, the greatest increase was recorded in the period
from April to June; from July to September the increase slows down and sometimes
Fig. 4. Soil moisture evolution under various conditions
Fig. 5. Average density of plant cover on three control plots (A, B, C) during the months April to September 1990. El Ardal Experimental Field.
LOPEZ-BERMUDEZ et al

stops altogether; from September to December 40%-50% of the plants experience a decrease; in the following months there seems to be a slight recuperation.

The quantity of leaf-fall produced by some species is in direct relation to the size of the plant. The greatest activity takes place between May and October.

Finally, for seasonal increase in scrub biomass, scrub protection of soil index and total rosemary scrub biomass calculation it is necessary to continue the study (although some data is available) in order to obtain significant results.

Acknowledgments

The first experiments on hydric erosion process control were begun under the auspices of Anglo-Hispanic Integrated Action 1982/84, London University (Bedford College), Bristol University and Murcia University (Dept. of Physical Geography). The scientists in charge were Professor J. Thornes and Professor F. López-Bermúdez. Since then this collaboration has grown and has carried out a large number of scientific projects. At present two projects on Climatic variability, erosion and desertification are being undertaken in semi-arid environments, as a part of the EPOCH Programme of the EEC. We would like to thank the British team of Prof. J. Thornes, Dr. C. Francis, Dr. J. Brandt and Dr. G Fisher for their efficient collaboration.

References


SOIL EROSION RESEARCH: EXPERIMENTAL
PLOTS ON AGRICULTURAL AND BURNT
ENVIRONMENTS NEAR BARCELONA.

M. A. MARQUES


ABSTRACT
Research on erosion was initiated in 1982 by Dr. M.A. Marqués of the Department of
G.D.G.P. of the University of Barcelona. The first part of the research was focused on the
agricultural sector as this was the sector most affected by erosion where the adoption of
relatively simple measures could result in considerable improvement. Quantification was
conducted by means of: a) small plots (5 to 10 m²) for sheetwash erosion processes and b)
calculation of volume of the eroded material in the rills. The sheetwash erosion showed
considerable interannual variability with rates of 2,400 g/m²/year to 81 g/m²/year. Poor
water management in the same zone caused a flow concentration and an increase in erosion
rates.
The subject of erosion in zones damaged by fire was raised in 1986 the year in which forest
fires were responsible for the destruction of more than 70,000 ha in Catalonia. The forestal
zone of Montserrat was selected. Four experimental plots 200 m² in size were prepared in
order to assess the influence of the orientation of the slopes and the cutting of burnt trees.
The responses were significantly different with respect to orientation. Erosion was six times
greater on south-facing slopes.
The results obtained in the two areas show the influence of extreme events on erosion which
may represent almost 99% of the total soil loss.

Key words: soil erosion, runoff, aspect control, human influence, extreme events, NE
Spain, burnt forest.

RESUMEN
En 1982 se inició la línea de investigación sobre los procesos y las tasas de erosión en el
Departamento de G.D.G.P. de la Universidad de Barcelona, bajo la dirección de M.A. Marqués.
En la primera etapa, la investigación se centró en el ámbito agrícola, por ser el más afectado
por la erosión y en donde la adopción de medidas relativamente simples puede mejorar
sensiblemente la situación. La cuantificación se realizó mediante: a) parcelas pequeñas (de 5 a

153
MARQUES

10 m²) para los procesos de arroyada difusa y b) cubicación del material evacuado en las incisiones debidas a la arroyada concentrada.
La erosión por arroyada difusa, en parcelas representativas de condiciones de mínima erosión, presentó una gran variabilidad interanual, con tasas entre 2.400 g/m²/año y 81 g/m²/año. En la misma zona la mala gestión del agua provocó una concentración del flujo y un aumento de la erosión, entre 10 y 40 veces superior a la producida arroyada difusa.
En 1986 se abordó el tema de la erosión asociada a los incendios, que durante ese año devastaron más de 70.000 ha en Cataluña. Se elegió la zona forestal quemada de Montserrat.
Se instalaron 4 parcelas experimentales de unos 200 m² para evaluar la influencia de la orientación de las laderas y de la tala o no de los arboles quemados. Las respuestas según la orientación fueron significativamente distintas; la erosión fue seis veces superior en las laderas de exposición sur.
Los resultados en los dos ámbitos indican claramente la influencia de los acontecimientos extremos en la erosión, que pueden llegar a representar hasta el 99% de las pérdidas totales de suelo.

Research on soil erosion at the Department of Dynamic Geology, Geophysics and Paleontology of the University of Barcelona was initiated in 1982 by Dr. M.A. Marqués. Since then, investigation focused on the influence of human activity and on the role of slope aspect in erosion has been carried out.

The need to pursue this line of research is based on: a) the social and economic importance of the problem which is recognized by the word scientific community.
b) the almost total absence of quantitative data and information on soil erosion rates in Catalonia.

As regards possible areas of investigation, the agricultural zone was initially selected since it is the most affected by erosion in Spain. This erosion may largely be attributed to the type of crop and to crop management. Crop management in many cases leaves the soil unprotected and tends to increase soil erodibility and rainfall and overland flow erosivity, e.g. keeping the land under continuous arable and bare soil between rows of soft fruit bushes and fruit trees, destruction of old terraces to increase plot size in order to mechanize production.

In 1986 the subject of erosion and its relationship with forest fires was raised. Forest fires are common in Mediterranean areas given the climate and the vegetation although in many cases they are provoked by man. In the period 1976-1987, 252.740 ha were destroyed by fire in Catalonia (with a total land surface of 31930 km²), which is an average of 21.000 ha/year. The summer of 1986 was an important one for forest fires due to meteorological conditions and to fires which were deliberately started. In this year more than 70.000 ha were destroyed by fire in almost 600 fires. These fires led to an increase in social awareness of the impact of the fires and galvanized opinion in political and administrative circles. Additional resources were obtained, new measures of prevention and control were adopted and the consequences of forest fires and those of post-fire management were debated. In this connection research on erosion in forestal areas damaged by fire was carried out in the Department.
EROSION ON AGRICULTURAL ENVIRONMENTS

1. Objectives

The first studies were carried out in an agricultural zone near Barcelona (Masquefa). Given the resources and the infrastructure available, the main aim was to assess the minimum erosion rates with respect to the management and the geomorphological characteristics of the zone.

In previous surveys the different situations or combination of existing variables in the zone had been analysed and the erosion rates had been assessed qualitatively or empirically. It was considered necessary to obtain for the first time quantitative values corresponding to the minimum erosion rates for the following reasons:

a) need for a smaller infrastructure and resources,

b) determination of the minimum values of erosion allowed us to consider that for any other situation where one or various factors were more unfavourable (slope angle, tillage, etc) the erosion rates would be higher and could supply initial information for soil conservation planning.

c) possibility to evaluate whether in this agricultural zone the erosion rates were within the acceptable limits on the assumption that values of erosion obtained were the lowest.

In this zone we selected a case in which the estimated erosion was greater and was caused by poor water management of a track giving rise to a rill system. The comparison of the different values obtained in the same field corresponding to two types of processes (sheetwash and rill) due exclusively to human activity offered a good example of this influence on soil erosion.

Research on forestal zones damaged by fire focused on the assessment of post-fire operations and the slope aspect impact on runoff and soil erosion. In the geomorphological surveys of the zones damaged by fire the control of the orientation in the evolution of slopes was noted. For this reason, it was considered necessary to assess the responses of post-fire erosion with regard to slope aspect. Our working hypothesis was that the slope aspect could be a significant cause of variability of runoff and soil loss in slopes damaged by fire. As regards the post-fire operations carried out in the region, it was decided to quantify runoff and soil loss associated with two operations: a) cutting and uprooting of burnt trees; b) non-modification of the slope leaving the burnt trees in situ. Other operations such as the construction of small dikes with remains of branches, etc. were assessed qualitatively.

The quantification of the influence of slope aspect and the post-fire operations in the runoff and soil erosion supplied the first real data on these variables in our region. They also constitute a fine example of the difficulty of extrapolation and generalization.
2. Materials and methods

The materials and methods utilized in the research projects were selected on the basis of the aims set and the resources available in each case. Therefore, in this section we shall treat separately the forestal zone damaged by fire and the agricultural one differentiating, in the latter case, between the specific techniques in accordance with the type of process (sheetwash and rill).

2.1. Agricultural zone

In the agricultural zone one aim was to evaluate the minimum erosion rates which previous surveys had shown to be associated with sheetwash. The other aim was to assess the erosion produced by a rill system associated with poor management of surplus water in a zone where the other characteristics were the same.

In order to assess the minimum erosion rates we selected some plots which were representative of the zone in which the control factors of erosion were the least favourable in terms of soil erosion and whose monitoring was relatively simple and feasible. The plots were selected:

a) with gentle slopes about 5° since they were widely cultivated.

b) with contour crop cultivation as conservation practice and without other conservation measures, since usually no other measures are taken or are used incorrectly. The contour crop is a fortuitous conservation practice given that the crop pattern and tillage direction are determined by the shape of the plot and not by any desire to combat erosion. It is not uncommon to find works aimed in theory at encouraging infiltration such as infiltration ditches which run from one end of the plot to the other which in some places are parallel to contour lines and in others are perpendicular. In the latter case they do not fulfill the objective for which they were constructed but encourage the concentration and drainage of runoff.

c) with orchards and vineyards usually with bare soil between, because of conventional tillage. This is the most common crop management and has the advantage of reducing the variability of the system. However, conventional tillage employed to eliminate weeds modifies both infiltration capacity and erosionability.

The localized formation of a system of rills was observed in one of the fields preselected for the installation of the experimental plots. This system was generated during heavy rain by poor drainage of the track which constituted the upslope edge of the field. The existence in one field of sheetwash under normal conditions and the appearance of rills due to human activity was a decisive factor in the selection of the research zone. It allowed us to obtain the rates of the two processes, make comparisons and to highlight the influence of man on erosion.
Photo 1. Open plot at Masquefa with a rectangular collector connected to a 30 l drum and equipped with a removable lid.

Photo 2. Collecting tanks with divisors which take one-twelfth of the flow from one of the twelve rectangular slots, installed in the Montserrat forest damaged by fire.
The system selected to assess the runoff and erosion rates was that of field plots under natural rainfall events. The main erosion process was sheetwash or interill given the characteristics of the plots selected (gentle slopes and contour rows). The capacity of rills parallel to the rows was only exceeded during heavy rains and small rills parallel to the slope were occasionally formed. Small plots (8 m long and 0.8 m wide) were justified considering the type of process and spatial uniformity. As for the plot boundaries, it was considered to be inadvisable to install lateral strips for a number of reasons:

a) The edge effects, which must be considered in all plots, are magnified in small ones, b) the interference of tillage operations and c) the uniformity of the slope controlling runoff direction and impeding the passage of water into and out of the plot. Removeable borders were considered to be more of a hindrance than a benefit. For this reason, in order to know the catchment area, the upper edge of the plot was located on a water divide. At the bottom edge of the plot the water and sediment were collected in a sunken trough running the width of the plot. The collector consisted of a rectangular trough (80 x 30 x 10 cm) made of galvanized iron with a slightly inclined lip with an edge which allows for a better adaptation to the slope. The box is connected to a 30 l drum so as to increase the capacity of the equipment. This equipment is placed in a row between two trees so as not to interfere with tillage.

The monitoring and sampling were carried out after every rainfall. Subsequently, as soon as the thresholds of effective rainfall were determined, the monitoring was restricted to these events. A detailed geomorphological survey was performed in addition to recording, sampling and emptying the water and sediments collected in the storage tanks.

A system for calculating the volume of material eroded by rilling was set up to assess this kind of erosion. To this end, the rills were mapped. This task was facilitated by the regular distribution of the trees which formed a reference grid with a space of 6 x 6 m. Next, a series of cross sections were performed to calculate the cross-sectional area. The separation and location of the cross sections depended on rill morphology. They were not performed at regular intervals but each time the rill changed its shape; the length of each morphological uniform stretch was measured simultaneously. The total eroded volume was calculated with a computer. A change of units was necessary so as to compare the erosion rates produced by sheet wash and rilling.

Rainfall data were obtained from a Hellman pluviograph installed near the plots.

2.2. Zones damaged by fire

After the prior geomorphological surveys the aim of the research was twofold: assess the impact of the post-fire management and assess the influence of slope aspect on runoff and erosion.
Photo 3. Close up of the bottom edge collector made with a plastic gutter fixed and adapted to the slope with a concrete and brick plank. The removable trough cover prevents direct rainfall input.

Photo 4. Close up of multislot divisors.
As regards the possible operations, we selected two possibilities: a) the cutting down and removal of burnt wood and b) the non-modification of the slope, leaving the burnt trees standing. Of the zones damaged by fire in Catalonia in the summer 1986 we selected Montserrat because of its social importance, its proximity to Barcelona (about 50 km) which reduced the cost of monitoring and because of the facilities offered by the landowners.

For the installation of the equipment two proximal slopes one facing the south and the other facing the north, developed on the same substrate, with regular and uniform slopes and similar angles, were selected. The main characteristics of the slopes had to be the same except for those derived from orientation. Other factors such as installation and monitoring facilities and safety guarantees were also taken into account.

The system of large experimental plots (200 m²) was employed for quantification of runoff and soil loss. This system was chosen because of the characteristics of cutting and tree removal and because of the desire to reduce as much as possible the interference with the rill development and to allow the cumulative effect of the slope length on the runoff. The plots were 20m long and 10m wide. The width was greater than that used habitually because in this way it was possible to have an integration of the erosion rates (rill and interrill). The use of smaller plots would have supplied distorted data or only local data (e.g. position of burnt trees, marks produced by dragging trunks, holes caused by combustion of tree stumps).

Four plots were planned: two adjacent plots on a south-facing slope and two on a north-facing one. In both situations one was left with all the burnt vegetation and in the other the large trees were cut and removed which is the normal practice in the region.

The plots were not limited laterally by artificial boundaries. The upslope border corresponded to the watershed except in the south-facing plot were we constructed a furrow and an earth ridge to divert the runoff of a rocky substrate outcrop situated on the higher ground. The inclusion of this outcrop in the plot would have introduced an element of variation in relation to the other plots. The furrow and the earth ridge are longer than the width of the plot and have a certain inclination to ensure drainage. These two factors prevent flooding and the entry of water into the plot.

At the bottom edge of the plot the runoff and sediment are collected in a sunken trough running the width of the plot. This is made up of a plastic gutter 25 cm in width and 10m in length fixed to the slope with concrete and brick plank. The whole of the gutter is covered with a removeable lid of galvanized iron so as to prevent rainwater from entering.

The validity of lateral limits was tested by the installation of tracers and monitoring after rainfall. It was confirmed that the width of the plot coincided with that of the collection canal and the lateral borders coincided with the line of maximum slope.
EROSION ON AGRICULTURAL ENVIRONMENTS

The collection tanks were equipped with a Geib multislot divisor due to the size of the plots (200 m²) and the estimated runoff rates. The apparatus consists of three tanks (the first two with divisors) fixed onto a concrete platform in order to ensure the horizontality of the divisor slots.

To monitor rainfall a meteorological station (SIAP 2000) with a continuous band to record rainfall, temperature, humidity and wind (direction and velocity) was installed. Moreover, on each plot rain gauges were set up at a height of 40 cm, one horizontally and the other with an inclination coinciding with that of the slope. The two plots situated on the north-facing slope were adjacent with the result that two pairs of rain gauges were set up, one on higher ground and the other on lower ground.

The plan of sampling and monitoring was similar to that of the agricultural plots with special emphasis placed on the development of vegetation cover.

3. Results

3.1. Agricultural zone

The published results of erosion plots on agricultural land corresponds to the period 1983-85 (MARQUES & ROCA, 1984, 1986 and 1987). The main conclusions to be drawn from these results are the following.

Table 1. Rain, runoff and soil loss at Masquefa (period 1983-85) showing the interannual variability of the parameters.

<table>
<thead>
<tr>
<th>Year</th>
<th>Rainfall (mm)</th>
<th>Rain days</th>
<th>Runoff (l/m²)</th>
<th>Soil loss (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>1983</td>
<td>582.5</td>
<td>403.9</td>
<td>178.6</td>
<td>46</td>
</tr>
<tr>
<td>1984</td>
<td>628.5</td>
<td>413.0</td>
<td>214.8</td>
<td>61</td>
</tr>
<tr>
<td>1985</td>
<td>389.0</td>
<td>129.0</td>
<td>260.0</td>
<td>46</td>
</tr>
</tbody>
</table>

1) Total; 2) Effect.; 3) No effect.; 4) Total; 5) Effect.

a) Great interannual variability in erosion rates which stress the need for long periods of monitoring to obtain significant results. The erosion rates were: 2.4 kg/m² in 1983; 0.358 kg/m² in 1984 and 0.081 kg/m² in 1985.

b) Importance of extreme events such as the event of 2nd September 1983. During these three years of records (1983-1985) the total soil loss was 2939 g/m² and one single event produced an erosion of 1669.3 g/m² that is to say 85.5% of the total.

c) Poor crop management produced an increase of erosion rates, between ten and forty times greater than the normal. This is a clear example of the influence of man on erosion: the oblique tillage enhanced runoff and produced an over -topping of the drainage channel situated along the upper side of an almost horizontal track. The
overtopped flow crossed the track and poured down the next field in a concentrated runoff. Sheetwash was the typical erosion pattern of this contour cultivated plot but the input of the concentrated runoff developed a rill system thus increasing erosion.

d) The threshold of effective rain in these plots is about 7 mm, but some greater rainfalls did not produce erosion. This is due to the variable physical conditions of the soil (mainly wetness and availability of erodible particles) dependent on the tillage operations and intervals between rains.

Moreover, the correlation between runoff and soil loss shows a linear distribution after eliminating the extreme event of 2nd September 1983. Nevertheless, there are some anomalous points which may be attributed to the aforementioned factors.

e) the plotting between total effective rainfall and the density of the flow collected in the tanks is especially interesting (Figure 1).

![Graph showing the relationship between density of runoff and rainfall](image)

Figure 1. Relationship between density of runoff and rainfall (MARQUES & ROCA, 1987)

At first glance, the points seem to be randomly distributed. However, there is a series of points which have a density that is practically constant (about 10 g/l) regardless of the amount of rainfall. The other group has an exponential distribution: density increases with rain. We consider that these two trends may be associated with different transport processes. The low density flows are related to the washing down of fine particles. The transport process associated with the second group (with higher density flows which even transport gravel size particles) seems to be a micro-scale mass movement by shear failure. The shear failure mainly results from an increase in pore water pressure. It is worth noting that dense flows are usually generated at times when
EROSION ON AGRICULTURAL ENVIRONMENTS

the ground has a greater infiltration capacity due either to long periods of drought or to recently ploughed ground.

3.2. Forest zones damaged by fire

Most of the results arising from the research carried out in forest zones damaged by fire are awaiting publication. At the Mediterranean Erosion Symposium held in August 1989 MARQUES & MORA (1989) presented the erosion rates of two plots with the same post-fire treatment but with contrary orientation.

This work focuses on the role of slope aspect on soil erosion. In the period between August 1987 and December 1988 the soil loss in the north facing-plot was 351.1g/m² and on the south-facing one was 2175 g/m², that is to say, six times greater.

In these experimental plots (Marqués and Mora in press) the importance of extreme events and the differential response versus these with regard to the slope aspect is stressed. Of the total erosion produced during this period, most erosion took place in two events. On the south-facing plot the soil erosion was 98,8% and on the north-facing plot it reached 99.1%.

As regards the differential response it should be pointed out that although the percentages were similar the absolute values of erosion were very different. On the south-facing plot the soil loss of these two events were 2,152 g/m² and on the north-facing one 348.9 g/m². As for the runoff, both the averages of runoff and those of the runoff coefficient recorded on both plots are different.

A paper on the impact of the post-fire management containing the quantitative data of the two adjacent plots treated in a different way is in preparation. Qualitative results of other types of operation such as the construction of small dikes with the remains of branches, track-opening to remove trunks, system of dragging and removal of trunks, etc. will also be included.

References


MARQUES


RESEARCH ON BIOTURBATION IN THE SPANISH MOUNTAINS

Juan P. MARTINEZ-RICA, Carlos E. BORGHI & Stella M. GIANNONI

Instituto Pirenaico de Ecología (C.S.I.C.), Zaragoza, Spain.

ABSTRACT
The role played by small fossorial mammals, mainly rodents, in soil movement and erosion of mountain soils is discussed. Research done in Spain is briefly described and compared to that done elsewhere. The results show that in some places the burrowing mammals are even the first geomorphic factor, controlling soil losses. Bioturbation by Pyrenean voles es of the same order of magnitude as that of other larger and more specialized fossorial animals, such as gophers, which are recognized as a major geomorphic factor in mountains of North America.

Keywords: Pitymys, Microtus, rodents, fossorial mammals, bioturbation, erosion, Pyrenees.

RESUMEN
Se discute el papel desempeñado por los pequeños mamíferos excavadores, y en especial por los roedores, en la bioturbación y pérdida del suelo en la montaña española. Se describe la investigación realizada en España y se comparan sus resultados con los obtenidos en otros países. Estos resultados demuestran que en algunos lugares dichos animales constituyen un factor de primer orden en el modelado de la superficie y en el control de la pérdida de suelo. La bioturbación por parte de los topillos pirenaicos es del mismo orden de magnitud que la debida a otros animales mayores y más especializados en la vida subterránea, como los geómidos, que se acepta son un factor geomorfológico principal en las montañas de Norteamérica.

As soil is nowadays a valuable and easily lost resource, it is not difficult to understand the interest caused by the studies of erosive processes. On mountains, erosion is almost always more intense than on lowlands, because, the remaining conditions being alike, soil loss depends on slope. This dependence is not linear but exponential (WISCHMEIER & SMITH, 1978); hence areas with a slope of 50 %, so
frequent in mountains, have a soil loss over ten times greater than others with a 5% slope (in fact, about 22 times greater).

All the mountain systems of the world are, thus, highly vulnerable to erosion. And some countries, such as Spain, which have a large average altitude and a complex topography, suffer from erosion in a specially intense way. Besides that, erosion is higher in mountains lacking arboreal vegetation. The part played by plant cover in erosion can be grossly estimated from the Universal Soil Loss Equation (USLE); while it is difficult to be precise, we can say that, in general, erosion is from 4 to 10 times greater for patchy grassland pastures than for forests. As a consequence, the most vulnerable areas in the mountains are epiforestal levels, which have the highest mean slope.

A third and probably main factor of erosion is related to climatology. Soil loss depends, as everyone knows, on the intensity and concentration of rainfall. Short and intense precipitations, with raindrops having high kinetic energy and with a fall rate high enough to prevent total absorption by soil, produce much greater erosive losses. These kind of rains are quite frequent in Mediterranean areas, where rainfall is often irregular and comes in torrential form.

All these conditions are found together in the Pyrenees, especially in the eastern part of the southern side, which has a high mean slope of about 48% for the epiforestal levels. The plant cover, although formerly a continuous subalpine grassland, has been deeply disturbed by man and livestock, giving birth to gaps and naked soil areas. Moreover, man has cut down or burned a large part of the Pyrenean forests, converting them into unprotected pastures.

The Mediterranean Pyrenees are specially vulnerable to erosion because of climatic factors. Rainfall is irregular, with autumn or spring peaks. In the Central Pyrenees the maximum rainfall in November reaches, on average, 275 mm, and about 70% of it falls as intense precipitations (DAVY, 1978). The French side has similar values (VIGNEAU, 1985). While the mean recurrence period for precipitations surpassing 100 mm/day is 19 years in Panticosa (Spanish Central Pyrenees) it descends to two years in the eastern extreme of the range (ELIAS, 1963). And from time to time, there is one enormous, catastrophic rainfall in one or other point of the Pyrenees, mainly towards the east: 120 mm/day in Navarre, 122 mm/day in Huesca province, 112 mm/day in Lerida province and 220 mm/day in Gerona. The highest rainfall record for the whole of Pyrenees is 1250 mm/day in the French Oriental Pyrenees (Haut de Camelade, October, 17, 1940: NOVOA, 1984).

All these reasons make the study of erosive processes in the Pyrenees worthwhile; it is not surprising, then, that the study of erosion in Spanish mountains started in the Pyrenees, with the work of many geomorphologists and ecologists (Creus & Garcia Ruiz, 1977; Sala & Salvador, 1980; Garcia Ruiz & Arbella, 1981). The majority of these studies tried to point to the main erosive factors and forms taken by erosion, and to measure the amount of soil lost under different meteorological
BIOTURBATION IN THE SPANISH MOUNTAINS

circumstances. But, amongst the many factors influencing erosion and soil movement, there is one which has been relatively ignored, not only in Spain but elsewhere: the organic agents, mainly animals: who remove the top soil layer at scales between cm² and hectares, making it available for the climatic erosive factors, carrying the removed earth outwards.

1. Bioturbation by animals

The part played by animals in soil movement has been known for a long time, and has been studied by such important authors as DARWIN (1881). Almost always, the emphasis of these studies has been put on the role of animals as soil fertilizers of lowland cultures and grasslands, sometimes on their function as forest soil decomposers, but rarely on their interference with erosive processes. Darwin himself, however, mentioned amongst the effects of earthworms activity their apparent contribution to soil erosion.

The amount of soil dislodged by earthworms has been evaluated at between 3 and 60 metric tons/ha.yr, with an average value of 27 tons on flat, cultured lowlands within temperate zones (EVANS & GUILD, 1947), although Darwin had already given higher estimates. Burrowing activity of earthworms was studied, thus, at least a century ago, while that of other animals has received attention more recently.

Many animals other than earthworms live and burrow into the soil, bringing it to the surface: some molluscs, many arthropods, some amphibians and reptiles, a few species of birds and a lot of mammals. This last group has the highest impact on soil movement, after the earthworms. By burrowing more or less complex tunnel systems, they remove earth at centimetric, metric or even larger scales.

Thirteen of the 19 orders of living mammals include fossorial forms, more or less adapted to subterranean life; of all them, the most important, both by the number of fossorial species and by the impact on soil movement, is that of rodents. Three factors explain this importance: their small size, the position of rodents throughout trophic chains, and their capability for demographic increase. Their small size allows them to shelter in small, easy to build holes, and is the cause of the place they have in the trophic chain, serving as an abundant prey to larger predators; because of this trophic level of primary consumers, they have evolved anatomical and behavioural mechanisms to seek refuge from its enemies quickly, and their fossorial habits are, just, one of these adaptations; in fact, several species of fossorial rodents only dig when inhabiting unprotected places, and have only epigeal habits if they live under a dense plant cover. Finally, population dynamics of rodents allow them sometimes to increase enormously in number, giving the well known population outbreaks, and starting huge migration processes.

Mammals other than rodents can be also good soil movers; damage or even erosion attributed to rodents is due, often to other species. It is not surprising that a geomorphologist such as Ineson mistakes fossorial animals for rodents whose erosive
activity he studied in Luxembourg Ardennes (IMeson & KWAAD, 1976), but the right identification of the animal erosive agents is important, not only for any researcher, but also because of the practical implications for the soil manager. To have a heavy impact on soil movement a mammal must dig extensively; having anatomical features well adapted to digging, living in soil burrows, or even building these burrows, is not enough. Thus, following this restrictive definition, the following non rodent mammal families can be considered formed by efficient soil movers:

Notoryctidae, or Marsupial moles (Australia)
Dasypodidae, or Armadillos (mainly South America)
Chrysochloridae, or Golden moles (Africa)
Talpidae, or Moles (Eurasia)
Orycteropodidae, or Aardvarks (Africa)
Ochotonidae, or Pikas (North America and Asia)
Suidae, or Hogs (mainly Eurasia and Africa)

Many other mammal families although not primarily diggers, include true fossorial species.

Amongst the rodents, the next families include forms having a clear influence on the top soil layer of their biotopes:

Sciuridae, or Squirrels (Eurasia, Africa, America)
Geomyidae, or Pocket gophers (North America)
Heteromyidae, or Pocket mice (North America)
Muridae, or Rats, Mice and Voles (Worldwide)
Chinchillidae, or Viscachas and Chinchillas (South America)
Octodontidae, or Mountain rats (South America)
Ctenomyidae, or Tucutucos (South America)
Bathyergidae, or Mole rats (Africa)

From the former list we can see that only two rodent families having some impact on soil movement live in Eurasia. However, most of the data on the role of rodents in soil movement comes from North America, where the family of pocket gophers has been specially studied. In Europe not many rodents play a heavy part on bioturbation, although there are several burrowing species. In the whole Palearctic Region, 34 rodent genera include burrowing species, and of these, only 11 (Marmota, Spermophilus, Cricetus, Mesocricetus, Spalax, Nannospalax, Arvicola, Pitymys, Microtus, Lagurus, and Prometheomys) have true fossorial species; good diggers are found also in other genera. Most of the soil movement due to European fossorial mammals is to be attributed to moles (Talpa), which are not rodents, mole-rats (Spalax), voles (Arvicola, Pitymys, Microtus) and wildboars (Sus). The erosion attributed by IMeson & KWAAD (1976) to rodents must refer, instead, probably to moles.
BIOTURBATION IN THE SPANISH MOUNTAINS

In the Pyrenean Range there are 17 species of mammals with more or less frequent burrowing behaviour. The list is given next; see MARTINEZ RICA & PARDO, 1990) for a brief comment on each species of the list.

Talpa europaea
Meles meles
Vulpes vulpes
Oryctolagus cuniculus
Sus scrofa
Apodemus flavicollis
Apodemus sylvaticus
Arvicola sapidus
Arvicola terrestris
Marmota marmota
Microtus agrestis
Microtus arvalis
Microtus cabrerae
Microtus nivalis
Pitymys duodecimcostatus
Pitymys lusitanicus
Pitymys gerbic

Not all these species have the same incidence on soil movement. Moles (Talpa europaea) are good diggers, but they do not like high slopes. Above the forest line, the species having a strong impact on soil movement are those of genus Pitymys, Sus scrofa and, in a lesser degree, Microtus arvalis.

2. Amount of soil removed by rodents

The importance of small fossorial rodents in the movement of soil has been known at least since the GRINNELL paper (1923). This and other values are listed in the adjoining table, by no means complete where the species able to live in mountains are marked by an asterisk.

Several of this table's comments are in order. Estimates of removed soil are quite variable, and although we have made some efforts to uniformize the data, many of these are not reliable, not only because the doubtful procedures used to measure or estimate the amount of earth or the density of animals, but also because the author himself does not supply the data. In several cases we have taken estimates of soil removed by one animal from some author and estimates of the density of animals from another, combining both estimates to get the result; in such a case, we have listed only one of the authors to save space; for the same reason we give the reference in the shortest form, but the list of bibliographic references at the end of the paper includes all the consulted papers.
MARTINEZ-RICA et al.

To uniformize listed data is not always easy. Volume data can be converted into weight data by multiplying by soil density. This is not known in the majority of the cases, but values measured by us are of 0.6 to 1 kg/dm$^3$; the values of weight must be, therefore, somewhat smaller than the values of volume. A greater problem is to uniformize the data differing in the area or the time span considered. In most cases the author does the estimate from a small area of high density, and extrapolation to larger areas is not reliable. If the data refers to different periods of time the uniformization is difficult. Estimates are given normally for one year, but in some cases they are given for one day, one month, one season, or even without time limit (in the last case the authors give just the amount of removed earth above the soil). As both the digging activity and the number of animals in one population change from month to month, extrapolation of results for the whole year is not feasible. Anyway, a good part of the removed soil remains under the surface, often serving as a plug in some entrance holes or in blind burrows. Because of all these reasons, the data in table 1 are only orientative, and rather conservative. Real data might be, in the majority of cases, much higher.

Taking into account all these considerations, and reducing the scope to species living in mountains above the timberline, it is possible to summarise the indications of the preceding table in the following way:

A common feature of the data is their magnitude; most of them are high, of the order of several tonnes a year in one hectare. From the viewpoint of soil movement, small mammals are of the same importance as the earthworms, and in mountains they have a far greater importance. Of course, removed soil does not mean lost soil, but given the high slope of mountain territory and the conservative character of the data, we can conclude that small fossorial animals must be considered as a geomorphological agent in the mountains of the northern temperate zone. The inclusion of southern fossorial species (such as the South American Telenomidae or the South African Bathysteridae) would reinforce our conclusion, because the highest recorded values of removed soil by fossorial mammals correspond to these families alone.

Bioturbation by northern fossorial rodents in mountains vary from 2.6 to 124000 kg/ha.yr (higher values, such as that of SETON, have been discarded). The small values correspond to small mice and voles, such as Microtus or Apodemus, and vary between 2.6 to 648 kg/ha.yr. Intermediate values correspond to other Muridae, and to geomyids and marmots, varying from 480 to 53000 kg/ha.yr. The highest values, from 54000 to 124000 kg/ha.yr correspond to one species (Arvicola terrestris monticola), and have been recorded in the Pyrenees; we must point out, however, that this is only an extrapolation from observations done on a 25 m$^2$ plot.

3. Types of erosion triggered by rodents in Spanish Pyrenees

Bioturbative activity of European rodents has been not so heavily studied as that of American species. A few papers (DUFOUR, 1971; AIROLDI, 1976; IMESON & KWAAD, 1976 a and b; DENDALETCHES et al., 1984; HIPPOLYTE, 1984, 1985
<table>
<thead>
<tr>
<th>SPECIES</th>
<th>LOCALITY</th>
<th>AMOUNT</th>
<th>REFERENCE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Thomomys talpoides</td>
<td>Yosemite Valley</td>
<td>8.9 Tm/ha</td>
<td>GRDNEILL, 1923</td>
<td>One winter intranival remains</td>
</tr>
<tr>
<td>*Thomomys monticola</td>
<td>White River Plateau</td>
<td>162.4 m3/ha</td>
<td>SETON, 1929</td>
<td>One month !!!</td>
</tr>
<tr>
<td>Thomomys sp.</td>
<td>Texas</td>
<td>6.2 Tm/ha</td>
<td>SHELFORD, 1929</td>
<td>One winter</td>
</tr>
<tr>
<td>Geomys breviceps</td>
<td>Texas</td>
<td>0.8 Tm/ha</td>
<td>BUECHNER, 1942</td>
<td>One year, no grazing</td>
</tr>
<tr>
<td>Geomys breviceps</td>
<td>Texas</td>
<td>19.7 Tm/ha</td>
<td>BUECHNER, 1942</td>
<td>One year, overgrazed area</td>
</tr>
<tr>
<td>*Thomomys talpoides</td>
<td>Washak Plateau</td>
<td>11-14.5 Tm/ha</td>
<td>ELLISON, 1946</td>
<td>One year</td>
</tr>
<tr>
<td>Cistennus pygmaeus</td>
<td>Rostov, Russia</td>
<td>60 kg</td>
<td>OGNEV, 1947</td>
<td>Rough estimate from his data</td>
</tr>
<tr>
<td>Cistennus undulatus</td>
<td>Amur province</td>
<td>3-15 Tm/ha</td>
<td>OGNEV, 1947</td>
<td>As before</td>
</tr>
<tr>
<td>Marmota bobac</td>
<td>Saratov, Russia</td>
<td>3-180 Tm/ha</td>
<td>OGNEV, 1947</td>
<td>As before</td>
</tr>
<tr>
<td>Spalax microphthalmus</td>
<td>Dneprorosvosk</td>
<td>Max. 3.9 Tm/ha</td>
<td>OGNEV, 1947</td>
<td>Only one animal</td>
</tr>
<tr>
<td>Spalax giganteus</td>
<td>Russian plain</td>
<td>0.2-0.3 m3/day</td>
<td>NOVIKOV et al., 1953</td>
<td>Forest steppe, one year</td>
</tr>
<tr>
<td>Apodemus sybaticus</td>
<td>Central Europe</td>
<td>12.0 Tm/ha</td>
<td>VORONOV, 1953</td>
<td>Calculated from their data, 1 year</td>
</tr>
<tr>
<td>Cletherionomys glareolus</td>
<td>Central Europe</td>
<td>2.6-6.6 m3/ha</td>
<td>VORONOV, 1953</td>
<td>Calculated from their data, 1 year</td>
</tr>
<tr>
<td>*Arvicola terrestris</td>
<td>Alps</td>
<td>23.5-51.8 m3/ha</td>
<td>VORONOV, 1953</td>
<td>Pastures above timberline, 1 year</td>
</tr>
<tr>
<td>Microtus socialis</td>
<td>Russian plain</td>
<td>2.1 m3/ha</td>
<td>HODASHOVA, 1960</td>
<td>Forest steppe, one year</td>
</tr>
<tr>
<td>*Thomomys talpoides</td>
<td>Logan, Utah</td>
<td>88.1 Tm/ha</td>
<td>RICHEINS, 1966</td>
<td>Extrapolated from one animal</td>
</tr>
<tr>
<td>Elllobius, Spalax, etc</td>
<td>Central Asia</td>
<td>3-15 Tm/ha</td>
<td>ZIMINA, 1970</td>
<td>Forest steppe, one year</td>
</tr>
<tr>
<td>*Marmota sp.</td>
<td>Tien Shan &amp; Pamir</td>
<td>18-120 m3/ha</td>
<td>ZIMINA et al., 1970</td>
<td>Mountain pastures, one year</td>
</tr>
<tr>
<td>Apodemus flavicolis</td>
<td>Czechoslovakia</td>
<td>3.9-253 m3/ha</td>
<td>PELIKAN et al., 1974</td>
<td>Calculated from their data, 1 year</td>
</tr>
<tr>
<td>Rodents (Taipa ?)</td>
<td>Ardennes, Luxemb.</td>
<td>3.3 kg</td>
<td>IMESON et al., 1976</td>
<td>One year, net soil loss, mild slope</td>
</tr>
<tr>
<td>Rodents (Taipa ?)</td>
<td>Ardennes, Luxemb.</td>
<td>101.0 kg</td>
<td>IMESON et al., 1976</td>
<td>One year, net soil loss, river bank</td>
</tr>
<tr>
<td>*Thomomys talpoides</td>
<td>San Juan Mts., Co.</td>
<td>1.3 Tm/ha</td>
<td>STOECKER, 1976</td>
<td>Alpine tundra, one year</td>
</tr>
<tr>
<td>*Thomomys talpoides</td>
<td>San Juan Mts., Co.</td>
<td>1.3 Tm/ha</td>
<td>STOECKER, 1976</td>
<td>On willow-tree plots, one year</td>
</tr>
<tr>
<td>*Thomomys talpoides</td>
<td>Front Range, Co.</td>
<td>3.9-5.8 m3/ha</td>
<td>THORN, 1976</td>
<td>One year</td>
</tr>
<tr>
<td>Crictetus cricetus</td>
<td>.......</td>
<td>0.5-33 Tm/ha</td>
<td>NECHAY et al., 1977</td>
<td>Rough estimate from his data</td>
</tr>
<tr>
<td>*Marmota baibacina</td>
<td>Western Tien Shan</td>
<td>7.8-452 Tm/ha</td>
<td>ZIMINA et al., 1980</td>
<td>Mountain pastures, no time limit</td>
</tr>
<tr>
<td>*Marmota caudata</td>
<td>Northern Pamir</td>
<td>2.5-242 Tm/ha</td>
<td>ZIMINA et al., 1980</td>
<td>Mountain pastures, no time limit</td>
</tr>
<tr>
<td>*Marmota caudata</td>
<td>Eastern Pamir</td>
<td>18-663 Tm/ha</td>
<td>ZIMINA et al., 1980</td>
<td>Mountain pastures, no time limit</td>
</tr>
<tr>
<td>Spalax microphthalmus</td>
<td>Chernozem Reserve</td>
<td>2.2-2.3 Tm/ha</td>
<td>ZLOTIN et al., 1980</td>
<td>Open steppe, 1 year</td>
</tr>
<tr>
<td>Spalax microphthalmus</td>
<td>Chernozem Reserve</td>
<td>0.2-0.3 Tm/ha</td>
<td>ZLOTIN et al., 1980</td>
<td>Open steppe, 1 year</td>
</tr>
<tr>
<td>*Arvicola terrestris</td>
<td>French Pyrenees</td>
<td>90.0 Tm/ha</td>
<td>HIPPOLYTE, 1984</td>
<td>Extrapolation from one colony</td>
</tr>
<tr>
<td>*Thomomys bottae ?</td>
<td>Kearny Mesa, Ca.</td>
<td>573.4 m3/ha</td>
<td>COX &amp; GAHAHU, 1986</td>
<td>From supplied data, no time limit</td>
</tr>
<tr>
<td>*Thomomys bottae ?</td>
<td>Cuyamaca Lake, Ca.</td>
<td>746.8 m3/ha</td>
<td>COX &amp; GAHAHU, 1986</td>
<td>Same as before, no time limit</td>
</tr>
<tr>
<td>*Microtus arvalis</td>
<td>Merced County, Ca.</td>
<td>1390.5 m3/ha</td>
<td>COX &amp; GAHAHU, 1986</td>
<td>Extrapolation from one colony</td>
</tr>
<tr>
<td>Jaculus jaculus</td>
<td>French Pyrenees</td>
<td>1.5-43.7 kg</td>
<td>HATOUCH-B., 1990</td>
<td>Calculated from his data, 1 year</td>
</tr>
<tr>
<td>Gerbillius dasyurus</td>
<td>Jordan</td>
<td>0.2-1.9 dm/3ha</td>
<td>HATOUCH-B., 1990</td>
<td>Calculated from his data, 1 year</td>
</tr>
<tr>
<td>*Microtus sp.</td>
<td>Spanish Pyrenees</td>
<td>0.1-0.8 dm/3ha</td>
<td>MARTINEZ et al., 1990</td>
<td>Pastures above forest, 1 year</td>
</tr>
<tr>
<td>*Thomomys bottae</td>
<td>Marin, County, Ca.</td>
<td>72-720 kg/ha</td>
<td>BLACK et al., 1991</td>
<td>Hills with grass and herbs, 1 year</td>
</tr>
</tbody>
</table>
3.1 Winter activity

Pyrenean voles are not always fossorial. Some species, such as *Microtus arvalis* only dig when no other protection is available, and hence, much of the digging activity of this and related animals takes place on the subalpine mountain zone, where there are few trees and bushes. Voles remain active during the winter under snow; they make burrows both in the soil and within the snow layer. Removed soil is brought to the snow tunnels, and when the snow melts long soil cores are laid down on the surface. Other remains of under-snow activity are the patches of vegetation-denuded ground and open paths on the soil surface, which can be seen in the spring around the melting snowfields.

The areas of undersnow activity for Pyrenean voles have been evaluated at between 36 and 250 m² on the French side. On the Spanish side activity patches are smaller (several square meters) and are always next to the spring-snow remains. In these areas 10-20 % of the surface is deprived of plants, and hence open to erosion. Average estimates of soil removed during the winter in activity areas is about 2 kg/m² in the Spanish Pyrenees. These areas are small and sparse; however, the significance of them for soil movement is, nonetheless appreciable.

3.2. Direct digging activity out of winter

After the snow melts, voles increase their digging activity in a quest for shelter from predators. This activity takes diverse forms depending on the nature of the biotopes. There are two major types of vole colonies: those located in areas with low slope and dense grass cover, and those located on more open and steep zones, exposed to frequent soil freezing. In the first case the animals make more or less branched burrows up to 1.5 m deep, with underground chambers. In the second case the animals prefer to settle on steps of small terraces among grass; here the animals use surface runs located near the edge of terraces, removing only small amounts of soil.

The extent of the disappearance of soil brought by voles to the surface as a result of their digging activity depends on specific situations, primarily the average slope of the colony locality. If the slope is low the losened earth compacts rapidly after the first rains, and is retained on the site and is rapidly covered by vegetation. However, in areas with even a moderate slope part of the soil slides down before compacting. Soil transported outwards from the mound location varies between 100 % (in that rare case all the earth disappears, leaving only a hole in the surface) and about 40 %.

A different situation arises on open slopes with a terraced surface. Here, the vole population density, as well as their digging activity, is low, and the plant cover is
to sparse to stabilize the soil: the soil movement here depends almost totally on the interaction of plants with climatic factors, the voles playing only a secondary part.

3.3. Interaction between voles and geomorphic processes

The role played by voles in soil movement depends on various abiotic and biotic factors, and often works through interaction with geomorphic processes. These interactions assume one of three main forms: interaction with freezing processes, interaction with the phenomenon of bank collapsing and interaction with water drainage.

Interaction with the cycles of freeze-thawing seem to be of small importance. Bank formation, instead, although local, is more important. This process begins with small breakings in the plant cover; if soil remains exposed for a sufficient time, a small gully can appear, because the soil is retained only in the upper parts of the scar, where plant roots can keep it in place. The bottom of the gully starts then to deepen and widen. These places are heavily populated by voles, specially if they face south; voles like the upper parts of the bank very much, because here they are protected by the grass cover which overhangs the scar border, and in the southern-facing places, they can be rapidly warmed by sun. As a result, just under the grass layer there are many holes made by animals, and, consequently, the overhanging border falls again and again. The voles become in such a place an additional erosion agent which accelerates upwards erosion.

Of considerable interest is the third type of interaction, the contribution of voles to water drainage through their burrows. These burrows often become a very active part of the general hydrological network, channeling the water during snow melting or during heavy rains. Water-flows through the burrow system are directly noticeable in the late spring near snow patches. Strong rains may have great importance on this flow, even in abandoned colonies, because while earthmounds in the surface disappear sooner or later, the structure of underground burrows is more permanent, supplying many waterflow pathways. Sometimes, during heavy thunderstorms, we observed the reactivation of closed burrows in old abandoned colonies: water pressure washed away the soil plugs closing burrow entrances. This is proof of the underground flow of water through the burrows, which most of the times remains undetected. BLACK & MONTGOMERY (1991) also consider the underground waterflow as the dominant transport system in a catchement colonized by Thomomys bottae.

3.4. Interaction with other animals

While several species of vertebrates can use or modify in some way the structure of burrows and earthmounds built by voles, the most important Pyrenean species, from the viewpoint of consequences leading to erosion is the wild boar. This animal searches for the underground food stores of voles, and digs up very large areas, frequently located on rather steep slopes. Uprooted plants do not always grow fast enough to allow soil stabilization, and sometimes the activity of wild boars is the
trigger mechanism for the start of the gullying processes already described, or for soil sliding movements. Association between wild boar activity and vole colonies has not been confirmed, but we have always found traces of vole activity in areas dug by boars in the mountain pastures.

4. Observations on the Spanish Pyrenees

The lack of previous data on burrowing species of Mediterranean mountains, and the difficult observation and differentiation of species of fossorial voles, made the study of bioturbation in the Pyrenees rather hard. We were forced to deal with several aspects of the problem simultaneously. From a geomorphological viewpoint the most interesting question is to find out the amount of moved soil by rodents in mountains. As we have seen, many of these more or less reliable estimates are available, but those for European mountains are scarce.

Our results refer to four species of voles, *Pitymys duodecimcostatus*, *P. lusitanicus*, *P. gerbill*, and *Microtus arvalis*. All these are found in the Pyrenees, are more or less fossorial, reach the subalpine pasture zone and live together in some places. This last circumstance makes the study of the activity of each species difficult, because they are morphologically quite similar, and cannot be distinguished without capture, or even when captured. We consider, therefore, the four species as a unique set, and refer all the data to "voles" without specific indications.

The study area is located in the Spanish Central Pyrenees, next to the Lecherines peaks, at an altitude of 2000 m (fig. 1). Some other data have been gathered in the Aisa valley, the Izas watershed and the Portaleit, all them being nearby localities. Most of the observations were made on a 100 x 100 m plot, where the four mentioned species are found, showing different levels of burrowing activity. Our study deals with several aspects of the ecology of the voles, but here we shall deal only with those related to bioturbation.

Moreover a single species, *Pitymys duodecimcostatus*, has been studied in the laboratory. Actual rate of excavation and its variability has been measured for this species in artificial conditions. More details on that are found in BORGHI et al. (in press) and GIANNONI et al. (unpublished).

4.1. Earthmounds density

Within the observation plot the total number of earthmounds was 1060. This may seem low when compared to other counts, such as that of BLACK & MONTGOMERY (1991) for gophers, about 2500 earthmounds/ha, but those authors counted the earthmound for a whole year, while our counts were done only during one month. As the plot was divided into 100 squares of 10 x 10 m, counts of mounds on each square was feasible. The average number was, of course, 10.6 mounds/square, the extremes being 0 and 193 earthmounds/square. These values are quite different, and this, together with the median value (5 mounds/square), and with the very high variance
BIOTURBATION IN THE SPANISH MOUNTAINS

(468.8), shows that distribution of earthmounds is strongly skewed towards low values. The majority of the squares have between 0 and 10 mounds, and only three have more than 50. These data reflect also a heavily clustered pattern in the spatial distribution of mounds (BORGHI et al., in press).

![Map of France and Spain](image)

Fig. 1. Location of the work area

The size of earthmounds is variable, with diameters between 11 and 35 cm; mean diameter is 16.4 cm, closer to the low extreme of the range; this point also to a skewed distribution. The area covered by an earthmound varies between 95 and 162 cm², with an average value of 211 cm². This means that on the whole plot, 22.4 m², 0.2 % of total surface, is covered by removed soil, but the percentage may reach 4 % in the squares where concentration is highest. The counts include only recent earthmounds. Taking into account the older remains of vole activity the proportion of denuded earth is much higher, and if we consider that available soil covers only a part of the plot the other being exposed rock the importance of the animals as geomorphic agents seems quite clear.

4.2 Amount of removed soil

Most of the authors who measure earthmound volumes use a beaker, the others making only crude estimates, without measurement. In fact, the measurement of earth volume is inaccurate because of the different conditions of soil compaction. Weight measures are influenced also by the water content of soil; the most accurate measurement would be, therefore, the dry weight of the earth, but this cannot be taken in the field. In our work, we have tried indirect measurement, that is, to take some easy measurement in the field and to calculate the corresponding volume from a known relationship. We shall not describe the procedure in detail (see BORGHI et al., in press) the main results of the study being sufficient.
After studying the relationships between geometrical measurements of the mounds and their dry weights in a sample of 100 mounds, we were able to supply a regression model. Calling $W$ the dry weight, $V$ the volume, $D$ the mound diameter and $H$ the mound height the model has the form:

$$(W)^{-3} = 0.25 D + 0.20 H + 1.61$$

For the volume, the corresponding model is:

$$(V)^{-3} = 0.25 D + 0.32 H + 1.48$$

Both models have all their terms significant, and their corresponding determination coefficients are 0.87 and 0.96, also clearly significant. These models were used to calculate the total volume carried to the surface by voles in the experimental plot, after measuring the height and diameter of all the mounds.

![Graph showing distribution of the size of rodent heaps in the experimental plot.](image)

Fig. 2.: Distribution of the size of rodent heaps in the experimental plot.

The mean volume of an earthmound is 585 cm$^3$. In the entire plot, the amount of removed soil is, thus, 620 dm$^3$, more than half a cubic meter. Given the mean soil density measured in the sample of 100 mounds, this represents a fresh weight of about 500 kg/ha, and a dry weight of 372 kg/ha. Distribution of the mound sizes is illustrated in fig. 2.
BIOTURBATION IN THE SPANISH MOUNTAINS

It is rather difficult to convert these measures on estimates of the amount of soil removed throughout the year. As only the fresh and recent mounds were counted, most of them had an age of one week or less; but the observations were taken in a period of high activity, and we cannot simply multiply the result by the 52 weeks in a year. On the other hand, the result of such a simple multiplication might be still too low, not only because a substantial part of the removed soil remains under the surface, but also because the age estimate given for the mounds, one week, is close to the maximum and far from the minimum. But to be conservative, let us suppose that the activity of voles lasts only three months, the plant growing season in the subalpine level (this is not true, of course, given the well known winter activity). In such a case, we must multiply the amount of removed soil by 13, giving a total of about 8 m$^3$/ha, corresponding to a dry weight of about 6.4 Tm/ha, and a dry weight of 4.8 Tm/ha.

These values, which are conservative, as we have said, are of the same order of the majority of those given by other authors for fossorial mountain rodents, mainly geomyids. Ours and theirs, however, have the common feature of being taken in localized areas, where concentration of animals is specially high.

5. Potential burrowing rate

Among the topics we shall briefly touch here, let us refer to the evaluation of the ability to dig of some fossorial voles. While observations in the field give some high values, the burrowing behaviour reaches a peak, of course, when conditions are optimal. These conditions are found by captive, well fed animals, having plenty of soil available, and without any possibility for shelter save digging. The peak of the excavation rate occurs when a vole is put in a new enclosure, during the first hours of observation.

We have measured this peak rate of excavation in one species, *Pitymys duodecimcostatus*, the study of other species being now underway. Lack of space prevents us from giving the detailed experimental procedures, and thus, we present only the results. We shall see that in natural conditions, voles realize only a small part of their potential digging capability.

One specimen of the mentioned Mediterranean vole dug, on average, 2092 g of well packed soil a day, that is about 2.4 dm$^3$. This means about 80 times their own weight. Direct extrapolation of these figures to natural populations is not allowed, but if done, would give enormous results, well over 1000 Tm/ha.yr. The important point about this excavation rate is that it is still too low. Experimental procedure caused most of the burrowing activity to take place during the first hour of observation, and during this time, excavation rate reached 10.8 g/min (GIANNONI et al., unpublished). This is more than seven times higher than the previously given rate, and shows the immense potential for soil movement the fossorial animals of the mountains have.

How do these results compare to those supplied by other authors, and to field observations done by ourselves? Well, of course, the burrowing activity of mountain
animals is not so high, but nevertheless noticeable, and is even a major geomorphic element in some places. While direct action is low, we cannot forget that every burrow, being not completely vertical, means some horizontal transport of soil. For other species, such as Thomomys bottae, this horizontal transport has been estimated between 0.91 and 2.33 cm³·cm⁻¹·yr⁻¹ (BLACK & MONTGOMERY, 1991). While much lower than long term transport, this direct component of the animal erosion is only the smallest part of it. The main influence of animals on erosion is indirect, as we have seen, and this is recognized by the mentioned authors. Rodents burrows and mounds for not only an effective system of waterflow channels, but also a heterogeneity factor, which provides the otherwise uniform subalpine soil with a complex structure.

In such a structured environment, even minor perturbations may have wide consequences. The collapse of an undermined area by simply stepping on it, is not rare when burrow density is high (GIANNONI, *in verbis*). Major perturbations, such as thunderstorms, are amplified by the rodents activity, and can give origin to landslides or important soil movements.

Perhaps the main interest in the study of mammals bioturbation stems from their multiple interaction capability. Limited to itself, the voles system is already a quite complex one, including several species, with a potentially explosive demography regulated by migration, predation, and environmental limitations. But voles are also a central link in the still more complex network of subalpine ecosystems. Vital for predators and other animals, strongly modifying vegetation structure because of their feeding on roots and stems, they interact also strongly with soil and other abiotic factors and elements. Thus, voles, and small mammals in general, are an indispensable element which integrated many of the processes and flows within a mountain ecosystem. Their study is, consequently, not only essential, but also paradigmatic.

References


BIOTURBATION IN THE SPANISH MOUNTAINS


APPLICATION OF SIMULATED RAINFALL FOR STUDYING RUNOFF YIELD AND EROSIIVE BEHAVIOUR OF GYPSIFEROUS SOILS

Ana NAVAS

U.E.I. de Edafología. Estación Experimental de Aula Dei. CSIC. Zaragoza.

ABSTRACT
Increasing awareness of the serious problem of soil loss around the world has emphasised the relevance of research in the field of soil erosion. Recognition of the major role played by rainfall impact and runoff on soil erosion in semiarid regions of Spain was the main reason for the design of a rainfall simulator. The assessment of the relative importance of physiographical factors in determining runoff yield and erosive behaviour of the studied gysiferous soils was approached through field experimentation applying simulated rainfall on soil plots under different experimental conditions.

The results showed that in this environment an average of 50% of total rainfall appeared as runoff. The greatest runoff yield was produced from plots with the stoniest and steepest slopes along with those having the lowest percentages of plant cover. Suspended gypsum yields ranged from 0 to 3.9 gm⁻²h⁻¹, the higher values occurring with steeper slopes and dry soil conditions. The dissolved gypsum transport was positively related to stoniness and slope and the load transported ranged from 5 to 40 gm⁻²h⁻¹. Erosion of these gysiferous soils has a clear effect on runoff salinity as proved by the increase in solute release when sediment concentration increases.

NAVAS

RESUMEN

La investigación sobre la erosión del suelo se ha visto potenciada por el creciente concienciamiento sobre la gravedad de la pérdida de suelo que se produce en el mundo. El papel preponderante del impacto de la lluvia y la escorrentía superficial sobre la erosión del suelo impulsó el diseño y construcción de un simulador de lluvia para el estudio de procesos erosivos en condiciones de campo. La reproducción de distintas situaciones experimentales sobre parcelas de 1.25 x 1.25 m a las que se aplicó lluvia simulada, permitió el análisis del efecto de distintos factores fisiográficos sobre la producción de escorrentía y el comportamiento erosivo de los suelos yesíferos estudiados.

Los resultados obtenidos mostraron que en este ambiente semiárido hasta un 50% del total de lluvia aplicada aparece como escorrentía. Las mayores producciones de escorrentía se obtuvieron en condiciones de más alta rocosidad y pendiente junto con mínimos porcentajes de cobertura vegetal. El transporte en suspensión de partículas de yeso varió para las condiciones investigadas entre 0 y 3.9 gm^{-2h^{-1}} presentando una relación inversa con el porcentaje de rocosidad y directa con la pendiente. Las mayores producciones de sedimentos se registraron en parcelas de máxima pendiente y condiciones iniciales de suelo seco. Por el contrario, el transporte de yeso disuelto se relacionó positivamente tanto con la rocosidad como con la pendiente y la carga transportada osciló entre 5 y 40 gm^{-2h^{-1}}. La erosión de los suelos yesíferos estudiados tiene un claro efecto sobre la salinidad de la escorrentía, evidenciado tanto por el paralelismo de las variaciones espacio-temporales de la salinidad y escorrentía, como por el incremento de solutos producido al aumentar la concentración de sedimentos.

Erosion of surface materials by water has long been recognized as a fundamental process in the degradation of agricultural ecosystems. In the last few years scientists of many countries have warned of the danger of the disappearance of some of the more productive soils, mainly along the European Mediterranean littoral. The main factor triggering the degradation of the mediterranean agrosystems is the hydrological process causing soil erosion.

Large areas of Spain have been identified as having some of the highest erosion rates in the world (OCDE, 1985). Around 25% of the surface area of the country has been identified as having a grave state of erosion and in some semiarid regions (Murcia, Andalucía, Aragón and Canarias) it reaches 40%.

In Aragón, and specifically in the central part of the Ebro valley, most of the soils are thin and have a low level of fertility. Along with these poor edaphic conditions, other limiting factors are climatic and topographic. Within this environment, overgrazing and intensive agricultural use of the land means that large areas have scarce plant cover, insufficient to protect the soil from erosive agents. On the
SIMULATED RAINFALL IN GYPSEIFEROUS SOILS

Other hand, the velocity of formation of these soils is very slow; consequently their degradation poses a major environmental problem as soil constitutes a non-renewable resource.

Although the traditional concern regarding soil erosion has focused on the reduction in productivity of agricultural land, interest in the significance of other problems indirectly related to off-site damage due to soil erosion has recently increased substantially.

Thus, in the semiarid central Ebro valley, the impact of heavy storms on abundant saline and gypsiferous soils and subsequent runoff (transporting solutes and detached gypsum particles) can contribute greatly to the salinization of surface waters from non-point sources in the Ebro basin.

This paper presents the technique of rainfall simulation and the field methodology used to study some aspects of the erosion processes affecting soils in the central part of the Ebro valley. Aspects concerning the runoff yield and erosion of gypsiferous soils under simulated rainfall as well as the influence of this process on the salinity of runoff are discussed. Also the more relevant results of the field experiments conducted to assess the effect of some selected factors on soil erosion are commented on.

1. Rainfall simulator and field methodology

Since the 1930's many researchers have designed different types of simulators with the aim of collecting data about erosion, infiltration, runoff and sediment transport. The usefulness of rainfall simulators has been widely discussed (e.g. MEYER, 1965).

Proper analysis of processes dealing with soil erosion and solute and sediment transport by runoff requires longterm record data. In natural conditions and in the climatic environment of the middle Ebro valley (semiarid conditions), the first problem posed is the sporadic occurrence of rainfall and its timing.

However, an extensive number of factors are simultaneously involved in soil erosion processes. If in addition, it is possible to select suitable experimental sites as well as to control the factors affecting these processes, either by suppressing those that interfere, or even better fixing them according to our interests, then application of simulated rainfall on field plots can be very advantageous.

A rainfall generating apparatus was designed for studying processes of soil erosion (NAVAS et al, 1990). It is basically composed of the following elements: a metallic frame with a spray nozzle, a metallic structure to define the plot perimeter, a
device to collect runoff, a gauged sampler and a pumping unit to supply water from the tank to the nozzle.

The simulator produces rainfall of 48 and 58 mmh⁻¹, representative of storm events encountered in the middle section of the Ebro valley. The drop size distribution of the simulated rainfall is close to that recommended by BUBENZER (1979). For D₅₀, fall velocities obtained by operating pressures of 29.4 and 58.8 kPa represent between 85 and 97% (rainfall of 48 mmh⁻¹) and between 86 and 98% (rainfall of 58 mmh⁻¹) of their terminal velocity. According to the sprinkling height, average kinetic energy values are 13.10 Jm⁻²mm⁻¹ for rainfall of 48 mmh⁻¹, and 13.00 Jm⁻²mm⁻¹ for rainfall of 58 mmh⁻¹.

An experimental methodology (NAVAS, 1989) applying the technique of rainfall simulation on field plots was developed for studying solute and sediment transport by runoff. This methodology consists of the following phases: i) Characterization of the experimental plot: selection of the soil type, and other physiographic factors such as vegetation type, stoniness and slope. ii) Series of experimentation in each plot. In this phase and for each set of simulation runs, several combinations of factors such as plant cover percentage, soil moisture condition and rainfall intensity can be considered. iii) Determination of hydrological, chemical and sedimentological parameters produced from the different conditions tested.

2. Runoff yield from soil plots under simulated rainfall

In semiarid regions, even though total annual precipitation presents low values, water losses due to runoff are very high (AGASSI et al., 1985). In the central part of the Ebro valley, lithology has a great influence on the infiltration determining whether runoff quickly reaches the surface streams. This fact along with recognition of the important role of runoff on soil erosion led to the design of a field experimental study on production of runoff from different soil types and experimental conditions (ALBERTO & NAVAS, 1988). In order to achieve this, the technique of rainfall simulation was applied on field plots following the experimental methodology outlined above.

Results of this study confirmed the direct relationship between physical environmental factors and the generation of runoff. Confirming the experimental data of HILLEL (1967) and AGASSI & ARBEL (1981), an average of between 50 to 55% of the total rainfall appeared as runoff. The greatest runoff yield was registered from soils of highest stoniness and slope with the lowest percentages of plant cover.

Runoff varied directly with rainfall intensity, thus a 10% increase in rainfall intensity produced a 3% increase in runoff. The relationship between runoff yield from
SIMULATED RAINFALL IN GYPSIFEROUS SOILS

unvegetated and vegetated plots (Figure 1) showed higher runoff yield from unvegetated plots, displaying the influence of vegetation on infiltration. The regression equation between values of runoff produced from wet, vegetated plots (x) and dry, vegetated plots (y): $y = -4.25 + 0.83x$ (where $n=9$, $r=0.756$, significant at 99.98%) confirmed a higher runoff yield from wet plots. Plant cover and soil moisture were the factors that either accelerated or delayed the timing of runoff appearance, this usually being produced three minutes after the start of each experiment. Initially, runoff volume was low but gradually increased showing a quick trend to stabilization with time.

![Regression line graph](image)

**Fig. 1.-** Linear regression between runoff yields from unvegetated and vegetated plots.

3. The effect of simulated runoff on soil erosion

Processes of denudation and sediment transport by runoff have been the subject of investigation by BRYAN & HODGES (1984), FROEHLICH & SLUPIK (1984) and IMESON et al (1984). There are very few erosion studies specifically concerned with erosion on saline soils, but some involving similar geological and climatic conditions to those found in the Ebro river valley (underlayed by thick gypsiferous formations in its central part) have been carried out by PONCE & HAWKINS (1978) and NATIV et al (1983). FRANCIS (1986) estimated annual soil losses from gypsiferous marls in Murcia (Spain) but did not distinguish between solute, suspended and bed load, nor the chemistry of soil erosion.

Four major interactive factors determine the magnitude of the soil loss. These are: climate, topography, vegetation and soil. In order to analyse the effect of some of these factors on the erosion processes affecting the gypsiferous soils in the central Ebro valley, several sets of field experiments were carried out (NAVAS, 1990 a,b). Among
the mentioned factors, rainfall intensity, antecedent moisture condition, slope angle, percentage of plant cover and soil type were considered.

Three types of the most representative gypsiferous soils were chosen for study sites. Simulated rainfalls of 48 and 58 mmh-1 were applied to experimental plots of 1.25 x 1.25 m, exhibiting representative characteristics of these soils. For each soil type, the simulation experiments were conducted on slopes of 4%, 8% and 16%. For each slope a sequence of 5 experiments lasting 15 minutes at 10 minutes intervals was undertaken. The first experiment starts with a rainfall intensity of 48 mm h-1 on dry soil with natural vegetation cover. This is followed by an application of rainfall intensities of 58 and then 48 mm h-1, for the successive conditions of wet soil with natural vegetation and, after suppression of plant cover, on the wet, unvegetated soil.

Runoff was collected in buckets to measure discharge. Separate samples for hydrochemical analysis were taken every 3 minutes for 1 minute starting 4 minutes after the commencement of the simulation run, totalling 5 samples for each experiment.

The experiments exhibited differing erosive behaviour under the several conditions tested. Suspended gypsum yields ranged from 0 to 3.9 gm-2 per hour, the higher values occurring with the steeper slopes and dry soil conditions. Transport of suspended gypsum was inversely related to rock outcrop, and positively related to slope. This study also showed that higher rainfall intensity produces higher soil erosion rates.

On the other hand, the dissolved gypsum load transported by runoff ranged from 5 to 40 gm-2 per hour and was positively related to rock outcrop and slope. Rainfall intensity produced a small dilution effect. Dry soil conditions and higher percentages of plant cover favoured higher gypsum concentrations. Runoff was undersaturated in gypsum with values ranging from -1.4 to -0.3. In terms of chemical denudation, if all the storm events in the area were of the same intensity as those considered in our study, the annual diminution of the surface of gypsiferous soil would be 0.04 mm.

The highest dissolved gypsum yields were recorded in Dystric Leptosols, followed by Gypsic Calcisols (lithic phase) and then Gypsic Calcisols. With reference to the suspended gypsum transport (which was not found to occur with Dystric Leptosols) the opposite sequence was registered.

4. The influence of soil erosion on runoff salinity

Soil erosion produced by overland flow greatly contributes to degradation of quality of runoff, mainly when soluble minerals are associated with transport of sediments. Relationship between the transport of soil particles and quality of runoff has
Fig. 2.- Spatial and temporal variations of the sediment concentration and runoff salinity for each soil type.
been studied by several authors (MUNDORFF (1972), PONCE (1975), WALLING (1978), LARONNE & SHEN (1982)), that have encountered signifiacative correlations between solute and sediment yields.

The effect of soil erosion produced by rainfall impact and overland flow on the salinity of runoff was examined in 9 plots of gypsiferous soils subjected to simulated rainfall of 48 mm h⁻¹ (NAVAS, 1990c).

\[ r^2 \times 100 \]

![Graph](image)

Fig. 3.- \( r^2 \) distribution of the linear regressions of electrical conductivity against sediment concentration for each soil type.

The results showed that salinity of runoff was spatially and temporarily related to sediment transport. The solute release increased with an increase in the sediment concentration. There fore, no dissolution from sediments was observed in Dystric Leptosols which presented mean sediment concentration of 213 mg l⁻¹, whereas in Gypsic Calciolts (lithic phase) and Gypsic Calciolts, with mean sediment concentrations of 439 and 326 mg l⁻¹ respectively, the increase in solutes from the dissolution of soluble minerals transported as particulate matter was 10% and 20% respectively.

Relationships between sediments and salinity of runoff analysed in this study suggested a clear causal relationship between these two parameters. This was sustained in the paralelism between spatial and temporal variations of sediments and runoff salinity as shown in Figure 2. Also, the increase in solute release when sediment concentration increased confirmed this relationship (Figure 3).
5. Conclusions

The use of the technique of rainfall simulation enabled experiments to be undertaken over a short time period, and so has proved suitable in obtaining runoff and soil erosion data which can be used in programmes of soil conservation.

Because of the high frequency of heavy storms in the area, preservation of the plant cover (reducing the impact of raindrops and allowing the infiltration of water) is required to avoid land degradation.

Estimations of annual diminution of soil surface have suggested that in the semiaridic climate of the region, the chemical denudation produced by overland flows and rills is probably an important process conditioning the relatively fast landform evolution of the gysiferous hillslopes.

Runoff was found to be implied in the dynamic evolution of gysiferous hillslopes, by transporting gypsum particles down slope which are then deposited on the talus and on the foot talus, thereby developing a characteristic profile as well as the genetic evolution of soils.

Anthropogenic activity in this environment, reducing the plant cover either by tillage, overgrazing, or deforestation, can produce a great environmental impact, with serious consequences for soil erosion and the quality of runoff.

References


A PRELIMINARY RESEARCH ON THE USE OF CESIUM-137 TO INVESTIGATE SOIL EROSION IN THE SEMIARID LANDSCAPE OF THE CENTRAL EBRO RIVER VALLEY

Ana NAVAS & Javier MACHIN

U.E.I. de Edafología. Estación Experimental de Aula Dei. CSIC. Zaragoza.

ABSTRACT
Because of its strong adsorption by clay minerals, cesium-137 measurements offer considerable potential in tracing soil movement. Some results of using this technique for investigating patterns of soil erosion in the central part of the Ebro river valley are reported. Sampling at various sites in the area gives evidence to support the close relationship between mobilization of $^{137}$Cs and that of the soil. Soil erosion was identified at some hilltop sites and slope talus by depleted levels of $^{137}$Cs. Sedimentation was indicated by $^{137}$Cs profiles extending to greater depths than the plough layer. Values of the reference inventories of $^{137}$Cs found in the region are within the range of values found in soils of Northern Europe. Variability of $^{137}$Cs concentration was high and the coefficients of variation were 19% at a forest site, 26% on a cultivated field and 60% at a mid-slope site. The $^{137}$Cs measurements have provided evidence of the feasibility of applying this approach for studying soil erosion and sedimentation in semiarid environments.

Key words: Cesium-137. Soil erosion. Landscape. Semiarid environment. Ebro river valley. NE Spain.

RESUMEN
Debido a la fuerte adsorción del cesio-137 por los minerales de la arcilla y la evidencia empírica de que su redistribución se asocia con la de las partículas de suelo, las medidas de este radioisótopo presentan un potencial notable para trazar el movimiento del suelo. Este trabajo presenta los resultados de una investigación preliminar para determinar la distribución de los contenidos de cesio-137 y su relación con la erosión del suelo en emplazamientos seleccionados de la parte central del valle del Ebro.
Los resultados del muestreo en distintos emplazamientos han demostrado la estrecha relación existente entre la movilización de cesio-137 y la del suelo. La erosión del suelo ha sido
In semiarid Spain, soil loss, which is mainly attributed to the poor land management of very fragile agrosystems and ignorance of soil limitation, poses a serious environmental problem.

Assessment of soil erosion is required in order to design effective strategies for soil conservation. Even though measurements of soil loss have been made all around the world, there is only limited information on the patterns and rates of soil erosion. Estimations of soil erosion rates are then very useful when compared with those considered as acceptable to maintain natural rates of soil formation.

For nearly two decades the radioactive isotope cesium-137 has effectively provided real data (rather than model data) of soil erosion. As the bibliographic review by RITCHIE & McHENRY (1990) shows, 137Cs has been used widely for studying erosion and sedimentation in many different environments around the world and this radioisotope is known as a unique tracer of the soil movement.

The 137Cs technique was pioneered in the USA by RITCHIE et al (1974). Research conducted in Canada by DE JONG et al. (1983), in Australia by LONGMORE et al (1983) and CAMPBELL (1983), and in Britain by WALLING et al (1986) and LOUGHRAN et al. (1987) has proved that the 137Cs technique is a reliable method in estimating rates of soil erosion.

The purpose of this study is to investigate the possibilities of application of the 137Cs technique in studying soil erosion in fragile agrosystems found in the semiarid central part of the Ebro river valley (NE Spain).

1. The problem of soil erosion and its assessment

In the last few years, soil erosion has been viewed with increasing interest in Europe. As a result, EC policy on natural resources and environment gives special consideration to this problem. Attention is being focused on fragile soil systems in aggressive climates mainly located along the European Mediterranean littoral.
USE OF CESIUM-137

Within this physiographic environment, abundant fragile agrosystems in Spain are quickly losing fertile top soil, and so the surface area seriously affected by erosion has been estimated at around 40% in some semiarid regions. Apart from the economical losses due to reduced productivity, costs of indirect effects of soil erosion affecting water quality, storage capacity and eutrophication of water bodies have been estimated as being much higher (CLARK, 1985).

Concerning the assessment of soil erosion, WALLING & BRADLEY (1988) highlighted the general lack of field techniques for monitoring the erosion and sedimentation within a basin scale, and WALLING & QUINE (1990) indicated that only limited information about the rates of erosion occurring in England exists. In Spain and despite the seriousness of the erosion problem, we face a similar concern over the lack of reliable data about the actual soil loss.

Estimates of soil erosion in sediment budgets are generally based on the use of the Universal Soil Loss Equation. Problems concerning the use of the USLE, applied to areas different from those that provided the data base from which this empirically based equation was derived, are well documented.

On the other hand, limitations of classical techniques used to measure soil erosion such as field erosion plots, collecting troughs across the slope and aerial photographic surveys have led to research in more accurate methods such as the tracer techniques.

According to WALLING & QUINE (1991), who have investigated the potential of the 137Cs approach for investigations in Britain, the technique offers the following important advantages over other methods: i) it provides a quantitative measure of rates and patterns of soil erosion, ii) all the contributing processes are represented in the erosion rate measured which represents a long-term average (ca. 30 years), iii) only one visit is required to the study site and no disturbance of the slope environment is done. Apart from these reasons, the 137Cs technique measures net soil loss and thus provides better information on true erosion rates and sediment delivery (MARTZ & DE JONG, 1987).

FREDERICKS et al (1988) indicated that 137Cs has the potential to provide a universal physically based method of estimating soil loss. Also LOUGHRAN (1989) and RITCHIE & McHENRY (1990) have identified the 137Cs as the tracer with greatest potential in soil erosion studies. On the other hand, improved computational procedures for estimating soil loss through several predictive models have increased the need for real data that can be provided by applying this technique.

2. The Cesium-137 technique

Cesium-137 is a radioactive isotope produced by atomic weapons tested between 1950 to 1970. Its initial atmospheric deposition started in 1954, and two major periods of deposition in 1958 and 1963-1964 and two other minor periods in 1971.
and 1974, corresponding to moratoriums on testing, can be distinguished (CARTER & MOGHISSI, 1977).

A recent source of 137Cs in Europe was produced from the Chernobyl nuclear reactor accident of in 1986. Nevertheless, WALLING & QUINE (1991) indicate that Chernobyl-derived 137Cs deposition is almost negligible over most of Britain. Our own data in samples of Spain also confirm this fact.

137Cs was injected into the stratosphere where it was global and homogenously distributed (LONGMORE, 1982) and reached the land surface by rainfall and fallout. Spatial distribution of 137Cs is clearly related to local precipitation patterns and rates (LONGMORE, 1982; CAWSE & HORNRL, 1986). Nevertheless, WALLING & QUINE (1991) indicate that local variation of 137Cs deposition following variation of individual rainfall events is minimised by deposition from numerous events over an extended period of time.

After fallout and because 137Cs is highly reactive, its incorporation into soil particles and sediments is very rapid and it remains strongly adsorbed on clay and organic particles (TAMURA, 1964). 137Cs is essentially nonexchangeable and has a limited mobility by chemical processes (LOMENICK & TAMURA, 1965). COUGHTREY & THORNE (1983) found that removal of 137Cs by crops is usually below 1% of total 137Cs in the soil. No movement of 137Cs by infiltration or root penetration was found and its redistribution occurs associated with other soil particles by physical processes such as tillage and erosion or deposition processes (ROGOWSKI & TAMURA 1970).

The isotope has a half-life of 30.17 years, therefore approximately half of the total 137Cs deposited remains today at stable uneroded sites. Cesium-137 emits a strong gamma-ray (662 keV energy level) and can be easily measured with gamma-ray spectrometry equipment.

3. The use of Cesium-137 to study erosion

The spatial distribution of 137Cs in an area can be used to determine rates and patterns of soil erosion and redeposition as well as movement of eroded material beyond the area (McHENRY & RITCHIE, 1977; WALLING & BRADLEY, 1988; WALLING & QUINE, 1990).

To measure erosion, a baseline input of 137Cs must first be determined. This can be estimated by measuring 137Cs in soil profiles at stable uneroded sites (CAMPBELL, 1983, WALLING et al, 1986). Eroded and uneroded sites are then distinguished according to the deviation of the total 137Cs inventory (mBq cm-2) measured in the soil profile from the input 137Cs value determined for the area. Where soil erosion has taken place the content of 137Cs will have been depleted. On the contrary, values of total 137Cs inventory higher than the local reference inventory are found when deposition has occurred.
USE OF CESIUM-137

Analysis of the distribution and depth of 137Cs in soil profiles also permits the distinction among eroding, non-eroding and depositional sites.

Eventually, rates of erosion and deposition can be determined if a quantitative relationship between loss and enrichment of cesium-137 and quantity of erosion and deposition is established. To achieve this several theoretical models (KACHANOSKI & DE JONG, 1984; QUINE, 1989; WALLING & QUINE, 1990, 1991) have been developed.

4. An attempt to apply the Cesium-137 technique in Spain

In order to examine the possibility of application of the cesium-137 technique for studying soil erosion in Spain a reconnaissance survey was undertaken. Aspects concerning depth and design of sampling, distribution of 137Cs in the landscape and within the soil profile, values of the reference inventory and spatial variability of 137Cs in the soil have been considered.

4.1 Sampling methods and laboratory analysis

To determine the 137Cs distribution in the landscape and within the soil profile, samples were taken at different locations within a large area comprising the central part of the Ebro river valley. Sites at cultivated, uncultivated and forest land were sampled with a 8-cm diameter tube to various depths. Collection of samples include two types: core samples and sectioned samples at 5 and 10 cm depth increments.

Soil samples were dried at 45°C for 72 hours and sieved through a 2 mm mesh screen. A representative fraction of the samples was packed into Marinelli beakers prior to analysis. The 137 Cs content was determined by counting the gamma emission of the 662 keV using a germanium detector connected to a multi-channel analyser. Counting times were about 30000-50000s. 137Cs content was expressed on a mass basis (mBq g-1) and on an area basis (mBq cm-2). Analysis were performed at the Department of Geography of the University of Exeter (England).

4.2 Determination of the sampling depth to retain the entire cesium-137 profile

Collection of the entire 137Cs profile is required so as to compare it with the reference inventory established for an area and so to be able to distinguish between eroded and uneroded sites. On the other hand, the depth at which 137Cs is no longer detectable can be used as a relative indicator of the amount of deposition that has occurred (BROWN et al., 1981).

One aim of this study was to investigate the depth to which the entire 137Cs profile is retained in both cases of eroding or aggrading profiles. In order to do this, samples sectioned into 5 and 10 cm depth increments were taken at various depths at: i) stable, uneroded ii) eroded and iii) depositional sites. According to the results obtained (Table 1), the depth of sampling must attain 30 cm for both undisturbed and eroded
sites. In the case of depositional sites, samples must be driven to a depth of 60 cm to assure collection of the entire 137Cs profile.

Table 1. Depth distribution of cesium-137 in an undisturbed forest, an eroded slope and a depositional field

<table>
<thead>
<tr>
<th>UNDISTURBED FOREST</th>
<th>ERODED SLOPE</th>
<th>DEPOSITIONAL FIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth cm</td>
<td>Activity mBq cm$^{-2}$</td>
<td>Depth cm</td>
</tr>
<tr>
<td>0-15</td>
<td>69.7</td>
<td>0-5</td>
</tr>
<tr>
<td>5-10</td>
<td>33.3</td>
<td>5-10</td>
</tr>
<tr>
<td>10-15</td>
<td>35.8</td>
<td>10-15</td>
</tr>
<tr>
<td>15-20</td>
<td>16.3</td>
<td>15-20</td>
</tr>
<tr>
<td>20-25</td>
<td>5.8</td>
<td>20-25</td>
</tr>
<tr>
<td>25-30</td>
<td>1.6</td>
<td>25-30</td>
</tr>
<tr>
<td>30-35</td>
<td>0.0</td>
<td>30-35</td>
</tr>
<tr>
<td>35-40</td>
<td>0.0</td>
<td>35-40</td>
</tr>
<tr>
<td>40-45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3 Values of the reference inventory of cesium-137 found in the region

As mentioned above, to distinguish between eroding, non-eroding and aggrading profiles it is necessary to determine the reference inventory of 137Cs for the area. In order to achieve this, samples were collected at stable, undisturbed sites. Because of the intense agricultural use in the region and its semiarid environment, the first problem posed is to find undisturbed sites. A reconnaissance survey of the region led to suitable sites being found mainly at the top of the tertiary central plateaux.

Table 2. Reference inventories of cesium-137 in soils of the Tertiary plateaux in the central part of the Ebro river valley

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>137Cs ACTIVITY mBq cm$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castellar 1</td>
<td>343.3</td>
</tr>
<tr>
<td>Castellar 2</td>
<td>263.6</td>
</tr>
<tr>
<td>La Muela</td>
<td>117.4</td>
</tr>
<tr>
<td>Loma Negra 1</td>
<td>192.9</td>
</tr>
<tr>
<td>Loma Negra 2</td>
<td>164.9</td>
</tr>
<tr>
<td>Loma Negra 3</td>
<td>212.2</td>
</tr>
<tr>
<td>Loma Negra 4</td>
<td>210.7</td>
</tr>
<tr>
<td>La Plana</td>
<td>201.3</td>
</tr>
<tr>
<td>Santa Quiteria</td>
<td>231.2</td>
</tr>
</tbody>
</table>

196
USE OF CESIUM-137

A total of 9 sites in areas of pasture and woodland were selected. Samples were taken to a depth of 30 cm with surface area of 30 x 30 cm. 137Cs content was measured and ranged from 117 to 343 mBq cm-2 (Table 2). The input baseline of 137Cs registered in Devon (England) by WALLING & BRADLEY (1988) was 250 mBq cm-2. In Northern Europe values for reference inventories ranged from 156 to 261 mBq cm-2 in soils located in the Belgian loamy region (VANDEN BERGHE & GULINK, 1987).

Seven of the reference sites sampled presented activities within this range (Table 2). Values below 200 mBq cm-2 should be considered as suffering some erosion. Because strong winds are very common in the region, special care is needed when selecting reference sites that, despite being level, could be affected by erosion or sedimentation processes caused by wind, thereby depleting or increasing the levels of 137Cs content.

4.4. Distribution of cesium-137 in the landscape

To examine the 137Cs distribution in the landscape, a selection of soil types representative of the physiographical conditions existing in the central part of the Ebro river valley was chosen.

Data collection was carried out on areas of gypsiferous, sodic and saline soils. In each of these areas, three sites along the slope: crest, talus and foot of the slope were sampled. In these, it is respectively assumed that there is no erosion, erosion is produced and sediment deposition occurs.

Table 3. Distribution of cesium-137 along slope profiles of gypsiferous, sodic and saline soils

<table>
<thead>
<tr>
<th>SLOPE LOCATION</th>
<th>SOIL TYPE</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gypsiferous</td>
<td>sodic</td>
<td>saline</td>
<td></td>
</tr>
<tr>
<td>137 Cs mBqcm⁻²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>crest</td>
<td>20</td>
<td>194</td>
<td>477</td>
<td></td>
</tr>
<tr>
<td>talus</td>
<td>125</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>foot slope</td>
<td>210</td>
<td>375</td>
<td>278</td>
<td></td>
</tr>
</tbody>
</table>

As shown in Table 3, a general agreement between 137Cs activity and relative site location along the slope was found. Therefore, higher activities were measured at the foot of the slope where sedimentation occurs. Severe erosion can be identified at the talus of the slope where activities in sodic and saline soils were zero, while less erosion has taken place on the talus of the slope of gypsiferous soils. At the crest sites, physiographic conditions apparently favoured wind erosion on the gypsiferous soils,
Fig. 1. Representative vertical distribution of cesium-137 content in soil profiles and variation along a slope profile. (A) Undisturbed site at the crest of the slope, (B) mid-slope site evidencing erosion, (C) depositional site at the bottom of the slope.
while wind sedimentation was thought to be responsible for the high activity found in the saline soils.

Sampling of three sites located along a slope profile confirmed the pattern of the 137Cs distribution mentioned above (Figure 1). This distribution reflects the processes of erosion or sedimentation that take place along the slope. The topmost sampling site had a 137Cs inventory of 210 mBq cm-2 and a typical distribution of 137Cs within the soil profile (70% of the total 137Cs being contained in the top 10 cm and an exponential decrease occurring below) confirms it as an stable, uneroded site. In the mid-slope site, evidence of erosion is demonstrated through both 137Cs depletion and shape of the 137Cs profile. At the bottom of the slope, the depositional area is identified by a 137Cs inventory of 341 mBq cm-2 and a depth of the 137Cs profile of 60 cm. Cultivation of the land at this part of the slope profile with more gentle slope produces the mixing of the soil, as shown by the shape of the 137Cs profile.

4.5 Assesement of the spatial variability in the distribution of cesium-137 in the soil

Attention has been given in the literature to problems of spatial variability when applying the 137Cs technique. This variability can be caused by several factors or processes (e.g. FREDERICKS et al., 1988; WALLING & BRADLEY, 1988): i) the sampling procedure (different surface area of the core samples, depth of sampling, differences between values from core samples and sectioned samples); ii) the natural variability in soil properties (stoniness, soil texture, porosity and permeability); iii) the initial distribution of 137Cs that can be affected by rainfall interception by the vegetation, local concentration of rainfall by the canopy effect, desiccation cracks favouring rainfall infiltration and iv) the redistribution of 137Cs affected by the microtopography, rainsplash, rainwash and rilling processes.

To assess the spatial variability of the 137Cs distribution a collection of 9 core samples was undertaken at three different sites. The sites considered were: a level forest, a mid-slope site with natural vegetation, and a cultivated field. Samples were taken in a closely spaced 3 x 3 grid.

The results of the statistical analysis are presented in Table 4. Coefficients of variation of 19% and 26% were registered at the forest and cultivated sites respectively. At the mid-slope site, the coefficient of variation reached 60%. In this site the variability is mainly attributed to erosion and redistribution of 137Cs affected by microtopography. High coefficients of variation have also been registered by other authors (LONGMORE et al, 1983; LOUGHRAN et al, 1987; FREDERICKS et al, 1988).

The degree of variability in the spatial distribution of 137Cs will eventually define the sampling density needed to establish a representative value of the 137Cs content in the soil. Therefore, it can be stated that a preliminary assessment of the spatial variability appears to be required to determine the number of samples needed for accurate estimation of the mean 137Cs inventory for an area.
Table 4. Coefficients of variation for each sampling site

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mean concentration (mg/kg)</th>
<th>Standard error</th>
<th>Coefficient of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest site</td>
<td>9</td>
<td>22.1</td>
<td>1.4</td>
<td>19.0</td>
</tr>
<tr>
<td>Cultivated site</td>
<td>9</td>
<td>4.5</td>
<td>0.4</td>
<td>26.0</td>
</tr>
<tr>
<td>Mid-slope site</td>
<td>9</td>
<td>9.4</td>
<td>1.9</td>
<td>60.0</td>
</tr>
</tbody>
</table>

5. Conclusions

This study served as a preliminary investigation to assess the possibilities of applying the 137Cs technique for studying soil erosion in Spain. The results obtained have confirmed the potential for using 137Cs in determining soil and sediment redistribution in semi-arid environments. Mobilization and transport of 137Cs appears to be closely related to that of the soil, and thus the technique presents a great step in tracing movement of soil particles in environments such as those studied here.

The spatial variability found suggests the need of establishing the degree of variability for an area prior to the careful design of the sampling strategy.

Because of the severity of the soil erosion problem in this region, the 137Cs technique appears to be the most suitable method in providing the needed empirical data to quantify soil erosion.

Acknowledgements

The authors are particularly indebted to Professor D.E. Walling, Department of Geography, University of Exeter, for many helpful comments and advice on this investigation. Much of the work in this paper was carried out at the Department of Geography, University of Exeter. The help and hospitality received by members of staff is gratefully acknowledged.

References


200
USE OF CESIUM-137


MIDDLE EBRO RIVER CHANNEL AND FLOODPLAIN: GEOMORPHOLOGY, RECENT CHANGES, RISKS AND MANAGEMENT ON A FLUVIAL SYSTEM OF FREE MEANDERS

Alfredo OLLERO OJEDA & Francisco PELLICER CORELLANO

Departamento de Geografía y Ordenación del Territorio. Universidad de Zaragoza, 50009-Zaragoza, Spain.

ABSTRACT

The present research is focused on channel and floodplain changes in the middle Ebro River (338 km in length), analysing the role of natural (previous geomorphology, hydrology, plant riparian formations) and anthropogeneous factors (man-made defence works and channeling) which work together in the system. The study is based on spatial and temporal changes in channels and floodplains throughout this century, and seeks to define in quality and quantity the changes and the role of each factor, to find risks and behavioural patterns for application in channel and floodplain management.

Key words: fluvial system, fluvial geomorphology, meanders, floodplain, channel changes, river bank erosion, ox-bow lakes, point bars, riparian vegetation.

RESUMEN

La presente línea de investigación estudia la dinámica del cauce y de las riberas del curso medio del Ebro, tramo de trazado libre de 338 km, analizando el papel de cada uno de los elementos y factores que interactúan en el sistema, tanto naturales (geomorfología previa, hidrología, formaciones vegetales de ribera), como antrópicos (obras de defensa y encauzamiento). El análisis se apoya en las variaciones espaciales y temporales del cauce y riberas a lo largo del presente siglo, con el fin de definir cualitativa y cuantitativamente la dinámica y el papel de cada factor, detectar riesgos y lograr modelos de comportamiento aplicables a la ordenación del espacio ribereño.

En el artículo se resumen los objetivos y fases de trabajo, los métodos, la cartografía a varias escalas como medio de representación, los resultados obtenidos hasta el momento y las líneas de desarrollo futuro de la investigación. El objetivo final consiste en la aplicación del
1. Spatial environment

The most significant feature of the middle Ebro fluvial system is the development of free meandering channels, which ramble over a floodplain from Logroño to La Zaida. Up and down stream of this, the meandering is confined. Our research environment is made up of the whole area of free meanderings in the river course, which has a channel length of 338 km. As for the width of the stretch under study, it coincides with that of the floodplain in both banks, reaching 5 km in the most highly developed places.

The study area is located in the arid centre of the Ebro basin, and is characterized, first of all, by periodical floods in spite of the progressive channel regulation, secondly by channel ramble on the present terrace and its contact and erosion of different sectors of tertiary escarpment, thirdly by the dynamic constant underlined by continuous and parallel erosion, transport and sedimentation, and fourthly by the existence of relict riparian vegetation in continuous regression due to progressive human action in the river area over the last decades. Nevertheless, in this general environment, there are a great number of spatial and temporal changes.

2. Conceptual framework

In our country, there are few antecedents in meandering channel fluvial geomorphology research; for this reason, it has been necessary to design a conceptual framework and to adapt our own methodology to the fluvial system.

The Ebro’s channel and river banks constitute an open system, made up of different elements and factors that work together in dynamic balance. Hydrology, which is the energy input into the system is the active factor, and is controlled by climate
conditions and the general characteristics of the whole upper drainage area. Rising water-
flow is fundamental in the morphogenesis. The elements of resistance that avoid or
distort the water's morphogenetic action are the characteristic materials and the inherited
landforms that form channel and banks, the riparian vegetation and infrastructure and
man-made defence works.

This interaction is defined by processes such as erosion forms and rate, flux and
transport forms, channel morphology and dynamic, colonization processes and plant
succession, etc. Only if we know the natural dynamic of the system and the complexity
of its interactions will it be possible to evaluate its sensitivity to human interventions.
The analysis of interaction complexity must be carried out from its recent spatial and
temporal variations.

3. Objectives and different work steps

The aim of this research is to achieve complete and integrated knowledge of this
system, because this is the only way to understand its whole complex operation. To do
this, temporal hierarquization of objectives and steps of work is required.

The first objective (already accomplished) is to establish a conceptual and
informative foundation, on which to base further study. The second objective, is to
apply it to a specific sector to test the research methodology, to observe its efficiency,
and to introduce corrections and new possibilities. This objective has been accomplished
in a first research study (OLLERO OJEDA, 1989a).

The third stage of the study was designed in order to know minutely the whole
fluvial system under study, not only in space (338 km of ramble course in middle Ebro
river) but in time (events and recent changes based on available information, since the
beginning of this century). The investigation is, at present, at this stage and has the
following work plan:

1. Methodological introduction and geographical environment: topic justification,
   fluvial system description, skills revision, location and perimeter of the study
   area.

2. System elements:
   - Geomorphological heritage: valley geomorphology, fluvial terrace and tertiary
     escarpments, floodplain landforms and materials which can be moved.
   - Hydrologic element: statistical study of fluvial regime at different river gauging
     stations (Mendavia, Castejon, Zaragoza y Sastago) and analysis of ancient and
     recent floods, with their morphological importance.
   - Riparian vegetation: ecological value of communities and their role in fluvial
     dynamic, and an inventory of riparian woods.
   - Anthropic actions: historic and recent changes with special attention to man-made
     defence works against the river, and inventory of them and their impact.

205
3. System behaviour:
- Changes in free meandering: background, general patterns of meandering geometry.
- Present bed and floodplain: longitudinal stream profile, sinuosity, meandering geometry, erosion and sedimentation, braided stretch, river confluences, secondary channel, "brazo ciego" (part of an antique channel opened to the active channel and closed in upper stream), ox-bow lakes.
- Spatial and temporal changes: at the channel and bank location: dyacronic and sincronic study of process supported by cartography. Evaluation and quantification of changes recorded: mobile surfaces, erosion speeds, spontaneous vegetation and human dynamic areas.
- Hydrological and geomorfological risks: location and analysis of flood spaces, fragile channel points, spaces with direct bank erosion, non-regulated channel stretch, slope break, consequence of man-made defence works, landslide of escarpment blocks directly eroded by the river.
- Selection of areas of greater interest or risk, looking towards further research through experimental stations, doing model and simulating situation.
- Behavioural patterns: levels of stability and fragility in each sector and future variations under natural and human conditions.

4. Conclusions: objective evaluation and definition of principal tasks for further investigation.

We will later go deeper into the behaviour of the system in very specific areas, where the greatest interest or risk has been detected: specific stretches of channel strechs and banks with special changes, as well as patterns of dynamic forms such as point bars, cut-off, ox-bow lakes, "brazos ciegos", erosion rates, etc. In the same way, we would like to extend the study area to other channels with similar characteristics (mainly in the Ebro river basin) such as the Arga and Aragon lower courses.

The final objective consists in applying the knowledge we have gained in future conduct risk prevention and correction and channel and floodplain management.

4. Methodology used: Cartography.

A great deal of information has been obtained from the records and offices of the Confederacion Hidrografica del Ebro, and from trips abroad (Torino, Toulouse and Lyon). The research is supported by this information and by field studies, but the fundamental method is the analysis of channel and river bank evolution from various aerial photographs that include the whole study area (1946, 1957, 1977, 1981, 1984-86) or a large sector of it (1927, 1967, 1974, 1980, 1990).

The presentation of the results is by means of cartography, working to different scales:
RIVER EBRO RIVER CHANNEL

-Surface cartography and planimetry in 1981 (scale 1: 25000) from the most recent flight showing the whole middle Ebro river. Channel geometry, gravel bars, spontaneous vegetation and human areas are represented.

-Risk cartography in 1981 (scale 1: 25000): flood places, active erosion point, places with an unstable channel drawn, man-made defence works, infrastructures, gravel quarry.

-Simple dyacronic cartography of channel drawn up from every possible date to detect variations (scale 1:50000).

-Detailed dyacronic cartography of the previously selected, places of interest, to a scale 1:10000 supported by every following aerial photograph that we had. The channel sketch, the gravels location and its degree of plant colonisation, plant formations like trees, shrub, *Phragmites communis*, ox-bow lakes evolution processes, location of cultivated places and human intervention.

-Sketch to different scales to show specific places: gravels, ox-bow lakes, evolution of river confluences,.....

5.- Principal results

In spite of being research which was begun less than four years ago, we have obtained important results which have been gathered in different publications, which we are going to specify later. These are the results of research into the middle Ebro river stretches which are interesting for their dynamic, and which give excellent examples of this system.

In the Rincón de Soto-Novillas sector (OLLERO OJEDA, 1989a), a stretch (Alfaro-Arguedas), with important channel changes and riparian communities evolution had already been chosen (PELLICER y OLLERO, 1987). The variations between dates were confirmed and analysed with more detail later (OLLERO OJEDA, 1989b y 1989c), and results of bank erosion because of man-made defence works location (OLLERO y PELLICER, 1989).

The area of Zaragoza is another interesting sector, in which several studies have been undertaken. Here we apply the investigation to channel and floodplain management, and particularly about definition and evaluation of riparian natural spaces (PELLICER et al., 1990; OLLERO, 1990c). The "Galacho de Juslibol" is an ox-bow lake which was cut off by a flood in January 1961. Over thirty years of history the evolution has been defined by the geomorphology dynamic, ecological series and gravels extraction, transforming the space into a natural laboratory in which we have worked on a large scale since the first article of PELLICER and YETANO (1985) to the recent study of recuperation conducted by PELLICER (1991).

The research has been carried out in a theoretical way, particularly in hydrological behaviour of middle Ebro river and its floods (OLLERO OJEDA, 1990a y 1990b), in channel quantitative analysis (OLLERO OJEDA, 1990d) or in riparian vegetation (PELLICER et al, en prensa). In the same way, a report on meandering channel studies (OLLERO OJEDA, 1989d) has been made.

207
The main results are summarized as follows:

- A large quantity of information has been obtained at all levels and on all the elements that work in the system. For this reason, we have to stress the location and the contribution to the scientific world of an aerial photograph of a large sector of the Ebro basin and channel, at a scale of approximately 1:9000, which was taken in 1927 by the "new" Confederacion Sindical Hidrografica del Ebro, being one of the first confederations in Europe.

Fig. 1. Spatial floodplain evolution between 1927-1986 (Estajo-Las Rozas, Alfaro, La Rioja sector)
In: OLLERO OJEDA (1989c)

- As for channel morphology, the general changes of this and its response to all the important floods have been verified, as well as the trends in each meandering sector towards regularization of radial curvature meander migration.

- Man-made defence works and channelling have increased in all the middle Ebro river since the January 1961 flood and especially in the eighties, during which the protection has been almost finished, restring the channel's natural tendency and, thus, eliminating its dynamic, except in specific locations.
RIVER EBRO RIVER CHANNEL

- The spatial evolution of natural areas, human activities, channel areas, etc. (fig.1) may be representative of the situation of the whole middle Ebro river. It shows the progressive development of cultivated and anthropic areas (infrastructures, gravel quarries,.....) to the detriment of the spontaneous vegetation areas; at present, these areas represent about 40% of the 1946 area. The important transformation of channel and floodplain as regards economic profit, has meant high investment in man-made defence work, ecologic unbalance, a reduction of natural dynamic and increasing risks.

6. Future research

We are trying to gain further knowledge of the system and study area, lengthening the time studied so as to detect, interpret and date the historical channel changes; to do this, we have to obtain more information and analyze the historical floods, and work with ancient cartography.

In the same way, we will enlarge the area with the next study in the lower sextors of the Arga and Aragon river, tributaries of the Ebro whose dynamic is similar to that of the main river. We also want to begin research, working together with other international teams, into the comparative analysis of other fluvial system.

A change in the work scale would allow us to analyze the working of system in special sectors, where we will undertake a geomorphological, sedimentological and ecological survey in experimental stations, so as to quantify the role of each factor in the channel and floodplain dynamic. Therefore, we will take into special account different subjects: bank erosion, ox bow lake evolution, stream confluences, sedimentation processes in main channel, secondary channel and "brazos ciegos", etc. Also, we will follow the system's dynamic in the future working with the new aerial photographs which are being taken.

At the same time, we will try to take part in and contribute to future projects and management planning of channels and floodplains.

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SOIL DEGRADATION AND EROSION IN SOUTHEASTERN SPAIN. CONTRIBUTIONS OF THE ZAIDIN EXPERIMENTAL STATION C.S.I.C. (GRANADA, SPAIN)

J. QUIRANTES, E. BARAHONA & A. IRIARTE

Estación Experimental del Zaidín, Profesor Albareda 1, 18008 GRANADA

ABSTRACT
Studies of the basins of the rivers Gualchos, Albuñol and Verde give estimated values ranging from 0.3 to 1.4 mm/year for water erosion and around 0.3 mm/year for wind erosion. Rainfall simulation experiments evidence that sediment concentration in runoff depends mostly on the amount of fine sized carbonates and the salinity of soils. 36% of the area covered by the LUCDEME project shows slight wind erosion; 56 %, moderate and 8% high or very high wind erosion.

Key-words: Hydric erosion, wind erosion, erodibility

RESUMEN
Se resumen los resultados de los trabajos realizados por la EEZ en relación con la erosión de los suelos en el ámbito del SE español. El estudio de 3 cuencas fluviales en la costa sur de Granada da los siguientes resultados: Cuencia del río Gualchos (filitas y cuarcitas), densidad de drenaje 5.7 km/km², erosión hídrica: 0.3 a 1.2 mm/año; erosión eólica: 0.33 mm/año. Cuencia del río Albuñol: (micaesquistos y calizas); erosión hídrica: 0.5-0.9 mm/año. Cuenca del río Verde: (micaesquistos, cuarcitas, calizas y dolomías); Erosión hídrica: 1.4 mm/año; erosión eólica: 0.32 mm/año.

Experimentos con un simulador de lluvia portátil ponen de manifiesto que la turbidez de la escorrentía depende esencialmente del contenido de los suelos en carbonato cálcico en las fracciones finas (limo y arcilla) y de la salinidad.

Una prospección de las propiedades de los suelos en el S de las provincias de Granada y Almería muestra que la fracción arena muy fina a cotas bajas y en zonas de poca pendiente, lo que probablemente refleja la erosión hídrica o eólica sufrida. Por otra parte, una evaluación tentativa de la erosión eólica en el área estudiada por el proyecto LUCDEME da como resultado
que el 36% del área sufre erosión eólica ligera o nula, el 56% del área, moderada erosión y sólo el 8% del área erosión alta o muy alta.

The first studies concerning soil erosion in this area were started by the Zaidin CSIC research team in Granada in 1978. In the period from 1978 to 1990, soil erodibility according to Middleton and specific soil degradation, following the Fournier and Kresnik’s methodology were studied in the catchments of the rivers Gualchos, Abuñol and Verde (South of the Province of Granada). In each case, the influence of the erosivity indexes on the parameters of the drainage network, as well as the influence of climatic, lithologic and topographic characteristics of each basin on these parameters were also studied.

From 1990 onwards, these local studies were widened to more extensive areas of southeastern Spain and, at the same time, more ample research projects were initiated concerning the intrinsic vulnerability of the study area to the desertification processes (sensu lato), the quantitative evaluation of soil erosion and the socioeconomic impact of the desertification. The studies already carried out or currently in progress are treated separately under the following headings:

1) River basins south of Granada.
2) Susceptibility of soils to interrill erosion.
3) Eolic erosion in southern Spain. (Granada, Almeria, Murcia).

The main object of these studies was the quantification of soil erosion in the zone, not only to gain knowledge on the erosion processes in the Mediterranean area but also primarily to obtain basic information to assist conservationists in establishing strategies for reducing erosion and regenerating soils where this is feasible.

1. Watersheds south of Granada

1.1 River Gualchos Catchment

The study of erosion in river watersheds of southern Spain was initiated with that of the Gualchos river, located to the East of Sacratif’s Cape, near the center of the Granadinian “Costa del Sol” (QUIRANTES & AGUIRRE, 1973).

The lithology of this watershed consists mainly of phyllytes and permowerfenian quartzites in addition to limestones, dolostones and triassic calcoschists.

The climate is subtropical mediterranean, with a mean annual temperature of about 8 °C. The mean annual rainfall is 450 mm, irregularly distributed throughout the year.
CONTRIBUTIONS OF THE Z.E.S.

In any case, the most prominent feature of the climate is its aridity, which controls the sporadic vegetation of the region, formed mainly of xerophitic formations with palm bush, sage, thyme and rosemary as dominant species. These occur as scattered shrubs rather than as a continuous cover. The area occupied by shrub and barren land increases with altitude, appearing at the same time some dense woodland tracts. These are small forests, in process of disappearance, in which pine trees dominate over oaks. Cultivated lands can be divided into two groups: a) those located on the foothills, used for rainfed agriculture vineyards, almond trees orchards and cereals; b) those located on the margins of the river valleys (ramblas) and along the coast, utilized for irrigated agriculture, mainly subtropical tree-crops, orchards, greenhouse and sand cultures ("enarenados").

A study of the drainage pattern at 1: 50,000 scale shows a drainage density of 3.4 Km per sq. Km, corresponding to 676 drainage channels, totalling 297 Km in length. A more detailed study carried out through the stereoscopic examination of aerial photographs at a scale of 1: 34,000 allowed the detection of 2049 drainage channels, with a total length of 490 km, which gives a drainage density of 5.7 km per sq. km.

On the assumption that ideal conditions i.e. well developed soils, almost continuous vegetal cover, etc were present, the average soils for the Gualchos river catchment should be of about 4 mm per year, on the basis of the mean annual rainfall. Nevertheless, if we take into account the irregularities in the distribution of rainfall in time, evidenced by a 84 year long record, this figure could rise to 1.2 mm per year.

The wind erosion, estimated from the moisture equivalent (7.3 %) is about 4.6 metric T/Ha, which correspond to 0.33 mm per year.

1.2. River Albuñol catchment.

The dominant materials are micaschists and some limestones. A complete topographic and morphologic study of the watershed was made (QUIRANTES & GARCIA-CHICANO, 1979) including total number and length of drainage channels, bifurcation ratio and drainage density. The physical and chemical analysis of the soils give a dispersion index of 15 which corresponds to very erodible materials. The moisture equivalent is well under 1.5, which also indicates a high erodibility. Comparable results are obtained from the erosion coefficient (Ce) which express the combined effect of both dispersion coefficient (Gd) and the moisture equivalent (Gr).

No data are available on the amount of eroded material, but being the catchment within the south Mediterranean zone, its climatic characteristics are well known. Thus, on the basis of an isoxeric map it was possible to determine the Fournier indexes for several points within the catchment. Although the p²/p values are few and local, the specific denudation of the catchment could be calculated. The average annual soil loss of 0.47 mm. The value derived from a detailed climatic record comprising a 84 years period is 0.90 mm/year. The soil losses due to eolic erosion were estimated to be about 4.5 Tm/Ha/year, (0.318 mm/year).
1.3. River Verde catchment

This catchment is located in the alpujarride Complex in the Betic Ranges. Micaschists, quartzites, limestones and dolostones are the dominant rocks in this area.

The topography, morphology and drainage system were analyzed and so was the climatology, emphasizing the aspects connected with aridity, which has a decisive influence on the erosion phenomena (QUIRANTES & SIERRA, 1982).

The distribution of altitudes is very regular: 28.6% of the area is located between 0 and 400 m altitude; 28%, between 400 and 800 m altitude, 34%, between 800 and 1200 m, and only 10% of the area has altitudes ranging between 1200 and 1400 m. The mean altitude (713 m) and the coefficient of massivity (7.03) result in a high orographic coefficient which will favour the erosion.

The study of the aerial photograph reveals the existence of 9898 drainage channels. The drainage density of limestone and dolomite landscapes is 17.3 km/sq.km. (high density and fine drainage texture). In landscapes dominated by micaschists and marbles, the drainage density decreases to 13 km/sq. km and the decrease is even greater in landscapes dominated by phyllites, schists and quartzite, where the drainage density is 12 km/sq.km. The last 2 values correspond to intermediate drainage densities and textures.

Only 7.3% of the area has slope gradients under 20%, 22.69% of the area has slope gradients between 20-30%, and 69% of the total area have slope gradients over 30%, The area having slope gradients over 50% totalizes 41.1%.

Soil losses due to hydric erosion are estimated at 1.4 mm/year for the whole basin. As regards elolic erosion, the value obtained is very similar to that of Rambla de Albuñol (0.32 mm/year). Total erosion by both phenomena is, therefore, 1.7 mm/year.

2. Susceptibility of soils to interrill erosion

The application of artificial rainstorms in small field plots by means of a portable rain simulator is a very favorable technique to obtain low price and short term results in studies concerning the erodibility of soils.

A rain simulator was designed, covering a surface of 1/2 sq m The aims of the design were: a) to obtain a high spatial homogeneity of the rain intensity. This was attained by constructing the drop formers in such a way that they could work under a relatively high hydraulic head without significant air clogging; b) to obtain proper working conditions within a wide range of rain intensities (10 to 150 mm/hour) and c) to provide continuous and precise regulation of rain intensities. Moreover, the device should be easily mounted and handled, and sturdy enough to support occasional misstreatment during the field work.
CONTRIBUTIONS OF THE Z.E.S.

This apparatus would serve the purpose of making a regional survey of soil physico-chemical characteristics controlling their erodibility (BARAHONA et al., 1990). The survey should cover the widest possible range of soil types and parent materials, so as to obtain a general view about the extreme values that are to be expected in a regional context. Thirty sapling points were studied in itinerant field experiments. The experimental schedule was as follows: Two 30 min, 40 mm/hour storms were applied with an intervening rest period of 15 min on the soil with dry antecedent conditions. Time to ponding and time to runoff were recorded. Samples of runoff water were taken and timed at intervals of about 5 min. In the case the runoff rate did not stabilize, the second storm was enlarged to 1 hour. Sediment concentration in runoff samples was determined in the laboratory. Previous to the experiment, site characteristics were recorded and composite samples of the surrounding surface soil (15 cm depth) were taken. Mechanical analysis, carbonate and organic matter content, pH, cation exchange capacity, exchangeable bases and salinity were determined in the laboratory. The mineralogy of soil materials was determined by XRD. Soil bulk density was determined on undisturbed samples taken by the cylinder method. Total runoff and sediment carried away were regressed against the compositional and site variables in order to obtain a prediction equation for erodibility.

In addition to this schedule, other experiments were carried out in which the rain intensity was changed from 20 to 100 mm/h in different sequences to determine the effect of rain intensity on final infiltration rates and soil removal.

Besides the rain simulator experiments, a systematic sampling of surface soils comprising about 350 soil samples was undertaken in order to determine the aerial distribution of properties controlling the soil erodibility in SE Spain (IRIARTE, 1990).

The most outstanding results could be summarized as follows: Depending on soil composition, the turbidity of runoff varies within a extremely wide range (0.3 to 96 grams per liter). The soil properties having the greatest bearing on the soil erodibility are a) the content in fine grained carbonates (in the silt and clay fractions) and b) the salinity of soils (measured through the conductivity of the saturation extract). Under the conditions of the experiment (60 min. 40 mm storm, nude soil, slope gradient around 25%), the soil loss seems to depend on runoff turbidity rather than on the volume of accumulated runoff, and can be fairly well predicted by the following equation:

\[
\text{Soil loss (gr/sqr m)} = -53.33 + 83.5 \times \text{clay sized Ca CO}_3 \% + 45.39 \times \text{CE25 (mS)}.
\]

\[R = 0.912\]

As regards the areal distribution of diagnostic properties in SE Spain, the thematic maps (IRIARTE, 1990) reveal that the very fine sand separate shows peculiar behavior: It is uncorrelated with the rest of the grain size fractions but well correlated with geographical parameters such as altitude and slope. It tends to accumulate in low and level terrain. The intermontane valleys that run parallel to the west coast of the

215
province of Almeria are zones especially rich in very fine sand. This could result from both hydric or eolic erosion.

3. Qualitative and quantitative approximation of wind erosion in SE Spain

The objectives of this study (QUIRANTES, 1989) were a) to gain knowledge on the present state of degradation of the soils of SE Spain by the effect of eolic erosion and on the future potential degradation; b) to establish an appropriate methodology for the study of the eolic erosion, which is valid for southeastern Spain; c) to evaluate qualitatively and quantitatively the eolic erosion in the area included in the LUCDEME project.

The most remarkable direct effects of wind erosion in SE Spain are: a) the hampering of siedling emergence due to direct damaging and denudation of the superficial root system; b) the superficial soil texture changes due to silt and sand deposition in some places and to blowing away of the fine fractions in others, leaving on the surface a sandy texture that impairs water and nutrient retention. Other secondary effects can be cited: the eolic transport of salts and gypsum to cultivated lands, the impoverishment of soils in available phosphorus, the damaging of grown-up plants, the desiccation of soils and indirect damaging and burial of public facilities.

In 1987 the scheduled studies were finished and the first wind erodibility maps were drafted at scale 1:400,000. On the base of these maps as well as on thematic maps on vegetation, litology and slope of the SE Spain, a map of erosion landscapes was prepared.

Six degrees of erosion (nil or very low, low, moderate, somewhat high, high and very high) and the corresponding landscape types gave rise to a consistent unit separation.

Class 1 (No erosion or very low erosion). It extends over 13.5% of the total area and is fairly homogeneously distributed throughout the area. The most extensive units are located in the central part of Almeria and in the vicinity of Murcia and the area between Ugigar and Motril.

Class 2 (Low erosion). This class occupies 22% of the total area. As in class 1 the areal distribution is fairly homogeneous although there are more extensive spots south of Sierra Nevada, Canjayar and Campo de Cartagena.

Class 3 (Moderate erosion). This is the most extensive class (32% of the total area). There are ample zones which belong to this class in the Alhamilla and Filabres ranges, the Almanzora river basin and the triangle formed by the towns of Murcia, Cartagena and Torrevieja.
CONTRIBUTIONS OF THE Z.E.S.

Class 4 (Somewhat high erosion). It occupies 25% of the total area. The map units belonging to this class occur mainly to the north of the river Almanzora, at Sierra de las Estancias, Sierra Maria, Pauce and España. There are also small areas to the NE of Sierra de Gata and SE of Sierra de Gador. In the Province of Granada the Sierras of Guajares and Lujar should be emphasised.

Class 5 (High erosion). Only 6% of the area belongs to this class. It occurs in small and isolated spots in the provinces of Murcia (Casas Nuevas, Sierra de las Estancias) and Almeria (Sierra de Gata and Sierra de Gador).

Class 6 (Very high erosion) This class occupies only 3% of the studied area. The units are located mainly in the provinces of Murcia (Aguilas, Velez Rubio and Royos), Almeria (Roquetas, lower Almazora basin) and Granada (Sierras de Lujar y Guajares).

To sum up, the sectors which have slight wind erosion make up about 36% of the area under study by the LUCDEME Project. Those with moderate wind erosion make up 56% and those with high or very high wind erosion, only 8% of the total area.

References


217
EROSION AND SEDIMENTATION DURING THE UPPER HOLOCENE IN THE EBRO DEPRESSION: QUANTIFICATION AND ENVIRONMENTAL SIGNIFICANCE

Carlos SANCHO (1), Mateo GUTIERREZ-ELORZA (1) & José L. PEÑA-MONNE (2)

(1) Dpto. de Ciencias de la Tierra, Facultad de Ciencias, Universidad de Zaragoza, 50009-Zaragoza, Spain.
(2) Dpto. de Geografía y Ordenación del Territorio, Facultad de Filosofía y Letras, Universidad de Zaragoza, 50009-Zaragoza, Spain.

ABSTRACT
The triangular slope facets and infilled valleys of the upper Holocene are very common in the Ebro Depression, which has a semi-arid Mediterranean climate. Reconstruction of these old landforms, combined with archaeological dating of the associated deposits, enable erosion and sedimentation rates to be calculated. Erosion rates calculated for the triangular slope facets are at least 14-15 tons/ha/year and the sedimentation rates for infilled valleys are at least 5-6 tons/ha/year. The effect of Upper Holocene paleoclimates and the action of man on the geomorphological processes is discussed.

Keywords: Erosion and sedimentation rates, triangular slope facets, infilled valleys, archaeological dating, Ebro basin.

RESUMEN
En la depresión terciaria del Ebro son muy abundantes las acumulaciones holocenas bajo la forma de facetas triangulares de ladera y rellenos de valle de fondo plano. En ambos modelados se reconocen varias etapas de acumulación separadas por otras de incisión. En el interior de estos depósitos se localizan, en numerosos lugares, gran cantidad de restos arqueológicos, que hacen posible su datación relativa.
SANCHO, GUTIERREZ & PEÑA

Mediante la reconstrucción de la geometría de las paleoformas de ambos modelados, es posible calcular el volumen de sedimentos erosionado o depositado. Los volúmenes obtenidos, en el caso de las facetas triangulares de ladera, se deducen a partir de la intersección de dos curvas de ladera correspondientes a etapas de regularización diferentes a lo largo del pie de la cornisa de la ladera. Para los rellenos de fondo de valle se efectúa la cubicación del material depositado en relación con su cuenca de drenaje. El intervalo temporal de actuación de los procesos, que viene dado por las dataciones arqueológicas, proporciona únicamente espacios temporales máximos, por lo que las tasas aproximadas de erosión y sedimentación obtenidas son valores mínimos.

El estudio de las facetas tripartitas de la región de Chalamera (Huesca) ha proporcionado unos valores de erosión de 14-15 Tm/Ha/año y las tasas de sedimentación para los rellenos de los fondos de valle del área de Mediana de Aragón (Zaragoza) son de 5-6 Tm/Ha/año. En este último caso los datos reales deberían ser superiores, ya que hay que tener en cuenta que existe una pérdida importante de material por disolución, al tratarse de formaciones yesíferas, y por aporte a un curso de orden mayor.

Las alternancias de etapas acumulativas y erosivas reconocidas en los depósitos obedecen a cambios en los procesos geomorfológicos. Las causas desencadenantes de estas modificaciones deben de ser de carácter climático y antrópico. Sería importante poder llevar a cabo una correlación entre los paleoclimas históricos y la actividad de los procesos de erosión-sedimentación, buscando situaciones en las que la influencia del clima sea claramente dominante sobre la acción del hombre.

The Ebro Depression is one of the three great tertiary basins in the Iberian Peninsula, infilled with materials of basically continental origin. The erosional activity of the River Ebro and its tributaries during the Quaternary affected the most significant geomorphological features, giving rise to a set of erosive forms (platforms and mesas as dominant reliefs) and accumulative forms (extensive deposits of mantled pediments and terraces).

This depression, ranging from 100 to 900 metres above sea level, is delimited by the Pyrenees, Catalan Coastal Range and Iberian Range. This situation gives rise to a continental influence, which manifests itself as a semi-arid Mediterranean climate, reaching its maximum expression at the centre of the basin, where annual precipitation is less than 350 mm.

During the Holocene, extensive accumulations built up around the main river beds, in the form of infilled valleys in the tributary network, small alluvial fans, and slope deposits. Inside the most recent accumulations there are often abundant archaeological remains and also fossilized constructions from different periods. This abundance of archaeological material in the Upper Holocene materials has given rise to much geoarchaeological research, most of which has been aimed at dating the deposits and interpreting the paleoclimate of that period and the action of man, all of which is

220
EROSION AND SEDIMENTATION IN UPPER HOLOCENE

based on the different erosion and sedimentation stages deduced from a study of these accumulations.

In many cases, the alternation of aggradation and downcutting phases enables us to reconstruct the old landforms existing in particular areas and, on the basis of this reconstruction, estimations can be made of the erosion and accumulation rates during time intervals, using archaeological dating. This can be done on triangular slope facets, to find the erosion rates, and in valley fills, to find the sedimentation rates. This article aims to explain the method used to obtain these quantitative data, based on two examples which can be extended to other places and situations of a similar nature. Although the results are approximate, they enable comparisons to be made with existing data on present day erosion and sedimentation in the Ebro Depression.


The slopes of the Ebro Depression characteristically have a scarp and a talus partially or totally covered by deposits, which are thickest on the north-facing slopes. All these accumulations are downcut by a network of gullies which reveal their thickness, ranging from decimetric figures up to 3 metres. The composition of the deposits is usually heterometric with extremely varied lithologies and they can contain archaeological remains.

The alternation of accumulation and downcutting stages in the slopes leads to the appearance of talus flatiron, which are remains of preceding slopes, and are typical of arid environments. One of the most representative points is in the Chalamera area (Huesca), at the confluence of the Cinca and Alcanadre rivers, where three talus flatirons and a more recent slope deposit is found (Fig. 1) (SANCHO et al., 1988). The deposits of the older stage (S\textsubscript{4}) are interfingered laterally with the Cinca river’s 20 m terrace, and the two most recent accumulations contain archaeological remains which permit relative dating. Inside the S\textsubscript{2} slope there are fragments of pottery from the Urnfield and Iberian periods (3rd to 1st centuries B.C.), A and B Campanian and terra sigillata (end of 1st century A.D.). The pottery remains in the S\textsubscript{1} slope deposits are the same as those in the previous accumulation, plus others from the Medieval period. All this indicates that the S\textsubscript{2} stage was finished after the 1st century A.D. and that S\textsubscript{1} is post-Medieval. These two aggradation stages are separated by a incision phase. SANCHO et al. (1988) developed a method for calculating the retreat of the scarp produced by the evolution of these slopes, and give a figure of 3 metres per thousand years.

One of the most characteristic geomorphological features of the Ebro Depression is the large network of infilled valleys. On the accumulations three stepped levels are
differentiated, heavily affected by gullies and therefore enabling the composition and thickness of the deposits to be studied. In general, gravels predominate at the base of the accumulation, and silts with lenses of gravel and sand predominate towards the top. The thickness is extremely variable, and can be up to 15 metres.

Fig. 1. Idealised block diagram of the four stages of slope accumulation, in which three phases of triangular facets are observed (from SANCHO et al, 1988).

The Mediana de Aragón area (Zaragoza) is one of the most representative examples of an infilled valley linked to prehistoric settlements (ZUIDAM, 1975, 1976; BURILLO et al., 1985). In this area, two stepped levels are distinguished; the higher, whose stratigraphy is shown in Fig. 2, contains numerous pottery remains from various periods, and fossilized houses of the Iberian-Roman period (2nd century to 50 B.C., according to a personal communication from E. MAESTRO). The age of these pottery remains indicates that the infill began to form shortly before or simultaneously with the Iron Age, since the base of the accumulation contains Urnfield pottery (7th-6th centuries B.C.). Sedimentation continued through the Iberian and Roman periods, since the
Fig. 2. Stratigraphic sections of upper level valley fill near Mediana de Aragón (Zaragoza) (from BURILLO et al., 1985)
deposits contain pottery from these periods, up to the Campanian A and B (75-50 B.C.). The most recent level has the same lithological characteristics as the previous one, and also contains pottery remains of the same periods. Therefore, with the available data, it can only be said that it is post-Roman.

The different alternation of accumulation and erosion stages found in Holocene deposits undoubtedly respond to substantial changes in geomorphological processes. The causes of these modifications, in this case, were climatic or anthropic, and related to the variations in the percentage of plant cover. Simple changes in the latter in these labile semi-arid zones can lead to sharp changes which manifest themselves in a transition from aggradation to downcutting. In the present case, in the Chalamera area the climatic change must have been the main cause of the generation of talus flatirons, given the considerable development in the Ebro basin of the two most recent phases of slope accumulation. On the other hand, in the Mediana de Aragón area, the action of man must have been the basic cause of the change in the geomorphic processes, as a result of the high population density in the area during the Iberian and Roman period, essentially (BURILLO et al., 1986; GUTIERREZ and PEÑA, 1989).

2. Methodology

In order to find erosion and sedimentation rates, we first need to know the volume of sediment which was mobilized. This is found by reconstructing the old landforms as precisely as possible. The time during which the geomorphic processes acted is determined, in this case, by relative dating using archaeological methods.

In the case of talus flatirons, it is necessary to reconstruct the whole slope profile. This is done by field surveying of the triangular slope facet profiles, and extrapolating the curves of the facets up to the prolongation of the scarp top. The best fits are found with second degree polynomial functions (SANCHO et al., 1988). Other models for reconstructing old slopes have been used by SCHMIDT (1987, 1989) and GERSON (1982, 1987). The volumes are calculated from two facets of the same age, compared to another two more recent facets.

To study the sedimentation in the infilled valleys, we need to know the basal surface area of the accumulations, which is partly given by the gully incisions, and the area occupied by the infill top. The calculations required are volumetric measurements of the accumulated sediment. Furthermore, it is necessary to calculate the drainage surface of each infilled valley.

In both the tripartite slope facets and the infilled valleys, the time interval is calculated from archaeological dating of the remains inside the accumulations, not on
the surface. These data then enable us to calculate the volumes mobilized per unit
surface area and per unit time.

3. Quantifying erosion and sedimentation processes

Three pairs of $S_2$ and $S_1$ facets (Fig. 1) were analyzed in the Chalamera area, the
distance between the extreme facets being 1800 m. Fig. 3 shows these profiles. The
situation of the scarp in the two stages, together with the intersection of the curves,
delimits a surface for each pair of facets $S_2-S_1$. Due to the variable situation of the
scarp, the areas are different, the average value being 153 m$^2$. To find the weight of
sediments we multiply by the extreme distance between facets and by an approximate
density of 2 g/cm$^3$, which was calculated by BENITO (1989) for similar deposits. The
final value obtained is 550,000 tons. The surface area affected by erosion, found from
detailed aerial photographs, is approximately 20 ha.

Since slope $S_2$ is later than the 1st century A.D., and $S_1$ is post-Medieval, the
time interval between the two accumulation phases is at most 1,900 years. Therefore,
the approximate erosion rate for these periods is at least 14-15 tons/ha/year. In the
"Mapa de estados erosivos de la cuenca hidrográfica del Ebro" calculated with the USLE,
LOPEZ CADENAS et al. (1987) found erosion rates of 12-25 tons/ha/year for the
Chalamera area, which agree with the figures found using the present method.

The volume calculations for the upper level accumulation in the infilled valleys
in Mediana de Aragón were made by first making a longitudinal profile of the top of the
accumulation, followed by a number of perpendicular transects in which the thickness of
the deposits and the width of the accumulation were determined. The accumulated
volume thus calculated is 17,000 m$^3$. This should be considered as a minimum datum,
since there is a considerable contribution to a larger infilled valley and because, as the
main rock type is gypsiferous, there must have been large losses through dissolution.
In any event, and in view of the approximate density of these infills (1.5 g/cm$^3$) found
from the density of gypsum (2.2-2.3 g/cm$^3$) and gypsiferous silts (1.15-1.53 g/cm$^3$),
the weight of the accumulation is approximately 25,500 tonnes. The area of the
drainage basin, calculated on the basis of detailed aerial photographs, is approximately
1.8 ha.

As the accumulation developed after the Urnfield period, the maximum interval is
2,600 - 2,700 years. Therefore, the minimum sediment yield is 5-6 tons/ha/year, which
should be below the normal rates found by other methods due to the fact that the long
time interval used and the loss of material by dissolution and to lower courses lead to an
underestimation of the real erosion rate.
Fig. 3. Eroded area between two slope evolution stages in three different cross sections (A,B,C)
4. Discussion

The method used here gives an estimation of erosion and accumulation rates, and has been applied to slopes and infilled valleys from the Upper Holocene. The dating of these deposits only gives maximum time intervals, so that the figures obtained are only minimum rates, although they have the advantage of referring to large areas and are therefore highly representative. If the initial and final dates of the processes were better defined, more reliable erosion and accumulation rates could be found for historic and recent prehistoric periods.

The paleoclimatic data for the historical periods to which the accumulations analyzed here correspond point to conditions which are very similar to the present time, since they are Subatlantic, with light fluctuations in precipitation and temperature. Thus it can be said that in the Ebro Depression, the processes have been active since the Iberian-Roman period in a similar way. From that period onwards, in semi-arid climatic conditions, the effect of human intervention on the vegetation cover increased progressively, thereby accelerating the degradation processes.

Given the validity of this approximate method, it would be recommendable to apply it in other areas with similar characteristics to find how general these erosive processes were in the past, with a view to establishing a model to correlate the historical paleoclimate with the degree of activity of these phenomena, which would then permit comparative predictions for a future climatic situation.

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How many years can a mountain exist
Before it's washed to the sea?

Bob Dylan, *Blowin' in the Wind*
(The Freewhelin, CBS, 1962)
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