Erosion, Debris Flows and Environment in Mountain Regions (Proceedings of the Chengdu Symposium, July 1992). IAHS Publ. no. 209, 1992.

Using caesium-137 to assess sediment movement on slopes in a semiarid upland environment in Spain

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Abstract The radioisotope ^{137}Cs has been used to identify patterns of soil movement within a small drainage basin located in the Cinco Villas region (northeast Spain). Two transects running across the upper and lower parts of the basin, were established. Along each transect, samples were collected using a grid network. Distinctive ^{137}Cs profiles were found at the top and bottom of both transects. At the top of the transects, characterized by natural vegetation cover and steep slopes (15° average) the ^{137}Cs profiles were mainly undisturbed. Cultivated soils on the more gentle slopes (5° average) at the bottom of both transects had significantly lower levels of ^{137}Cs and their depth profiles evidenced mixing throughout. Mobilization and transport of ^{137}Cs appears to be closely related to that of the soil. Agricultural use of the land appears to be the main factor causing erosion on the bottom parts of both transects as indicated by the depletion of the ^{137}Cs levels. The measurements presented have demonstrated the feasibility of applying the ^{137}Cs approach for studying patterns of soil erosion and sedimentation in semiarid environments.

INTRODUCTION

Some semiarid regions in Spain have as much as 40% of their surface seriously affected by erosion (ICONA, 1987). The severe soil losses affecting these fragile agrosystems pose a serious environmental problem as soil essentially constitutes a non-renewable resource. Assessments of soil erosion rates are therefore required in order to design effective strategies for soil conservation. However, despite the seriousness of the erosion problem in Spain, there is a lack of reliable data relating to both the magnitude and the spatial patterns of soil loss.

The ^{137}Cs technique can provide a reliable method for estimating patterns and rates of soil erosion. The recent review by Ritchie & McHenry (1990) shows that ^{137}Cs has been widely used for studying erosion and sedimentation in many different environments (e.g. Ritchie *et al.*, 1974; De Jong *et al.*, 1983; Longmore *et al.*, 1983; and Walling *et al.*, 1986). The basis of using ^{137}Cs for investigating rates and patterns of erosion is well established (Walling

& Quine, 1990). The purpose of the study reported here was to investigate the possibility of applying the ^{137}Cs technique to study soil erosion within the fragile agroecosystems found in the semiarid central part of the Ebro river valley (northeast Spain).

STUDY AREA

This study was conducted at the semiarid Valareña basin located 67 km NNW of Zaragoza (Fig. 1). Within the basin, two contrasting physiographic areas can be readily distinguished. The outer slopes (15° average) are characterized by a sparse cover of shrubs mixed with grass species forming a continuous cover, broken by rills. The valley bottom has been cleared for cultivation and cereal crops (mainly barley) are grown one year in two. The whole basin is affected by sheet erosion. Rill and gully erosion are also well developed in some parts of the basin, including the valley bottom. The results of physico-chemical analysis presented in Table 1, indicate that the soils of the valley bottom are calcic cambisols, the soils on the hilltops are rendzic leptosols and the soils on the mid slope are calcic regosols.

SAMPLE COLLECTION, PREPARATION AND ANALYSIS

Two transects respectively located across the upper and lower parts of the basin on its east-facing side were established. These extended from the outer margin of the basin towards the central gully running along the valley bottom (cf. Fig.

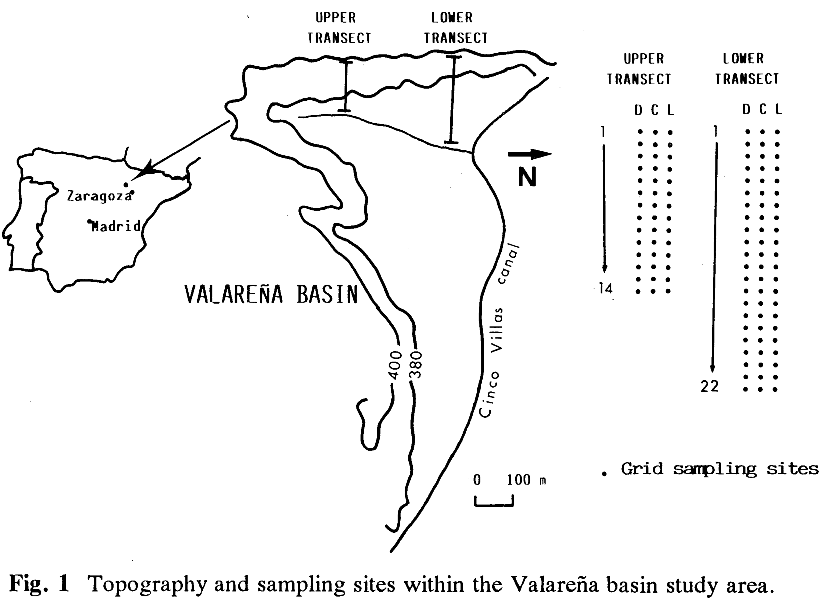

Fig. 1 Topography and sampling sites within the Valareña basin study area.

Table 1 Chemical characteristics and grain size composition of the soils of the Valareña basin.

Sites		EC (1:5) (dS m^{-1})	CO_3 (%)	Organic matter (%)	pH H_2O	% sand	% silt	% clay
LN3	hilltop	0.2	26	5.5	8.7	19	35	46
OP	hilltop	0.2	12	6.6	8.7	12	43	45
P1	mid	0.2	39	3.0	8.7	10	47	43
P2	slope	0.07	42	3.1	8.8	10	47	43
D2	valley	0.4	54	1.5	8.7	29	52	19
D6	bottom	0.6	59	1.0	8.7	32	54	14

EC: electrical conductivity

1). Along each transect, a rectangular grid network was established. The upper transect (UT) with a 3 × 14 grid was 130 m long. The lower transect (LT) with a 3 × 22 grid was 240 m long. Sampling points were spaced 10 to 12 m apart. In both transects, rows 1 to 10 were uncultivated, supporting a natural vegetation cover of shrubs and grass, whilst rows 11 to 14 and 11 to 22 on the UT and LT respectively were cultivated for cereal crops. A total of 42 and 66 samples were collected from transects UT and LT respectively.

In order to determine the distribution of ^{137}Cs within the soil profile, samples were collected (using a hand operated 8.2 cm diameter core sampler) at depth increments of 5 or 10 cm down to 30 cm and to 60 cm at the sites where the slope form changed towards concavity and some deposition was therefore likely. To estimate the ^{137}Cs reference inventory for the area, a number of additional level sites at hilltop locations within the basin and nearby were sampled. Measurements of slope length, slope angle and altitude were recorded for each sampling point.

Soil samples were oven dried at 45° for 48 h, disaggregated, weighed and sieved through a 2 mm sieve. The finer fraction of the sample was separated and weighed. A representative sub-sample of this fraction was weighed and loaded into a Marinelli beaker for ^{137}Cs analysis. Soil samples were analysed for ^{137}Cs by gamma ray spectrometry using coaxial germanium detectors coupled to multichannel analysers. Gamma emission of ^{137}Cs (661.6 kev) was counted for 30 000-60 000 s. The analytical precision of the gamma spectrometry measurements is approximately ±6%. The ^{137}Cs content of the soil samples may be expressed as a concentration (mBq g^{-1}) or on an area basis (mBq cm^{-2}) by dividing the total amount of ^{137}Cs in the sample by the internal area of the core sampler. The total inventory of a profile is obtained by addition of the individual inventories for each depth increment.

THE RELATIONSHIP BETWEEN ^{137}Cs DEPTH PROFILES AND THEIR POSITION ON THE SLOPE: TYPE PROFILES

Along the transects, ^{137}Cs depth profiles exhibit characteristics closely related to their location on the slope. In general, un-disturbed soil profiles are found at hilltop locations, eroding profiles are common at the mid slope, and deposition and consequently aggrading profiles occur at the bottom of the slope. Nevertheless, in this lower zone, cultivation of the land promotes soil erosion and eroding profiles are again found. Typical ^{137}Cs depth profiles representative of different slope locations is shown in Fig. 2.

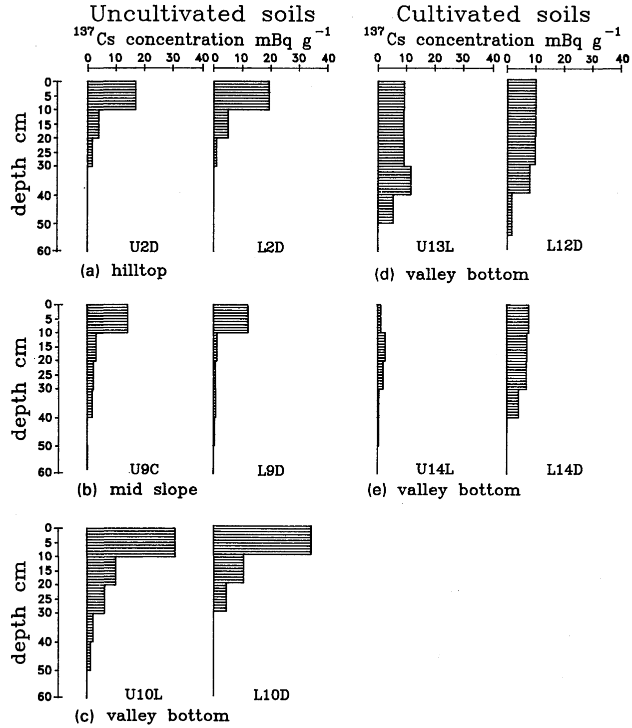

Fig. 2 Normal sequence of non-eroding, eroding, aggrading and eroding ^{137}Cs depth profiles, found along the slope from the hilltop to the valley bottom and typical ^{137}Cs depth profiles found in the uncultivated and cultivated soils of the Valareña basin.

Within the uncultivated zones, non-eroding profiles were most common (50% of the UT sites, 33% of the LT sites) but eroding sites were also well represented (27% of the UT sites and 50% of the LT sites). Deposition was only registered at 23% of the UT sites and 17% of the LT sites. The ^{137}Cs depth profiles associated with the uncultivated soils are very distinctive. ^{137}Cs accumulates at the top of the profile, its concentration declines exponentially with soil depth and its maximum depth of penetration is around 30 cm (Fig. 2(a)). Eroding sites within the uncultivated zones have been identified by the existence of low ^{137}Cs concentrations in the upper 10 cm of the profile (Fig. 2(b)) whilst the contrary is observed for aggrading sites (Fig. 2(c)).

Within the cultivated soils, the ^{137}Cs depth profiles are modified by the mixing action of ploughing and their shape exhibits a more uniform depth distribution of ^{137}Cs within the plough layer (25-30 cm deep). Deposition is indicated when significant activities of ^{137}Cs are found at depths greater than 30 cm and thus aggrading profiles can be identified by the extended depth of ^{137}Cs occurrence down to 40-50 cm, reflecting the burial of the previous profile (Fig. 2(d)). Eroding sites exhibit down-profile concentrations of ^{137}Cs which are significantly lower than in the non-eroding profiles (Fig. 2(e)).

Patterns of soil redistribution by erosion and deposition processes can thus be identified on the basis of the ^{137}Cs profile shapes. Deposition of soil bearing no ^{137}Cs, indicating a source of soil from an already eroded area, was identified at site 17D on transect LT (Fig. 3(a)). Also on this transect, particularly severe erosion was evident at sites 17L, 18L and 19L, where almost no ^{137}Cs was found in the whole profile (Fig. 3(b)).

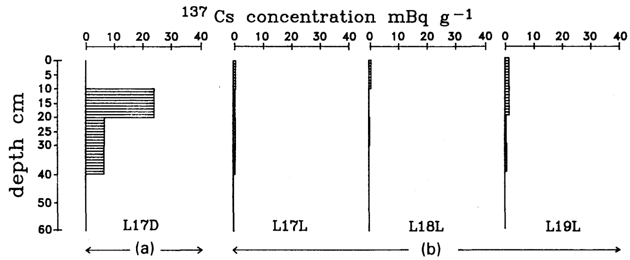

Fig. 3 (a) ^{137}Cs depth profile reflecting the deposition of soil containing no ^{137}Cs within the top 10 cm. (b) ^{137}Cs depth profiles indicating severe erosion reflected by the very low ^{137}Cs concentration within the entire soil profile.

SPATIAL VARIABILITY

A high variability has been found in the distribution of ^{137}Cs depth profiles along the transect. An example of this variability for sites having very similar altitudinal locations on the slope is shown in Fig. 4(a) for transect UT and Fig. 4(b) for transect LT.

To investigate further the reasons for the high spatial variability, granulometric analyses were undertaken on two sets of four core samples, each collected from a small area but exhibiting very different ^{137}Cs activities. As shown in Table 2, the samples from site D have a silty loam texture and low stone contents. Higher fine fraction contents and stone contents are found in samples from site P. Variations in texture and stoniness do not explain the variability in the ^{137}Cs activity values recorded for the two sites, since samples with very similar texture and stone content can possess values of ^{137}Cs activity that differ by more than 100%. Hence, this feature can be only explained by physical processes of erosion or deposition. Some of the variability may reflect an initially non-uniform distribution of ^{137}Cs in the landscape but it can be mainly ascribed to the effects of the micro- and meso-topography in controlling small scale redistribution of ^{137}Cs by erosion or deposition processes. Also, because of the distinctive physiography of this semiarid environment, where vegetation cover is not uniformly distributed, rocks and plants can trigger very

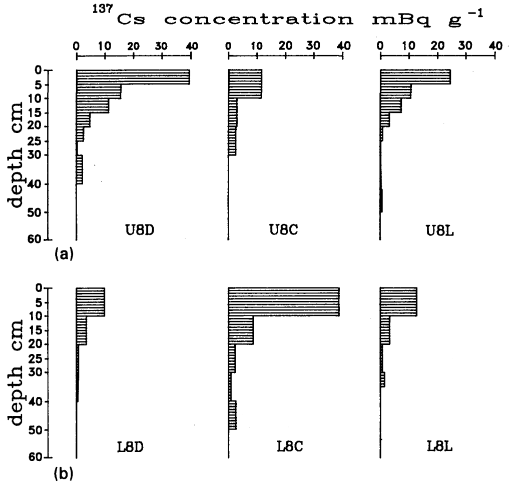

Fig. 4 Spatial variability of the ^{137}Cs depth profiles found at sites having very similar altitudes on the upper transect (a) and the lower transect (b).

localized erosion and deposition.

Nevertheless, a high stone content can have an effect on the ^{137}Cs activity by reducing the relative content of the finer fraction (<2 mm) in the soil sample. This effect is evidenced when comparing the form of different ^{137}Cs depth profiles with their overall ^{137}Cs inventories. The local reference inventory for the area is approximately 200 mBq cm^{-2}. As shown in Fig. 5(a), sites 2D and 3D on transect LT exhibit ^{137}Cs depth profiles indicative of a non-eroding site, but their high stone contents result in a low value of ^{137}Cs activity. As a result, they could be interpreted as eroding sites, in the absence of supplementary information on the ^{137}Cs distribution within the soil profile. Similarly, as shown on Fig. 5(b), an aggrading profile (10D from transect LT) with a high stone content, can exhibit a ^{137}Cs inventory that could suggest a non-eroding profile or even a slightly eroding profile; and an eroding profile (4L from transect UT) having a low stone content is characterized by a ^{137}Cs activity value that could represents a non-eroding profile. These findings emphasize the need to consider both total ^{137}Cs inventory and depth distribution to produce meaningful results.

Table 2 Stone content, grain size distribution, texture, and ^{137}Cs activity for four closely spaced (60 × 60 cm) samples collected from sites D and P.

Sample	Stone content (%)	Sand content (%)	Silt content (%)	Clay content (%)	Texture	^{137}Cs activity (mBq cm^{-2})
D2	13	29	52	19	silty loam	630
D3	10	31	56	13	silty loam	360
D6	0	32	54	14	silty loam	262
D7	0	19	622	18	silty loam	658
P1	18	9	47	43	silty clay	729
P2	22	10	47	43	silty clay	285
P3	16	9	47	44	silty clay	135
P5	23	9	47	43	silty clay	323

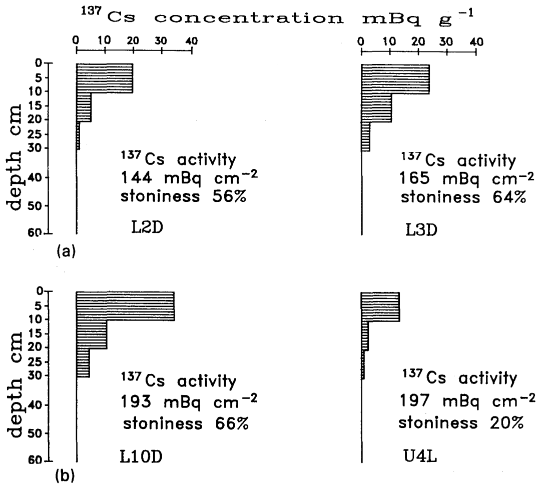

Fig. 5 (a) Effect of the high stone content on the ^{137}Cs inventory for two non-eroding ^{137}Cs depth profiles. (b) Contrasting effect of the high stone content on the ^{137}Cs inventory for an aggrading ^{137}Cs depth profile and of the low stone content for an eroding ^{137}Cs depth profile.

VARIATION OF ^{137}Cs INVENTORIES AND DEPTH PROFILES ALONG THE SLOPE

For both transects, the variation in the ^{137}Cs inventory and in the form of the depth profile along the slope has been analysed using several parameters. These include the total ^{137}Cs inventory, the depth containing 80% of ^{137}Cs activity, the depth to zero ^{137}Cs activity, and the depth to the ^{137}Cs peak. Analysis of these parameters can provide information on the associated patterns of erosion and deposition. Values of the depth at which ^{137}Cs is no longer detectable can, for example, indicate the relative amount of deposition that has occurred. Values of depth to peak activity lying in the range 0-10 cm (along with normal values of ^{137}Cs concentration for this depth increment) would suggest the existence of undisturbed sites. Deposition can be identified when peak activity is found at depths greater than 10 cm.

As shown in Table 3, average ^{137}Cs activity is higher for the upper transect than for the lower transect. More severe erosion appears to be affecting both the uncultivated and cultivated soils of the lower transect as reflected by the lower average ^{137}Cs activity values. Values of depth to peak ^{137}Cs activity, depth to undetectable ^{137}Cs and depth containing 80% of the ^{137}Cs are, however, very similar for both transects.

The average values for the various measures of ^{137}Cs distribution differed markedly between the uncultivated and cultivated parts of both transects. The depth containing 80% of the ^{137}Cs almost doubles for the cultivated soils of both transects. Depth to zero ^{137}Cs activity is 21% and 35% deeper for the cultivated soils of the lower and upper transects respectively. Depth to peak

Table 3 Average values of total ^{137}Cs activity, depth containing 80% of ^{137}Cs activity, depth to undetectable ^{137}Cs and depth to peak ^{137}Cs activity for the two transects.

	^{137}Cs inventory (mBq cm^{-2})	Depth containing 80% of ^{137}Cs (cm)	Depth to zero ^{137}Cs (cm)	Depth of ^{137}Cs peak (cm)
Upper Transect				
Total transect	221	21	48	12
Uncultivated part	222	17	43	10
Cultivated part	220	30	58	18
Lower Transect				
Total transect	142	23	48	14
Uncultivated part	162	14	42	10
Cultivated part	128	30	52	17

activity increased by 65% and 77% for the cultivated sites on the lower and upper transects respectively. On the uncultivated soils peak activity was always found within the 0-10 cm depth increment, reflecting the strong binding of ^{137}Cs near the surface. No distinct peaks have been found for most of the sites on the cultivated soils, because tillage mixes ^{137}Cs through the whole plough layer. Nevertheless, some sites evidenced peak activities at greater depths (20-30 cm deep), this peak probably represents a buried surface soil horizon. This fact along with high activity in the topsoil indicates recent deposition.

According to the ^{137}Cs inventories associated with the four reference samples, the local fallout inventory is around 200 mBq cm^{-2}; greater and lesser values would indicate deposition and erosion respectively. Variation of the ^{137}Cs activity along the slope for each sequence of both transects is portrayed in Fig. 6(a). A slight trend towards an increase in the ^{137}Cs activity values indicating some deposition is observed at the bottom of the upper transect from row 11 (76% of the slope length). However, this feature is not found on the lower transect where soil erosion caused by cultivation of the valley bottom appears to be predominant.

Figure 6(b) shows the geomorphological significance of the slope form and its effect on sediment movement as reflected by the increase of the depth to undetectable ^{137}Cs downslope of the sites where the slope becomes concave, which in turn provides evidence of deposition. Furthermore, at the sites where soil is cultivated, a general trend towards an increase in the depth to zero ^{137}Cs content is evident.

CONCLUSIONS

Patterns of soil redistribution along the slope transects have been identified by analysing the distribution of ^{137}Cs within the soil profile. The depth distribution of the ^{137}Cs concentration within the soil profile differed markedly for the uncultivated and cultivated soils of both transects. In general, a normal sequence of non-eroding, eroding and aggrading ^{137}Cs depth profiles has been

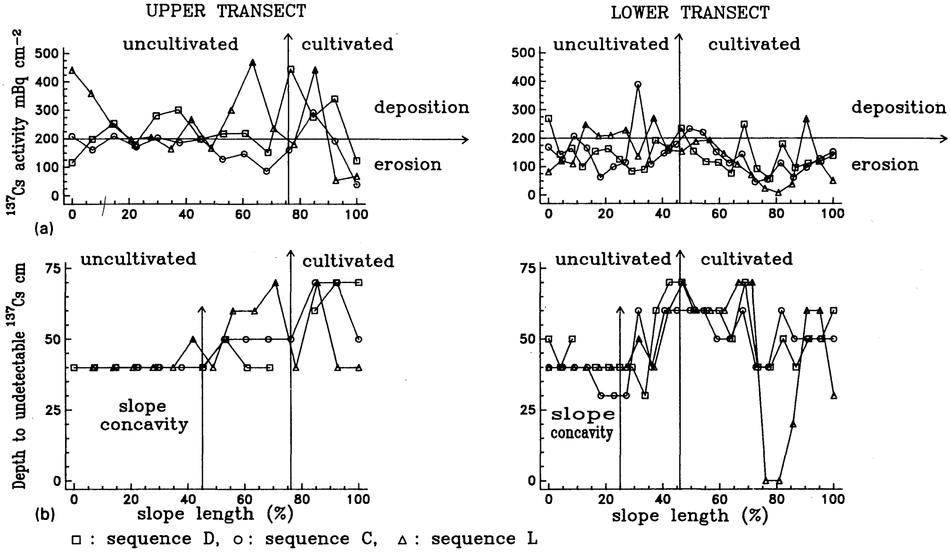

Fig. 6 (a) Variation of the ^{137}Cs activity and (b) the depth to undetectable ^{137}Cs along the slope sequence of both transects.

found in relation to their location on the slope, from the hilltop, the mid slope and the valley bottom respectively. Higher ^{137}Cs levels are found within the uncultivated upper parts of both transects where the slopes, although steeper, are protected from erosion by the vegetation cover. On the cultivated soils of the valley bottom, ^{137}Cs is mixed within the plough layer. Marked differences in the depth containing 80% of the ^{137}Cs activity and in the depth to undetectable ^{137}Cs and to the ^{137}Cs peak, between the uncultivated and cultivated parts of both transects, reflect the important effect of tillage on the severe soil erosion process occurring in the valley bottom area of the basin. Slope form influences soil movement, as evidenced by the deposition occurring at the slope concavity.

The distribution of vegetation cover along with the micro- and meso-topography, which control small-scale redistribution of ^{137}Cs by erosion or deposition processes, appears to be the main reason for the high spatial variability found. This fact reinforces the need for prior analysis of the spatial variability in order to design a suitable sampling strategy. The stone content also appears to have an effect on the ^{137}Cs activity within the soil profile, by reducing the relative content of the finer fraction, particularly when high stone contents are involved.

This study served as a preliminary investigation to assess the possibilities of applying the ^{137}Cs technique for studying soil erosion in Spain. The results obtained have confirmed the potential for using ^{137}Cs in determining soil and sediment redistribution in semiarid upland environments. Hence the technique presents a useful advance in tracing movement of soil particles in environments such as those studied here and in addition it appears to be the most promising method for providing the empirical data necessary to quantify soil erosion. Because of the severity of the erosion problem in the Spanish context, there is an urgent need to move towards a more quantitative approach in order to obtain estimates of actual erosion rates.

Acknowledgements The authors are particularly indebted to Dr J. Machín for his helpful collaboration in the field work and to Isabel de Santiago for producing the diagrams. The constructive comments and advice on this investigation provided by Dr T. Quine are gratefully acknowledged. Much of the work in this paper was carried out at the Department of Geography, University of Exeter. The help and hospitality received from members of staff is gratefully acknowledged. The research was made possible by the financial support of the British Council and the Ministry of Science and Education of Spain.

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