Article

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Changes in land-use and their impact on erosion rates and overland flow generation in the Maghreb region

Impact des changements d'utilisation des sols sur la production d'érosion et de ruissellement superficiel dans la région du Maghreb

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SUMMARY

The ongoing intensification of grazing as well as the replacement of traditional land management systems in the Maghreb has brought to the forefront the fundamental role of land-use in determining soil erosion hazard. This paper reports on erosion rates and soil hydrological characteristics of a variety of land uses in Morocco and Tunisia. The results were obtained through rainfall simulation experiments carried out in the field using a portable simulator, following the design of CERDÀ *et al.* (1997).

Traditional land management systems – typically involving a combination of agriculture, animal husbandry and forestry – produced the least amounts of overland flow and the lowest soil erosion rates. Over-exploitation of these systems apparently has only minor hydrological and erosional impacts. Heavily grazed, degraded "maquis" shrublands, on the other hand, produced considerable amounts of overland flow. At the plot scale of the rainfall simulation experiments (0.24 m^2), the corresponding sediment loads are rather insignificant. Nevertheless, slopes where "maquis" shrublands (which generally have very compacted soils) occur upslope from more erodible soils may present a major erosion hazard.

Key words: *landuse change, overland flow, erosion risk, Maghreb.*

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RÉSUMÉ

Les zones marginales du Maghreb subissent actuellement de rapides changements au niveau des types d'usage des sols. L'augmentation de la pression démographique au cours des dernières décennies a poussé leur population à intensifier leur système traditionnel d'agro-sylvo-pastoralisme et à adopter des pratiques de gestion des sols non traditionnelles (LAOUINA, 1999).

Il est possible de distinguer trois grands types de changements d'usage des sols aux causes et aux conséquences étroitement liées, menant à une augmentation de la dégradation des sols et de l'érosion :

(1) La mise en culture de sols jusqu'alors considérés comme non arables (lithosols pauvres sur pentes escarpées), à l'origine uniquement consacrés aux activités de pâturage et de sylviculture. Le labour est réalisé généralement dans le sens de la pente ; il est en plus mécanisé partout où la pente le permet.

(2) Le surpâturage des zones de maquis. Il résulte d'une part de l'augmentation du nombre de têtes de bétail et, d'autre part, de la réduction de la surface réservée à l'activité de pâturage conséquente à la reconversion de ces terres en zones de culture. (MIKESELL, 1960).

(3) La plantation d'espèces à croissance rapide telles que les eucalyptus et les pins. L'extension de ce type de plantation se fait aux dépens des plantations de chênes liège et des zones de maquis (NAFAA *et al.*, 2000). Elle a pour origine une tentative d'approvisionnement en bois et en combustible des populations locales.

De ces changements d'usage de sol résultent une augmentation de l'érosion du sol et la dégradation des terres, comme décrit par LAOUINA (1990, 1998), LAOUINA *et al.* (1993), HAMZA (1994), et COELHO *et al.* (2002), menant pour les cas extrêmes à la formation de ravines et de « badlands ». La dégradation des terres peut souvent être considérée comme le résultat direct de l'abandon des pratiques traditionnelles de gestion durable (LAOUINA *et al.*, 1993).

Cet article présente les implications, sur l'érosion et le ruissellement superficiel, des changements d'usage de sol survenus dans les zones marginales de la région du Maghreb. Une hiérarchisation des différents niveaux de pression sur le sol sera également établie pour trois différents usages (pâturage, sylviculture et agriculture).

La méthodologie utilisée établit, pour chaque usage du sol, une description de la couverture végétale et de la litière sur des transects de 25 m. Les caractéristiques d'humidité du sol, de ruissellement superficiel et de taux d'érosion ont été déterminées par le biais d'une série d'expériences de simulation de pluie (CERDA *et al.*, 1997). Le simulateur de pluie est constitué d'un diffuseur placé à une hauteur de 2 m capable de produire une intensité de pluie spatialement homogène de 50,5 mm/h sur une surface au sol de 1 m^2. Une structure métallique circulaire délimitant une surface expérimentale de 0,24 m^2 est insérée dans le sol. À l'intérieur de cette surface, une sonde de mesure de l'humidité du sol « Theta probe » est installée jusqu'à une profondeur de 6 cm. Les mesures de ruissellement superficiel et d'humidité du sol sont effectuées toutes les minutes. Cinq échantillons d'eau de ruissellement superficiel sont recueillis pour permettre la détermination de l'évolution de la charge en sédiment. Chaque simulation a une durée totale de 60 minutes.

Après chaque simulation, un échantillon de sol est prélevé afin de déterminer au laboratoire, par un granulomètre « Coulter LS Particle Size Analyser », la texture du sol de la fraction inférieure à 2 mm. La teneur en matière organique est déterminée par calcination à 550 °C durant 120 mn. La détermination de la résistance du sol à la pénétration et à la torsion est réalisée par 20 tests effectués autour de la parcelle à l'aide d'un pénétromètre et d'un « torvane ».

L'analyse du couvert végétal indique que les peuplements d'espèces exotiques présentent des sous-strates végétales significativement plus faibles que les peuplements de chêne liège. Ceci s'explique par le labour précédant la plantation et la production de litière plus faible des peuplements d'eucalyptus en zone semi-aride.

Les zones de pâturage présentent un large éventail de couverture végétale variant de 0 à 80 %. Les résultats relatifs aux « badlands » ont été obtenus dans une zone de pâturage ouverte incluant à la fois des zones de prairie avec une couverture atteignant 80 % et des zones ravinées sans aucune végétation. On observe une diminution de la couverture herbacée avec l'augmentation de la pression de pâturage.

Au niveau des caractéristiques de résistance à la pénétration du sol, excepté pour les sites ayant subi un labour profond et les jachères qui présentent des valeurs plus faibles, tous les usages de sol présentent des valeurs supérieures à 2 $kg \cdot cm^{-3}$. Les « badlands » atteignent de manière homogène les valeurs les plus élevées. Les caractéristiques de résistance à la torsion du sol des peuplements forestiers, aux taux de matière organique élevés, présentent des valeurs inférieures à 0,25 $kg \cdot cm^{-2}$ en moyenne. Les surfaces labourées dont la structure du sol a été détruite atteignent les valeurs les plus faibles. Les zones de pâturage intensif sous couvert de chêne liège révèlent des valeurs de résistance à la torsion élevées. Les valeurs mesurées pour les « badlands » sont élevées mais très hétérogènes. Ce qui implique pour certaines zones de « badlands » une grande fiabilité du sol en dépit d'un degré de compaction élevé.

Concernant le ruissellement superficiel, les peuplements de chêne liège présentent des valeurs faibles, inférieures à 20 %. L'augmentation de la pression de pâturage entraîne un accroissement significatif du ruissellement qui dépasse 50 % de la pluie incidente pour certains « badlands ». Les plantations d'eucalyptus présentent des taux de ruissellement supérieurs aux peuplements de chêne liège. La pratique du labour augmente la quantité de ruissellement, cependant le labour suivant les courbes de niveau semble une technique conservatrice contrairement au labour dans le sens de la pente.

Les taux d'érosion les plus faibles sont mis en évidence pour les peuplements de chêne liège. La garrigue et les « badlands » présentent des taux d'érosion à peine plus élevés malgré des ruissellements importants. Les zones de pâturage intensif sous couvert de chêne liège montrent une érosion très importante. Dans les plantations d'eucalyptus, les quantités de sédiments produites sont réduites de moitié par rapport à la production de sédiments dans les zones de surpâturage. Ce sont les zones labourées qui présentent les taux d'érosion les plus élevés. En effet, cette pratique élimine le couvert végétal et la litière et détruit la structure et la cohérence des sols. La pratique du labour dans le sens de la pente sur des versants très pentus.

En conclusion, pour chaque type d'usage du sol étudié, un indice de risque d'érosion des sols a été attribué. Les plantations d'eucalyptus ont été classées comme l'usage de sol ayant les conséquences négatives les plus faibles en matière de conservation des sols et de l'eau. Par ailleurs elles permettent de réduire la surexploitation des peuplements de chênes liège et représentent donc une alternative tout à fait acceptable.

Les zones labourées présentent les taux d'érosion des sols les plus élevés. Cependant, le sol étant travaillé régulièrement, elles ne présentent pas les structures classiques des sols dégradés par l'érosion tels que les ravines ou les « badlands ». Cependant, l'érosion est évidente et pourrait se traduire par une baisse de fertilité des sols. Pour résoudre ce problème, le recours à des associations d'agriculteurs ou au remembrement foncier permettant l'emploi de techniques plus conservatrices serait nécessaire.

Le surpâturage est souvent associé à des formes très marquées d'érosion. Malgré la très bonne cohérence des sols, les capacités d'infiltration réduites augmentent le ruissellement superficiel, et entraînent la formation de ravines et de « badlands ». Une solution à ce problème serait d'augmenter la surface de pâturage, soit par l'élargissement des surfaces de végétation naturelle, soit par le maintien d'une surface agricole en jachère plus importante, permettant au sol de se régénérer et d'alimenter le bétail.

Mots clés : *altération de l'usage du sol, ruissellement superficiel, risque d'érosion, Maghreb.*

1 - INTRODUCTION

Rapid changes in land-use are occurring in the marginal areas of the Maghreb, i.e. in areas not suitable for agriculture, such as steep slopes originally used as natural areas for grazing or forestry (COELHO *et al.*, 2000, 2002; LAOUINA, 1999; HAMZA, 1994). Current trends include replacement of evergreen oak forest by fast growing trees such as *Eucalyptus* species, and an increase in agriculture and grazing activities. The use of the high-quality soils for commercial crops and population growth pushes local communities to cultivate steep slopes, decreasing the forest and shrubland areas (MIKESELL, 1960). In addition, an increasing number of grazing animals, noted already in the 1960's by MIKESELL (1960), adds extra pressure to replace traditional land-uses. Therefore, areas traditionally occupied by sustainable forest and shrub land-uses are experiencing a change in intensification of land management practices, leading to the use of the poor Lithosols in an unsustainable way.

Three main changes in land-use can be observed. These changes are tightly linked and enhance soil degradation and erosion: (1) Ploughing of steep slopes, generally in the direction of the slope; (2) Overgrazing of the shrubland areas ("Maquis" and "Garrigue"), as a result of the increase in agriculture; (3) Afforestation with exotic species. For example, in the Ksar el Kebir region, changes in land-use are responsible for a sharp reduction of cork oak forest and shrubland areas (NAFAA *et al.*, 2000).

Soil degradation is often linked to inappropriate agricultural practices, particularly on marginal and easily eroded hillsides, or land abandonment (FAO, 2000). Agriculture and overgrazing produce major changes in soil superficial structure, with significant variations in soil compaction, shear stress, organic matter content, percentage of litter and vegetation cover, that ultimately affect soil wetting patterns, overland flow production and erosion rates (COELHO *et al.*, 2002). The social, economic and environmental implications of such changes can be serious (CARVALHO *et al.*, 2002), particularly since the Northern Africa rural population is increasing steadily. In some Moroccan rural areas, human density exceeds 100 inhabitants per square kilometer, leading to an overwhelming pressure on the "marginal" areas. The increase in a population making a living from an agro-forest-grazing system is inducing serious land degradation, and, consequently, leading to socio-economic deterioration and

poverty. Shrinking traditional land-use areas suffer mounting pressure from increasing numbers of sheep, goat and cow herds. In addition, there is a replacement of native forest by fast growing exotic species (e.g., eucalyptus represent 42.5% of all the stands planted in Morocco during the 1989-1990 period), used mainly to provide wood and fuel to local populations.

Clearly, intensification of agriculture and grazing has led to the use of non-traditional land management practices (LAOUINA, 1999). The resultant increase in soil erosion and land degradation has been reported by LAOUINA (1990, 1998), LAOUINA *et al.* (1993), HAMZA (1994), and COELHO *et al.* (2002), including in the worst case scenario: the formation of gullies (LAOUINA *et al.*, 1993) and "badlands". This degradation is a direct result of the abandonment of the traditional, more conservative, land management practices (LAOUINA *et al.*, 1993).

This paper presents the implications of current land-use changes in marginal areas of the Maghreb region on erosion rates and overland flow. The relation between different levels of soil pressure under three current land uses (i.e. grazing, afforestation and agriculture) is also addressed.

2 - CHARACTERIZATION OF THE STUDY AREAS

All the studied areas are within the climax distribution regions for *Quercus suber* L. (i.e., with annual rainfall amounts between 500 and 1200 mm) with the exception of the semi-arid Sousse study area (figure 1). All the sites are marked by a dry summer period that extends over 6 months in the semi-arid region of Sousse (table 1).

2.1 Morocco

The *Ben Slimane* region is the most southerly *Quercus suber* L. forest along the Atlantic coast, covering some 22,700 hectares. Rainfall varies between 400 and 550 mm per year, with 50 to 60 rainy days and 5 to 6 dry months. This region has a low human population density, grazing activity is high in some places, and *Eucalyptus spp.* forest stands are planted in order to provide wood to the local residents. The region being at the edge of the natural distribution of *Quercus suber* L., the trees are currently under water stress and regeneration is difficult. The main land uses are: *Quercus suber* forest with overgrazing, re-growth *Quercus suber* stands, where grazing is forbidden by law, mature *Eucalyptus* stands and re-growth *Eucalyptus* stands. Due to a decrease in yearly rainfall amounts over the last two decades, trees are currently experiencing increased water stress. This, along with overgrazing, makes regeneration difficult or absent.

The *Ksar El Kebir* region is located in the southern foothills of the Rif Mountain. Once covered by cork oak, pine and cedar forest stands, these trees retreated drastically in the region during the 20th century. Presently, they only remain on the inaccessible slopes and summits of the Rif Mountain. Rainfall in this study area varies from 600 to 800 mm per year, exceeding 2000 mm in the

Rif summits, with 60 to 80 days of rainfall per year and 3 to 4 dry months. The study areas of Tatoft and Boujediane are mountainous parishes in the Ksar el Kebir municipality. While the more fertile lowlands are used for commercial crops (i.e., sugar cane, sugar beet, ...), a demographically increasing population (the present population density is over 100 inhabitants·km^{-2}) is forced to cultivate marginal land such as the steep foothills and the southern slopes of the Rif mountains. Currently, most of the foothill slopes are ploughed and the natural vegetation is increasingly degraded. Shrubland areas are decreasing, either because gullies and badlands have formed or because the "natural areas" are increasingly being used for agriculture. This leads to an increase in grazing activities over the remaining very degraded shrubland, yielding bare compacted soil. Even the steep slopes of the Rif mountain are under heavy pressure from grazing, agriculture (*Cannabis sativa* L. Hemp. can be found in the more inaccessible parts of the Rif slopes), and fire wood gathering.

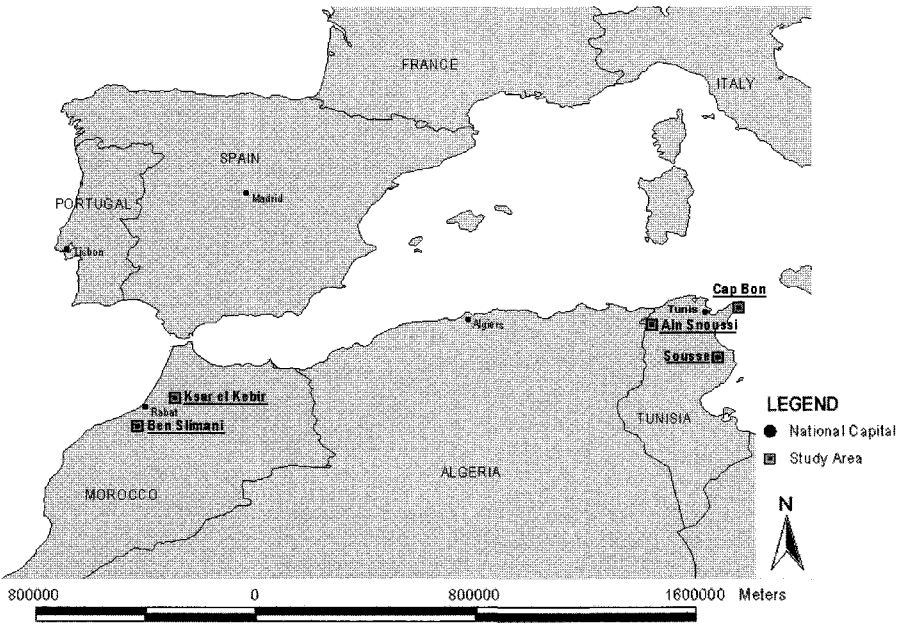

Figure 1 Study area location.
Localisation des sites d'étude.

2.2 Tunisia

Ain Snoussi is located in the Eastern Atlas mountains, in the northern part of Tunisia, in a sub-humid to humid environment. Annual rainfall varies from 1000 to 1500 mm. The main land-uses are cork oak trees and pasture land.

This mountain ground has a high human density that lives mainly upon agriculture and grazing (the exploitation of cork, in the cork oak forest stands, is reserved for the government). The high population pressure is reflected by impressive and extensive soil degradation features, which include badlands

and gullies. The landscape is still dominated by *Quercus suber* L. stands with a high tree density.

The *Cap Bon* region, in the north-east region of Tunisia, is a sub-humid region, with an annual rainfall amount ranging from 450 to 700 mm. Agriculture and grazing areas are the dominant land-uses. The measured eucalyptus stands were located on weekly developed sand dune soils, with a high percentage of the soil lacking an A horizon or any kind of litter or vegetation cover. This area has a high population density, living mainly from agriculture. Crops cover most of the available land. This includes steep slopes that are frequently ploughed from the top to bottom. Grazing is mainly performed on land under fallow and on the few remaining degraded "garrigue" areas. The impressive number of landslides observable throughout the landscape demonstrates the impact of man on the land.

Table 1 Study areas location.

Tableau 1 *Localisation des sites d'étude.*

Study Areas	Geographic co-ordinates	Average yearly rainfall (mm)	Soil Types	Dominant land uses	Demographic Trend
Ksar el Kebir (Morocco)	34°59'N 05°50'W	600 – 800	Lithosols and yermosols	Agricultural land with highly degraded grazing "garrigue" areas	Population Increase
Ben Slimane (Morocco)	33°36'N 07°06'W	400 – 550	Lithosols	*Quercus suber*, *Eucalyptus* stand, Grazing areas.	Population Increase
Ain Snoussi (Tunisia)	36°47'N 8°58'E	1 000 – 1 500	Lithosols	*Quercus suber*, Grazing areas.	Population Increase
Cap Bon (Tunisia)	36°57' N 11°02' E	450 – 700	Lithosols	Agriculture, Grazing "maquis" areas, Forest stands	Population Increase
Sousse (Tunisia)	35°49'N 10°37' E	300 – 500	Lithosols	Olive groves with agriculture, *Eucalyptus* stands.	Population Increase

Sousse is located on the eastern coast of Tunisia in a semi-arid region. The average annual rainfall amount (300-500 mm) does not allow the survival of *Quercus suber* L. trees.

Located on the outskirts of the town of Sousse, the study area suffers a high human impact. Agriculture fields are typically small, well-delimited, with a high density of olive trees making the use of machinery difficult. The main land-use at Sousse is olive groves associated with other crops. Areas with poor soils are generally planted with *Eucalyptus spp*. The main land-uses for each study area are presented in table 2.

Table 2 Representative land use at the study areas.

Tableau 2 *Usages du sol représentatifs pour les sites étudiés.*

	Ksar el Kebir (Morocco)	Ben Slimane (Morocco)	Ain Snoussi (Tunisia)	Cap Bon (Tunisia)	Sousse (Tunisia)
Cork oak forest	present	**dominant**	**dominant**	0	0
Eucalyptus forest	present	present	0	present	present
Ploughed steep slope	**dominant**	present	present	**dominant**	present
Ploughed along contour	trace	trace	trace	trace	trace
Fallow	present	trace	trace	present	trace
Heavy grazed forests	present	present	present	0	0
Heavy grazed "maquis" and "garrigue"	present	0	present	present	0
Badlands	present	0	present	present	present
Olive groves	trace	0	0	0	**dominant**

Table 3 Soil characteristics for the study sites.

Tableau 3 *Caractéristiques du sol des sites d'étude.*

		Soil density g/cm^3	Organic Matter content (%)	Texture >2 mm (%)	Sand (%)	Silts (%)	Clays (%)
Morocco							
Ksar el Kebir	Max.	1.2	8.5	2.3	16.9	55.1	40.5
	Avr.	1.0	7.5	1.3	10.6	52.5	34.8
	Min.	0.9	6.5	0.3	2.6	49.9	33.0
Ben Slimane	Max.	1.4	9.4	41.5	49.5	17.8	6.0
	Avr.	1.2	8.2	34.0	48.0	13.2	4.8
	Min.	0.9	5.8	30.1	45.7	6.9	2.9
Tunisia							
Sousse	Max.	1.53	5.5	35.9	78.2	23.0	25.5
	Avr.	1.05	3.9	22.6	46.9	12.0	18.3
	Min.	0.71	2.4	9.2	15.6	1.0	11.0
Cap Bon	Max.	1.20	9.8	13.2	93.9	2.0	6.0
	Avr.	0.83	5.2	7.6	86.6	1.8	4.0
	Min.	0.45	2.0	2.0	79.2	1.5	2.0
Ain Snoussi	Max.	1.54	8.9	38.3	52.7	12.0	29.0
	Avr.	1.03	6.6	32.1	39.0	10.3	18.6
	Min.	0.66	4.7	26.9	32.0	6.6	12.5

Table 3 presents the soils characteristics for the study sites. Soils are unsuitable for agricultural uses and are predominantly lithosols. They have densities ranging from 0.85 to 1.2 g·cm^{-3}, and organic matter contents below 12%. Ben Slimane soils are very stony (stones represent in average more than 30% of the dry weight). Ksar el Kebir soils have a silty clay loam texture, due to underlying limestones and mudstones. The soils from Cap Bon, Tunisia are mainly sandy soils with minor percentages of stones, silts or clays. The other Tunisian soils are comparable to the Ben Slimane soils in terms of soil density, percentage of stones and sand, and present a smaller percentage of silts and higher clay content.

3 - METHODOLOGY

For each land-use, point measurements were made every 20 cm in a 25 m transect to assess vegetation and litter cover. Soil wetting patterns, overland flow amounts and erosion rates were determined with the help of a rainfall simulator (CERDÀ *et al.*, 1997). It consists of a sprinkling device placed at 2 m above the soil. The device provides a reasonably spatially homogeneous rainfall intensity of 50.5 mm per hour over a 1 m^2 area. A small 0.24 m^2 round plot is inserted carefully into the soil. Inside the plot, a Theta probe connected to a soil moisture meter is inserted to a depth of 6 cm. Measurements of overland flow and soil moisture content were made each minute. Overland flow samples were collected to measure sediment concentration. Three samples were taken within the first 15 minutes after overland flow production began. A fourth sample was taken in the middle of the experiment, and a fifth at the end of the experiment. Rainfall simulation experiments were performed for one hour.

A soil sample was collected after the rainfall simulation for physical parameters measurements. Twenty measurements were taken for soil resistance to penetration and to torsion at each experiment around the plot. Soil resistance was assessed using a pocket penetrometer and a torvane (small instrument to measure soil shear strength in the field). A 2 mm sieve was used to divide the soil samples. A Coulter LS Particle Size Analyzer performed soil texture analysis for the fraction under 2 mm. Organic matter content was determined by Loss on Ignition at 550°C during 120 minutes.

4 - RESULTS

4.1 Changes in shrub and litter cover

Exotic forest stands have significantly less vegetation cover when compared with the cork oak stands, as a result of ploughing prior to plantation and lower leaf litter production by the semi-arid eucalyptus stands (Tunisia) (figure 2). In figures 2 to 6, the extreme of the thin lines represent the maximum and the minimum values, while the top and bottom of the blocks represent the 3^{rd} and 1^{st} quartile, respectively.

Grazing areas showed a wide range of vegetation covers from 0% to over 80%. One of the monitored "badland" areas was located in an open grazing field and included grassland. This is the main reason why some of the measurements show more than 80% cover. No vegetation cover was reported in the gully area. There is a steady decrease of grass cover and leaves with increasing grazing activity.

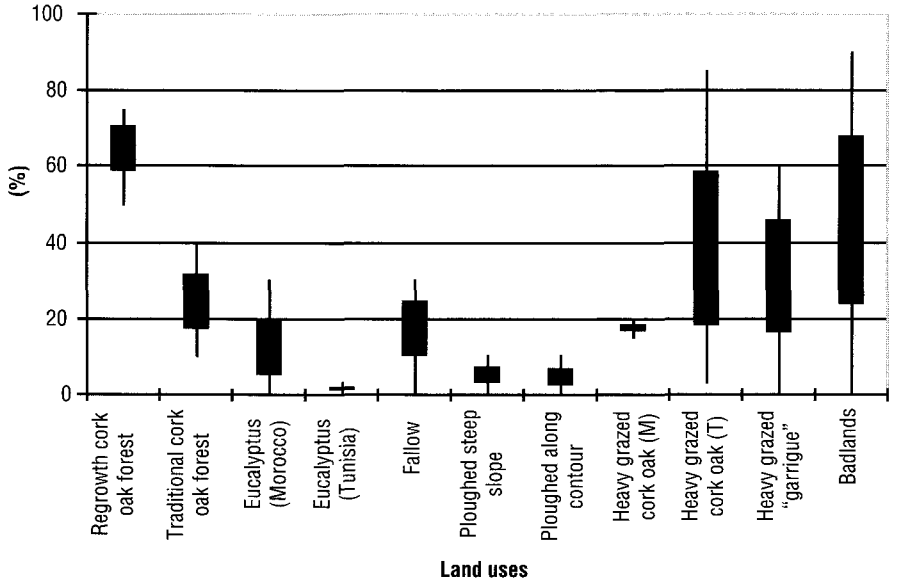

Figure 2 Shrub and litter cover.
Couverture végétale arbustive et litière.

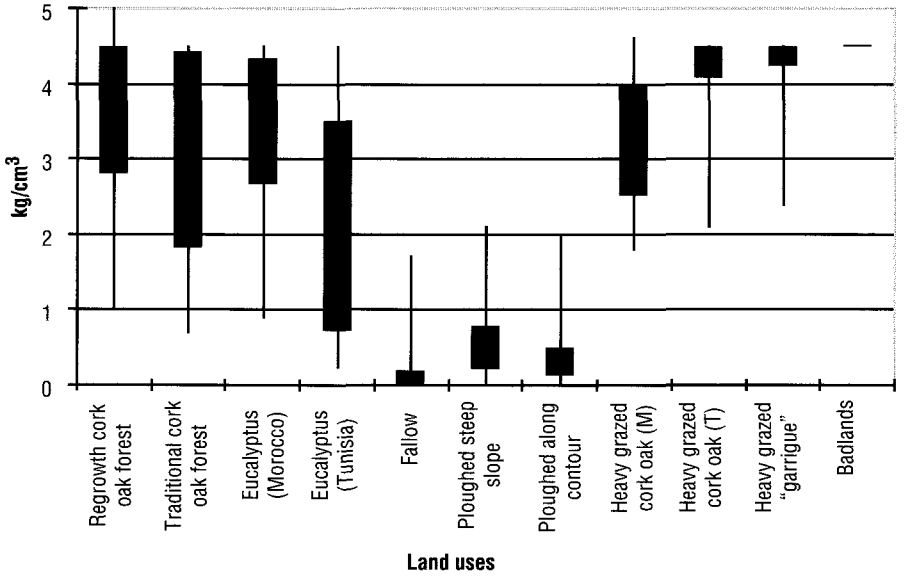

Figure 3 Soil resistance to penetration.
Résistance du sol à la pénétration.

4.2 Changes in soil resistance to penetration and shear strength

With the exception of the deeply disturbed ploughed and fallow soils, which presented values below 2.5 kg·cm^{-3} with more than 75% of the measurements below 1 kg·cm^{-3}, all the other land-uses had soil resistance to penetration above 2 kg·cm^{-3}. While the eucalyptus stands showed similar penetration values to the cork oak forest stands, the heavily grazed areas present either identical values (heavily grazed cork oak forest in Morocco) or significantly higher values (heavily grazed cork oak in Tunisia and heavily grazed "garrigue"). Soil in the "badlands" have a very high and notably homogeneous resistance to penetration.

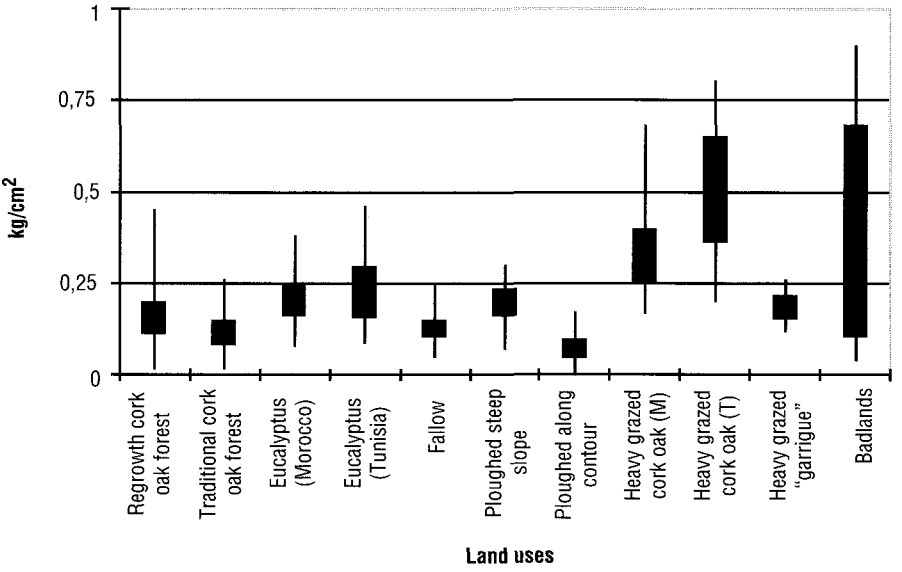

Figure 4 Soil shear strength.
Résistance du sol à la torsion.

Due to the high organic matter content, all the forest land-uses presented average values of soil resistance to torsion that are inferior to 0.25·kg◊cm^{-2}. Ploughed areas have slightly smaller torsion resistance due to the destruction of the soil structure. Heavy grazing significantly increased soil resistance to torsion under cork oak forest stands, although the values for the heavily grazed "garrigue" are similar to the ploughed areas. In contrast, the "badland" torsion measurements showed a broad distribution, although presenting the second highest average 0.44 kg·cm^{-2}. This implies that, in some areas, the soil in the "badlands" are highly friable, despite the high resistance to penetration due to soil compaction.

4.3 Overland flow production

Responding to high intensity rainfall (50.5 mm·h^{-1} during one hour), the cork oak land-use showed similar reactions, with less than 20% of incident rainfall

flowing as overland flow (figure 5). Increasing grazing pressure significantly enhanced overland flow. Values were particularly high for heavily grazed areas, especially under cork oak trees and on "badlands", where some of the rainfall simulations had more than 50% of rainfall flowing overland.

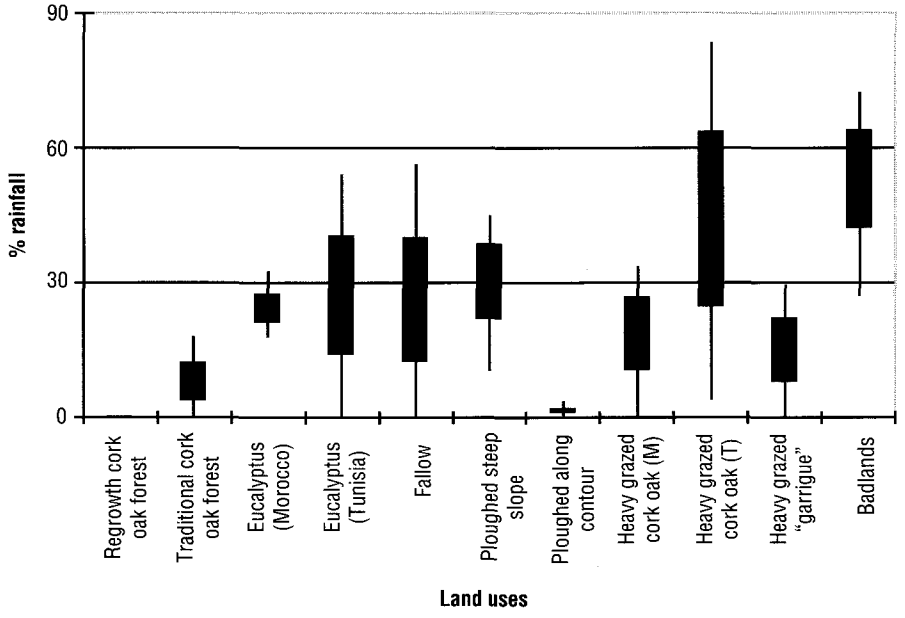

Figure 5 Overland flow production.
Production de ruissellement superficiel.

Eucalyptus stands presented significantly higher overland flow amounts than the cork oak forest stands. The re-growth cork oak area shows no overland flow, which might be connected to the very stony soil in the Ben Slimane cork oak forest in Morocco. Ploughing significantly increased overland flow. The values did not, however, typically exceed 40% of rainfall. Ploughing along the contour is a more conservative land management practice, while areas either under fallow or ploughed from the top of the slope present the higher overland flow values (above 20% of rainfall in average).

Some of the heavily grazed areas presented very high overland flow amounts, namely the heavily grazed cork oak at the Ain Snoussi area in North-West Tunisia, where average overland flow exceeded 40% of rainfall. The worst situation was in the "badlands", where average overland flow amounts accounted for more than 55% of rainfall.

4.4 Erosion rates

Traditional cork oak stands presented little or no erosion yields. No sediment loss was noted in the re-growth cork oak stand because overland flow did not occur (figure 6). The *"garrigue"* and the "badlands" in Tunisia had only

slightly higher erosion values, in spite of high overland flow values. Heavily grazed areas under cork oak trees, presented very high erosion rates, although values never exceed 300 $g \cdot h^{-1} \cdot m^{-2}$.

Erosion rates in the eucalyptus stands were typically less than 25 $g \cdot h^{-1} \Diamond m^{-2}$ and represented less than half of the sediment yielded under heavily grazed areas. The semi-arid eucalyptus plantation was the only forest land-use presenting an average erosion rate above 5 $g \cdot h^{-1} \cdot m^{-2}$.

Ploughed land presented the highest erosion rates. Ploughing completely destroys vegetation and litter layer cover and breaks up the soil structure, reducing the coherence of the soil and therefore its shear strength and compaction. Under these circumstances, erosion rates are expected to be important.

The traditional low grazing cork oak agro-forest-grazing stands typically showed erosion rates below 5 $g \cdot h^{-1} \cdot m^{-2}$. Ploughing along the contour produced erosion rates within the same magnitude, while fallow lands presented values below 100 $g \cdot h^{-1} \cdot m^{-2}$. The most deleterious land-uses were those where steep slopes are used for agriculture and are ploughed in the direction of the slope. Under these situations, erosion rates can exceed 2000 $g \cdot h^{-1} \cdot m^{-2}$.

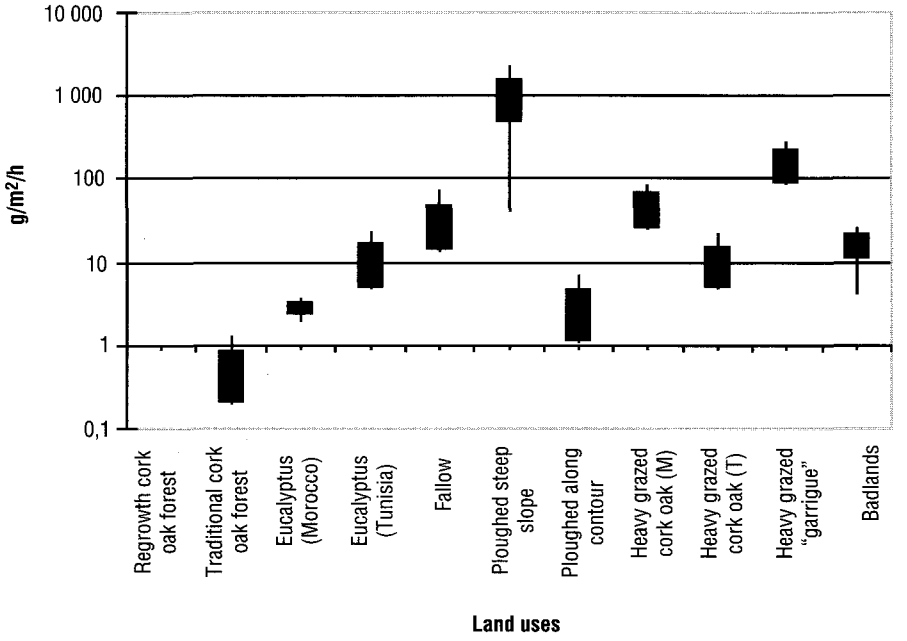

Figure 6 Erosion rates.
Taux d'érosion.

5 – DISCUSSION

5.1 Impact of land-use on erosion rate and overland flow.

Although measured at a 0.24 m^2 scale, rainfall simulations allow a direct comparison of all land uses. This approach has been proven to have a significant relation with catchment erosion at a semi-arid environment in Tunisia (HAMED *et al.*, 2002).

It is possible to establish a degradation tendency, for the different land-uses at all Moroccan and Tunisian study sites, based on the degree of pressure associated with each land-use. This degradation tendency is driven by one of the following land use change processes: (1) Use of inadequate soils for agriculture; (2) Afforestation with exotic species (i.e. eucalyptus), and (3) Overgrazing.

Starting with the initial low grazing *Quercus suber L.* agro-grazing-forest conservative management system, we can identify several degradation levels, in terms of vegetation and litter cover, soil compaction and soil shear strength. These factors will have a major impact on overland flow and erosion rates.

The introduction of exotic species significantly reduces shrub and litter cover, although no significant impact can be found on soil compaction and soil shear strength even if it is slightly higher than in the cork oak forests. As a result, the introduction of exotic tree species (namely eucalyptus) significantly increases overland flow and erosion rates, when compared with the conservative cork oak forest stands. Nevertheless, overland flow values and erosion rates are not very high, explaining partially why no erosion features such as rills, gullies or "badlands" are found. These findings agree with those reported by DESCROIX *et al.* (2001) that tree cover is inversely correlated with runoff and soil loss.

Overgrazing has a more devastating impact on soil and water conservation. In fact, overgrazed areas present a wider variation of shrub vegetation cover, with some areas of bare soil, and with others reaching vegetation and litter cover as high as 80%. Soil compaction is significantly higher for the heavily grazed areas, as is the case for soil shear strength. As a result, these areas typically present the highest overland flow amounts and significantly higher erosion rates when compared with the forest land uses. The increase of soil compaction due to overgrazing produces higher overland flow amounts but reduced erosion rates. Although erosion rates may not be significant at a plot scale, they might induce rill and gully features downslope, as is the case in the Ksar el Kebir in Morocco and Ain Snoussi in Tunisia (where the traditional natural land-uses retreated to the steepest slope areas, surrounded by cultivated land).

Continuity in landscape is thought to enhance overland flow and erosion rates, decrease soil fertility and water infiltration potential (VALENTIN *et al.*, 1999), and affect water and sediment fluxes at various scales (FERREIRA and COELHO, submitted). The disappearance of a mosaic landscape is mainly due to socio-economic constraints (CARVALHO *et al.*, 1999), and, unlike in the Sahel region, these constraints impede the implementation of banded vegetation in order to create run-off-run-in systems that greatly limit soil erosion (VALENTIN *et*

al. 1999). Therefore, the reduction of natural forest and shrubland grazing areas increases erosion hazard due to (a) a higher soil compaction, reducing infiltration capacity, and (b) a loss of patchiness (VALENTIN *et al.* 1999), which enhances connectivity and, therefore, overland flow.

Ploughing of steep slopes used for agriculture sharply reduces the soil vegetation cover, soil compaction and soil resistance to torsion. Two opposite scenarios can be found: (1) When ploughing is made along the contour, overland flow is reduced and erosion rates are similar to those in the mature cork oak forest. Providing that rainfall intensity does not exceed the storage capacity of the furrows, this is a soil conservation tool; (2) When ploughing is made in the sense of the highest slope angle, from the top to the bottom, erosion rates are overwhelming and soil erosion hazard is enormous.

Nevertheless, few major erosion features can be found in these areas. The only erosion features that can be found are rill networks. Yearly or seasonal re-working of the soil performed by the farmers may explain the absence of gullies and "badlands". Re-working the soil erases small erosion features, preventing their growth. However, this practice has severe implications on loss of soil fertility associated with soil erosion (VALENTIN *et al.*, 1999).

5.2 Implications for land planning and management

The introduction of exotic eucalyptus species has a negligible impact on erosion rates and overland flow. Since the main objective of the government is to alleviate human pressure on the cork oak forests by providing alternative sources of firewood, the use of eucalyptus plantations seems to be a useful solution.

"Maquis" and "garrigue" areas are frequently located at the top of slopes, and frequently suffer from overgrazing, which compacts the soil, reduces the infiltration capacity and increases overland flow production. This will increase the amount of water in the small first order streams during rainfall events, leading to the formation of rills, gullies and "badlands". When the overgrazed areas are located above agricultural ploughed land (as is often the case), this process might be catastrophic, ruining agricultural land and sharply increasing the sediment yield. The disappearance of a mosaic landscape (VALENTIN *et al.* 1999) increases the connectivity and therefore the transmission of water and sediments downslope (FERREIRA and COELHO, submitted).

Measures should be taken to reduce grazing activity on the "natural" areas of cork oak forest and "maquis" and "garrigue". This would be achievable through the inversion of the current tendency to shrink the areas of "natural" ecosystems, or by maintaining larger fallow areas in order to reduce the animal pressure on the "natural" areas.

Ploughing is generally made from the top to the bottom of the slope following the steepest slope angles. This is mainly due to the land property structure. Division of farms by the inheritors is made in narrow strips of land, from the top to the bottom of slopes, so that all the properties remain identical (COELHO *et al.* 2002). Therefore, the property division does not allow the use of conservative ploughing along the contour. Since the most deleterious management practices are related to the inheritance system that reduces the length of parcels (each son inherits a parcel including good soils at the bottom and bad

soils at the top of the slope) measures have to be found to promote a more sustainable soil management system, either through farm association, which would allow for joint soil management, or land redistribution in order to make possible the use of conservative measures to reduce erosion yield.

6 – CONCLUSIONS

We presented a comprehensive analysis among Maghreb land-uses, representative of "marginal" regions, and their impact on vegetation cover, soil resistance, overland flow amount and erosion rates. There is a clear tendency for an increased pressure on the poor marginal areas as a result of the current socio-economic and demographic trends in the Maghreb. This increasing pressure has long exceeded the carrying capacity of these fragile ecosystems, as shown by the number of rills, gullies and badlands widely spread in the landscape, and is linked to three main trends of land-use change: (1) Afforestation with exotic species, (2) Overgrazing, and (3) Agricultural use of steep slopes where ploughing is made from the top to the bottom of slopes.

Afforestation with eucalyptus is the land-use change tendency with the fewest implications for soil and water conservation. Because it is meant to reduce the pressure on cork oak forests, it can be considered an acceptable solution.

Ploughing presented the highest erosion rates, but since the soil is frequently reworked, ploughing is not associated with major soil degradation features (i.e., gullies and "badlands"). Nevertheless, erosion is evident and may result in loss of soil fertility. To overcome this problem, measures to create farmer associations or land redistribution would be necessary so that more conservative techniques can be socially accepted and employed.

Overgrazing is frequently associated with impressive erosion features. Although the soils are very coherent, they also present a small infiltration capacity, which enhances overland flow. This frequently originates and increases gullies and "badlands". To overcome this problem, it is necessary to increase the grazing area, either through the enlargement of natural vegetation areas or by maintaining wider agriculture areas under fallow, allowing the soil to recover and the herds to feed.

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REFERENCES

CERDÁ A.; IBÁNEZ S., CALVO A., (1997). Design and operation of a small and portable rainfall simulator for rugged terrain. *Soil Technol., 11 (2): 161-168.*

CARVALHO T.M.M., COELHO C.O.A., FERREIRA A.J.D., LAOUINA A., NAAFA R. & HAMZA A. (1999) MEDCHANGE – Os efeitos das mudanças no uso da terra e nas técnicas de maneio em sistemas agro-silvo-pastoris, sobre os processos de degradação do solo: 1. O contexto sócio económico e a percepção do risco, *Actas do Colóquio Ibérico de Geografia*, Lisbon, pp. 104-111.

CARVALHO T.M.M., COELHO C.O.A., FERREIRA A.J.D. & CHARLTON C.A., (2002). Land degradation processes in Portugal : Farmers' perceptions of the application of European Agroforestry programmes. *Land Degradation & Development,* 13, 177-188.

COELHO C.O.A., LAOUINA A., FERREIRA A.J.D., NACIRI R., CHAKER M., NAAFA R. R., CARVALHO T.M.M., BOULET A.K. & PEREIRA J.B.P., (2002). Forest and grazing impacts on hydrological and erosional processes in Southern Portugal and Northern and Central Morocco. *Man and soil at the Third Millennium*, Geoforma Ediciones, Logroño, pp. 1255-1264.

COELHO C.O.A., LAOUINA A., FERREIRA A.J.D., CHAKER M., NACIRI R., NAFAA R., BOULET A.-K., (2000). As mudanças no uso do solo e o risco de desertificação: o exemplo de Marrocos. *Territorium*, 7, 33-38.

DESCROIX L., VIRAMONTES D., VAUCLIN M., GONZALEZ BARRIOS J. L., ESTEVES M., (2001). Influence of soil surface features and vegetation on runoff and erosion in the Western Sierra Madre (Durango, Northwest Mexico), *Catena*, Volume 43, Issue 2, 115-135.

FAO (2000). Manual of integrated soil management and conservation practices. FAO Land and Water Bulletins, N° 8. FAO ; Rome, 230 p.

FERREIRA A.J.D., COELHO C.O.A, (submitted), Overland flow and sediment yield and transport at different scales on burned and unburned forest areas : the impact of connectivity. *Earth surface processes and landforms.*

HAMED Y., ALBERGEL J., PÉPIN Y., ASSELINE J., NASRI S., ZANTE P., BERNDTSSON R., EL-NIAZY M., BALAH M., 2002. Comparison between rainfall simulator erosion and observed reservoir sedimentation in an erosion-sensitive semiarid catchment, *Catena*, Volume 50, Issue 1, 1-16.

HAMZA A., 1994. L'érosion des terres en Tunisie. La variabilité du climat et l'homme en Tunisie, Fac. Des Sciences Humaines et Sociales de Tunis, Université de Tunis I, *Série Colloque 7e*, Vol. III, pp. 191-203.

LAOUINA A., 1999. The participation of the rural population, condition for the success of interventions in mountains. The case of the Rif and pre-Rif slopes, Morocco. In Proceeding of the *International Seminar on Land Degradation and Desertification,* 24-30 August, Évora, pp. 101-106.

LAOUINA A., 1998. Northern Africa. In: Conacher A.J. & Sala M. (eds.). Land degradation in Mediterranean Environments on the World. Nature and extent, causes and solutions, Wiley, pp. 91-108.

LAOUINA A., CHAKER M., NACIRI R., NAFAA R., 1993. L'érosion anthropique en pays méditerranéen, le cas du Maroc septentrional, *Bull. Assoc. Géogr. Franç.*, Paris, pp. 384-398.

LAOUINA A., 1990. Implications spatiales et environnementales des transformations socio-économiques et technologiques dans les campagnes marocaines. Le cas du périmètre irrigué des Triffas et de ses bordures. In: Bencherifa A. e Popp H. (eds.) *Le Maroc : espace et société* – Passau 1990, Vol Spéc. 1, pp. 175-181.

MIKESELL M.W., 1960. Deforestation in Northern Morocco. Burning, cutting, and browsing are changing a natural wooded area into a land of scrub. *Science*, Vol. 132, N° 3425.

NAFAA R., LAOUINA A, CHAKER M., 2000. Gestion des ressources naturelles et développement durable dans les basses montagnes du Nord Marocain. Le cas des communes de Tatoft et Bou Jédyane. In: Laouina, A. (ed.) La Montagne Marocaine, Publications de la Chaire UNESCO-Gas Natural, pp. 105-141.

VALENTIN C., D'HERBÈS J. M., POESEN J., 1999. Soil and water components of banded vegetation patterns, *Catena*, Volume 37, Issues 1-2, 1-24.