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Vegetation succession and its consequences for slope stability in SE Spain

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Abstract

The effect of land abandonment as a result of changing land-use policies is becoming more and more important throughout Europe. In this case study, the role of vegetation succession and landslide activity on steep abandoned slopes was investigated. The influence of vegetation succession on soil properties over time, as well as how developing root systems affect soil reinforcement was determined. The study was carried out in the Alcoy basin in SE Spain, where the marl substratum is prone to landsliding along steep ravines. The bench-terraced slopes have been abandoned progressively over the last 50 years and show various stages of revegetation. The study was carried out at two scales; at the catchment scale long-term evolution of land-use, vegetation succession and slope failure processes were investigated. At a more detailed scale, vegetation cover, soil properties and rooting effects on soil strength were determined.

Results showed that the soil has changed over a period of 50 years with respect to soil properties, vegetation cover and rooting, which is reflected in the activity of geomorphological processes. Vegetation succession progressively limits surface processes (sheet wash and concentrated overland flow) over time, whereas slopes affected by mass wasting processes increase in number.

The spatial heterogeneity of infiltration increases over time, leading to increased macro-pore flow towards the regolith zone, enhancing the potential risk of fast wetting of the regolith directly above the potential plane of failure, as was concluded from rainfall simulations. In situ experiments to determine soil shear strength in relation to rooting indicated that roots contributed to soil strength, but only in the upper 0.4 m of the soil. Most failures however, occur at greater depths (1.0–1.2 m) as anchorage by deeper roots was not effective or absent. The observed initial increase in mass wasting processes after land abandonment can therefore be explained in two ways: (1) the limited contribution of anchorage by root systems at potential slip planes which cannot counterbalance the initial decline of the terrace walls, and (2) the fast transfer of rainfall to the potential slip plane by macro-pores enhancing mass movements. However, after approximately 40 years of abandonment, mass wasting processes decline.

Introduction

Land-use change is an important issue in Mediterranean Europe and is principally driven by socio-economic factors (Geeson et al., 2002; MacDonald et al., 2000). This type of change is dominated by agricultural land abandonment or conversion to agro-industrial land-use, and implies drastic changes in management policies. Sustainable land use can only be achieved when one also assesses changes in process and

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landscape patterns (Romero-Calcerrada and Perry, 2004). The effect of land abandonment on vegetation, hydrology, soil quality and erosion is not very well known but may have significant consequences (Garcia-Ruiz et al., 1996; Lasanta et al., 2000). A case study is presented where the role of vegetation succession in landslide activity on steep, abandoned slopes was investigated. Land abandonment and vegetation succession affect the mechanical and hydrological properties of soil, especially by the effect of developing root-systems. Therefore, measurements were carried out to quantify the possible effect of reinforcement of the soil by roots as well as the effects on soil properties such as infiltration. The effects of land abandonment and vegetation succession on active geomorphological processes related to slope stability have rarely been evaluated.

The study area was located in the Alcoy basin in SE Spain (Figure 1), where the marl substratum is prone to landsliding along steep ravines, which is well described in La Roca-Cervignon and Calvo-Cases (1988). The bench-terraced slopes were abandoned at various times and show various stages of revegetation. A first reconnaissance survey suggested that mass wasting activity increased after land abandonment, which was not fully understood, as vegetation cover appeared greater after abandonment. It might be expected that colonizing plants expanding their roots systems into the soil would enhance slope stability (Coppin and Richards, 1990).

This paper aims at determining the explanation of the processes involved, by exploring the following research questions:

- Do geomorphological processes, on a catchment scale, change in relation to land abandonment and vegetation succession?
- What is the impact of vegetation succession on soil (hydrological) properties and soil mechanical properties and can this effect explain the changes in geomorphological processes observed?

Materials and methods

Field site description

The Valles de Alcoy (Figure 1) are situated within the upper basin of the Serpis river where Cretaceous limestone and Miocene marls of the *Tap* formation dominate the geology. The marls of this formation are very homogeneous in the sense of stratification and composition (IGME, 1975). Colluvial and residual soils have formed on the pediment surface on top of Miocene marl. Deep river incisions with associated steep ravines (barrancos) have developed in the pediment itself. Details of the study area can be found in La Roca-Cervignon and Calvo-Cases (1988) and Van Beek (2002).

On the marl, calcic and haplic regosols (FAO, 1989) have formed with typical depths ranging between 0.6 and 1.2 m (Van Beek, 2002). These profiles are characterised by a relatively well developed root zone over a regolith of weathered marl or colluvium. With depth, the permeability decreases rapidly and at the regolith-bedrock contact, perched water tables may develop (Van Beek, 2002). In combination with the steep slopes, their occurrence makes the barrancos vulnerable to frequent landsliding, especially under extreme rainfall events. Potential planes of failure are typically found between 1.0 and 2.0 m at the contact between the regolith and the unweathered parent material. The climate in the region is sub-humid to humid, with annual rainfall totals between 500–1000 mm and a mean annual temperature of 14.5 °C.

Land-use and vegetation

On the pediments and marl slopes, bench terraces have been constructed, on which rain-fed perennial crops, mainly cherries (*Prunus ávium* L.), olives (*Olea europaea* L.) and almonds (*Prunus dulcis* (Miller) D.A. Webb), were cultivated. The bench terraces were cut in the marl parent material itself and risers are not reinforced with stones or concrete. As the weathering rate of the marls is very high, the regolith depth in the terraced slopes is also large (1.2–2.0 m). No irrigation or extensive drainage works are provided on these terraces. However, mechanisation and a decline in agriculture have changed cultivation on steep slopes. Bench terraced slopes are abandoned at increasing rates, especially on slopes steeper than 10–15°, and consequently are no longer maintained. Water and nutrient availability do not severely limit the colonization

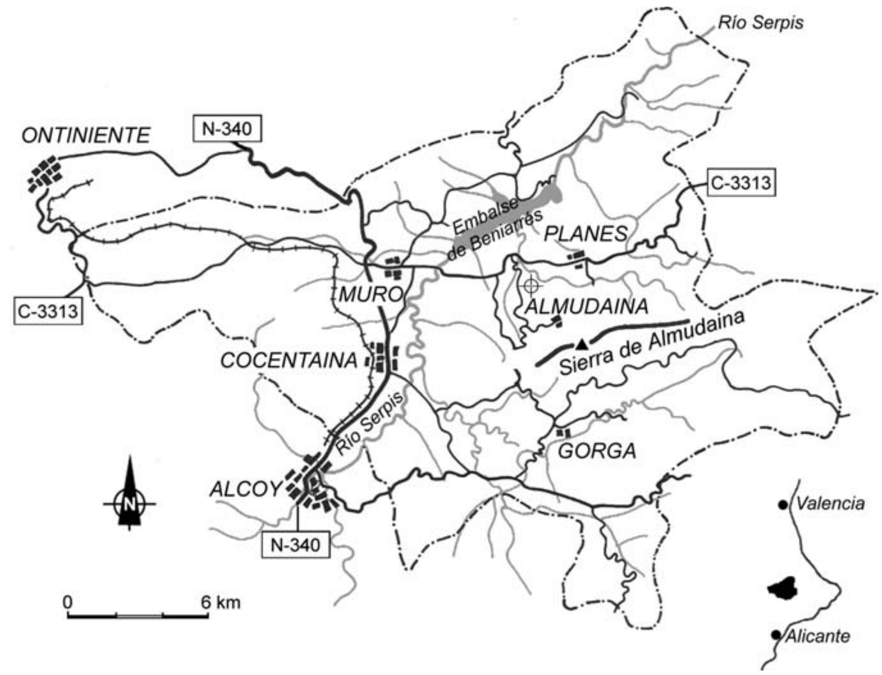

Figure 1. Location of the study area.

of the abandoned fields severely and regeneration is prompt. After one year, a complete cover with annuals and grasses is present. Common shrubs on longer abandoned fields are Gorse (*Ulex parviflorus* Pourret) and Hawthorn (*Crataegus monogyna* Jacq.), as well as the Aleppo pine tree (*Pinus halepensis* Miller).

Field methods and experimental set-up

To answer the research questions different methodologies were applied needing different approaches, set in a nested experimental design.

With regard to the question on the possible changing geomorphological processes in relation to land abandonment, a catchment wide study was carried out based on sequential aerial photo interpretation and a field survey. Within this study area 78 field plots were selected for field validation of the aerial photographs as well as to determine the actual geomorphological processes and vegetation properties (Figure 2). At least five field plots were present in each land abandonment class. Space-time substitution (Paine, 1985) was applied to overcome the problem of long term monitoring under the presumption that parent materials do not significantly differ within the area of study.

A further selection of sites was made to gain insight in the vegetation succession related processes observed and to study soil property changes and their effect on geomorphological processes. This selection involved in situ detailed scale experiments on infiltration and soil shear strength. As these experiments are time consuming and expensive only a limited amount of these experiments could be carried out.

Catchment scale inventory techniques

Sequential aerial photo interpretation was carried out using a complete set of panchromatic photos from the years 1956, 1965, 1973, 1989 and 1994 at scales ranging from 1:15 000 to 1:30 000. From this interpretation the time of abandonment was inferred and additional information on dates of abandonment was obtained from local farmers. This information resulted in the differentiation into six classes of land abandonment as determined by the time frames between subsequent aerial photographs.

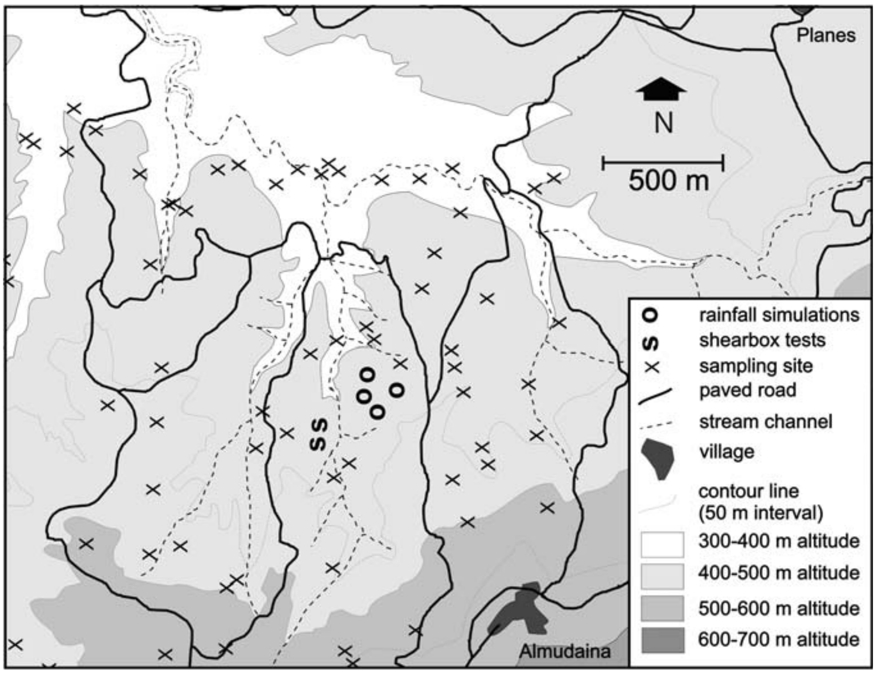

Figure 2. Location of sampling sites and experimental sites within the catchment.

Field survey of active surface processes. For the study area, 78 areas of landscape instability were investigated with respect to surface erosion and mass wasting processes (Figure 2). The areas were classified into activity classes, depending on the dominant geomorphological process and the activity of the process involved: creep (signs of denudation by slow processes such as creep and solifluction), slump, slide and flow (fast movement of soil material, partly coherent) sheet wash (signs of erosion resulting from sheet wash and splash processes), rill flow (signs of erosion resulting from concentrated overland flow).

The activity was defined in five classes ranging from: never affected, inactive, $<10\%$ of surface area active, 10–70% of surface area active and $>70\%$ of surface area active.

Vegetation characteristics were determined for the same 78 plots covering five different land abandonment classes. At each plot vegetation composition and cover was determined for the canopy layers. The actual vegetation measurement site within the plot was selected at random. As the number of plants per surface decreases with canopy height the plot size depended on the type of vegetation. The plot size for herbs was $1\ m^2$, for bushes $25\ m^2$ and for the tree layer $100\ m^2$. The number and cover of each individual plant were determined within the vegetation plots. Standard measurement techniques were applied, using grid frames of 1 m × 1 m or measurement tape grids in the case of larger areas (shrubs and trees).

The upper 0.1 m of the soil was sampled and the following standard soil properties were determined; *organic carbon* by the wet oxidation method using $KCrO_6$ (Allison, 1935) and $CaCO_3$ contents using the method of Wesemael (1955), which is based on weight loss on dissolution. *Texture* analysis was carried out by dry sieving and the pipette method (Gee and Bauder, 1990), but without decalcifying the soil, as $CaCO_3$ levels are $>550\ g\ kg^{-1}$. Soils were described and classified following FAO guidelines (FAO, 1989; FAO 1990).

Detailed scale field and laboratory measurements

The regional characteristics of the land units with different land abandonment histories were derived from the analysis of the sequential aerial photographs. The general characteristics of geomorphological processes and vegetation were studied at the 78 selected plots. Using this information several sites were selected to study the interaction between vegetation and soil properties in more detail, and in particular, with respect to hydro-geomorphological processes and soil mechanical properties. Rather than carrying out many very detailed scale infiltration measurements, tests were carried out covering larger surface areas and soil volumes, to incorporate detailed spatial heterogeneity. This choice limited the possibilities of replication due to high costs in labour and materials.

Rainfall simulations: The infiltration of water into the soil and its flow path in the soil itself is known to be strongly spatially heterogeneous, due to by-pass flow processes (Beven and German, 1981) and is also affected by changes in top-soil structure following vegetation succession (Cerda, 1997) creating source and sinks for overland flow. As the connections and distributions between the sink and source areas are very important with respect to hillslope scale patterns of infiltration and runoff generation (Imeson and Lavee, 1998), rainfall simulations were performed that covered a larger area and also included the detailed patterning of infiltration characteristics connected to vegetation patterns. Therefore, only four *rainfall simulation* experiments were carried out on sites that are considered to be characteristic for the stages of vegetation succession corresponding to the stages following: cultivated, recently abandoned (2001–1989), abandoned (1989–1973), and abandoned before 1973 (see Figure 2 for location). The simulations were carried out using a two nozzle simulator (nozzle type S.S.C.O. Fulljet 3/8 44 SS 27 W), covering an area of 2.75 × 6.5 m. Each experiment consisted of a series of six consecutive artificial rainfall events of 7 mm and 12.2 min duration with a constant rainfall intensity of 34.4 mm h^{-1} spread equally over two days, to mimic typical natural rainfall. The rainfall intensity applied is not uncommon and the return period of the total applied rain, based on daily totals was less than one year (Elias-Castillo and Ruiz-Beltran, 1974). Distilled water was used as the soil is sensitive to dispersion (Shainberg et al., 1981). Wetting fronts in the soil profile were measured immediately after all simulations in a trench of 1 m length at the side of the simulated plot. Additionally, colour dyes were applied to accentuate the wetting front (pyranine) and preferential flow paths (rhodamine) as both dyes have different adsorption behaviour.

The *shear strength* of the soil was determined in the field and in the laboratory. Consolidated, drained and strain-controlled direct shear tests were carried out in the laboratory on saturated samples measuring 60 × 60 × 20 mm (e.g. Van Beek, 2002). All 232 samples originated from various soil horizons of the weathered marl throughout the studied catchment. As spatial heterogeneity in shear strength was not known, a pre-investigation was performed using the simpler tor vane test as a first indicator for spatial trends in soil mechanical properties and helped in selecting the proper places for the larger experiments.

Large in-situ direct shear tests were carried out on the root permeated soil. The dimensions of the shear box were 0.6 × 0.6 m in plan and the box extended 0.4 m into the soil, comparable to tests as carried out by Wu et al. (1988). These large tests enabled to quantify the possible effects of anchoring roots on soil mechanical strength, which effect is impossible to study in the laboratory or with very small sampling volumes. The tests were limited to two types of cover, a cover type with anchoring taproots (Aleppo pine; *Pinus halepensis* Miller) and a cover with only fine roots (grass, annuals and small herbs, of which the most important were: *Brachypodium distachyon* L. Beauv.; *Tymus vulgaris* L., *Helichrysum stoeachas* (L.) Moench; *Sedum acre* L. and *Sedum album* L. subsp. *album*) representing cover stages in the early stage and in the final stage of vegetation succession after abandonment on directly neighbouring hillslopes (see Figure 2 for location). Shear was applied by means of a jack and the generated shearing resistance was measured with a proving ring. A normal load was applied by means of a dead weight (3.3 and 4.1 kPa) of concrete blocks. The soil was slowly wetted thoroughly prior to testing to eliminate any suction-derived resistance, and the shear rate was kept low (4 mm min^{-1} on average) to avoid the build-up of positive pore pressures. For seven tests, a root count was made at 0.1 m depth intervals while extensive root descriptions were made in soil pits under similar vegetation cover in the direct neighbourhood of the test locations, under the presumption that the local spatial heterogeneity of the soil material was negligible.

Results

Land abandonment and vegetation succession

Aerial photo interpretation, field survey and interviews with farmers resulted in a subdivision in four groups of land units based on date of abandonment: before 1965, 1965–1973, 1973–1989, 1989–2001 and still cultivated. Steep barranco sites were abandoned earlier than less steep areas, and the flat pediment areas are still under cultivation. The change in vegetation cover and the presence of the different types of vegetation is indicated in Figure 3. The vegetation succession evolves from presently cultivated fields to open Mediterranean forest dominated by Aleppo pine. Generally speaking, two trends can be recognized; first of all, with abandonment, the proportion and vitality of the crops declined. Secondly, the bare soil between the fruit trees was colonized by grasses and herbs and finally shrubs (mainly Gorse and Hawthorn) and Aleppo pine trees colonised. During the first ten years after abandonment the fruit trees died off. On land units, which were abandoned before 1965 open natural stands of Aleppo pines are developing. This vegetation was associated with the formation of well-developed and stratified soils on top of the marl regolith and soil. Vegetation succession was found to be independent of aspect and slope angle.

Activity of surface processes

Geomorphological processes were studied in areas representing each phase of abandonment. These processes were divided into surficial (concentrated overlandflow and sheet flow) and shallow mass wasting processes originating from processes in the soil (creep and landsliding). Overland flow and sheet flow were generally present on cultivated fields and clearly diminished over time since abandonment (Figure 4). For the mass wasting processes a reverse trend was observed with at first increasing activity with prolonged abandonment, and a reduction of activity in the fields that were abandoned longest (Figure 4). Bench-terraces are not maintained after abandonment. The increase of overland flow processes directly after abandonment and the lack of vegetation cover, affected the redistribution of water on the terraces. This enhanced local saturation, promoting mass wasting activities and initiation of local disintegration of terraces. However, terraces were still clearly recognisable up to 30–40 years after abandonment.

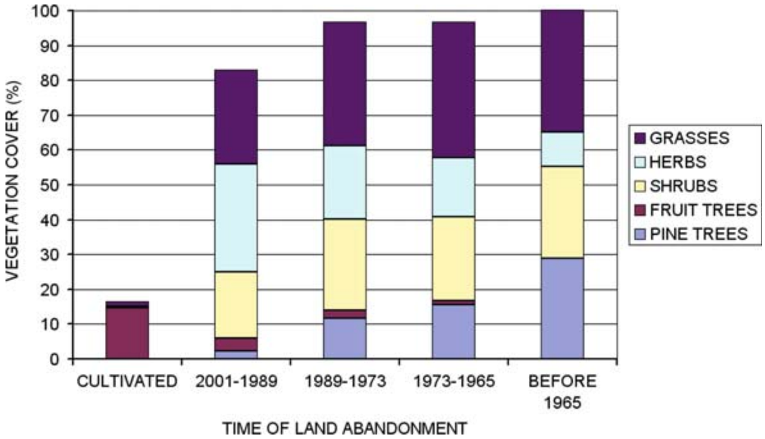

Figure 3. Vegetation cover type and date of abandonment (after Koppel, 2001).

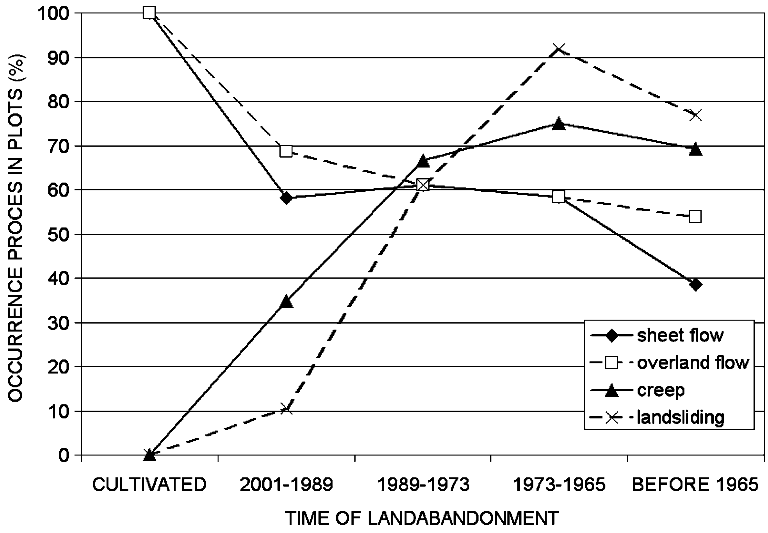

Figure 4. Observed activity of geomorphological processes at the 78 studied sites.

Table 1. Soil properties of a characteristic soil profile in the direct neighbourhood of the area where the in situ shear tests were carried out

Horizon	Depth (cm)	Texture			Org C ($g\ kg^{-1}$)	$CaCO_3$ ($g\ kg^{-1}$)	Dry bulk density ($g\ cm^{-3}$)	Undrained shear strength (kPa)	Porosity ($m^3\ m^{-3}$)
		Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)					
Ah	0–20/25	20	660	320	220	550	1.03	3.4	0.37
Bw	20/25–30/38	10	650	340	65	570	1.37	3.8	0.32
C1	30/38–56	10	660	330	48	550	1.57	8.0	0.27
C2	>56	20	650	330	35	540	1.61	7.0	0.25

Soil properties

Regolith properties such as bulk density, porosity, $CaCO_3$ content did not change over time. For the organic carbon levels and porosity, there was a clear decrease with depth (Table 1), and a clear increase of the undrained shear strength with depth (Table 2). The upper soil (Ah horizon) showed a gradual but significant increase in organic carbon over time since abandonment (Figure 5) ranging from 14 $g\ kg^{-3}$ for cultivated fields to 44 $g\ kg^{-3}$ for fields abandoned before 1965. The amount of $CaCO_3$ is always greater than 500 $g\ kg^{-3}$ and in some profiles a calcic horizon was present with even higher $CaCO_3$ levels.

Preferential infiltration and soil waterflow

The six large size successive rainfall simulations enabled a study of the progressive evolution of the wetting front through the soil profile (Figure 6). This study revealed that infiltration in the upper soil was quite homogeneous, especially for the cultivated and recently abandoned fields. These areas also showed a regular homogeneous, slightly wavy infiltration after application of larger amounts of precipitation after the third run (>21 mm). The areas which were abandoned for longer showed increasingly irregular wetting fronts with deep (>20 cm) and narrow wet pockets penetrating into the soil. Preferential flow was observed to become greater in the soils abandoned longest, showing deeper flow down vertical root systems and macropores.

Undrained shear test

The large number (n = 232) of consolidated-drained direct shear tests on saturated material revealed that the cohesive component of the

Table 2. Shear strength properties (6 tests per horizon at three imposed normal loads between 59 and 117 kPa)

Horizon		Depth (m)	c' (kPa)	c_u (kPa)	c_u*kPa	ϕ' (°)
Ah	Top soil	0.00–0.17	4.8	4.5	13.7	34.4
Bw	Weathered soil	0.17–0.26	1.9	4.8	15.9	35.3
C1g	Gleyic horizon	0.29–0.59	10.2	8.1	6.5	31.2
C12	Colluvium	0.59–0.69	9.8	8.2	14.0	31.7
C2	Regolith	0.69–0.92	4.1	6.5	15.6	36.4

c' and ϕ' are the drained shear strength parameters, c_u the average undrained shear strength interpreted as a cohesion ($N = 232$) from field measurements. c_u* is the undrained shear strength of the direct shear samples after consolidation). Depth is the average of the observed layers and indicative only. Note that the horizons Ccol and Cg are not necessarily present.

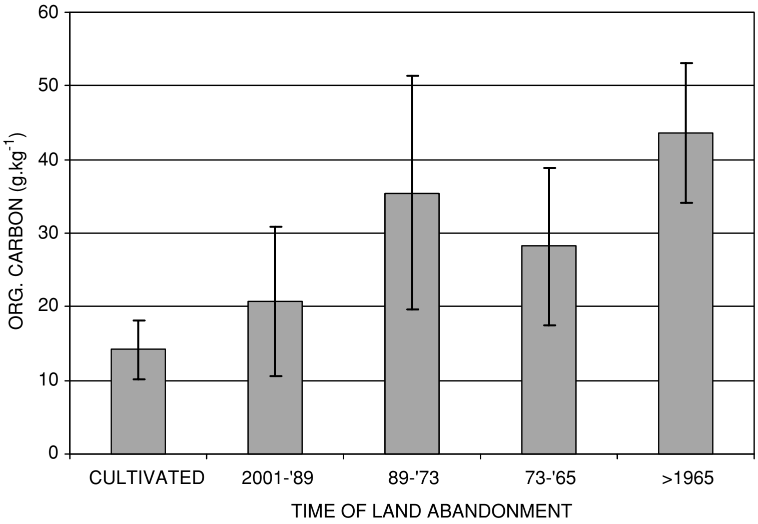

Figure 5. Change of organic carbon after land abandonment. The org. C content of the soil under cultivation and the period 2001–1989 differ significantly from the longest abandoned fields (abandoned before 1965). Means are ± standard deviation (after, Hakvoort 2003).

shear strength, c', was weak and variable. Statistically, the material strength can be characterized as frictional only with mean friction angles ϕ' between 31° and 36°. Notwithstanding, for the material taken at one of the two sample slopes there seems to be a weak differentiation in cohesion and friction with depth (Table 2). A lower cohesion but a higher friction angle was found in the B horizon below the Ah horizon, while the reverse was observed in colluvial and gleyic horizons above the regolith. There was little variation in the strain at which the maximum shear strength was mobilized (12% or 7 mm on average).

There was a close similarity between the mean tor vane readings and the drained cohesion of the horizons, which suggests that the former can indeed be interpreted as the cohesive strength of the soil. The readings confirmed the variability and trends inferred from the laboratory direct shear tests. The cohesion increased and the differences in cohesion become less marked when the samples were consolidated with the exception of the gleyic layer for which the cohesion decreased.

In situ shear box testing

In the case of the in-situ tests on rooted soil, the strain at failure was more variable than the undrained shear tests, ranging between 6 and 25%, and weakly correlated to the root reinforcement of the soil. During the tests roots could be heard snapping and the corresponding drops in the

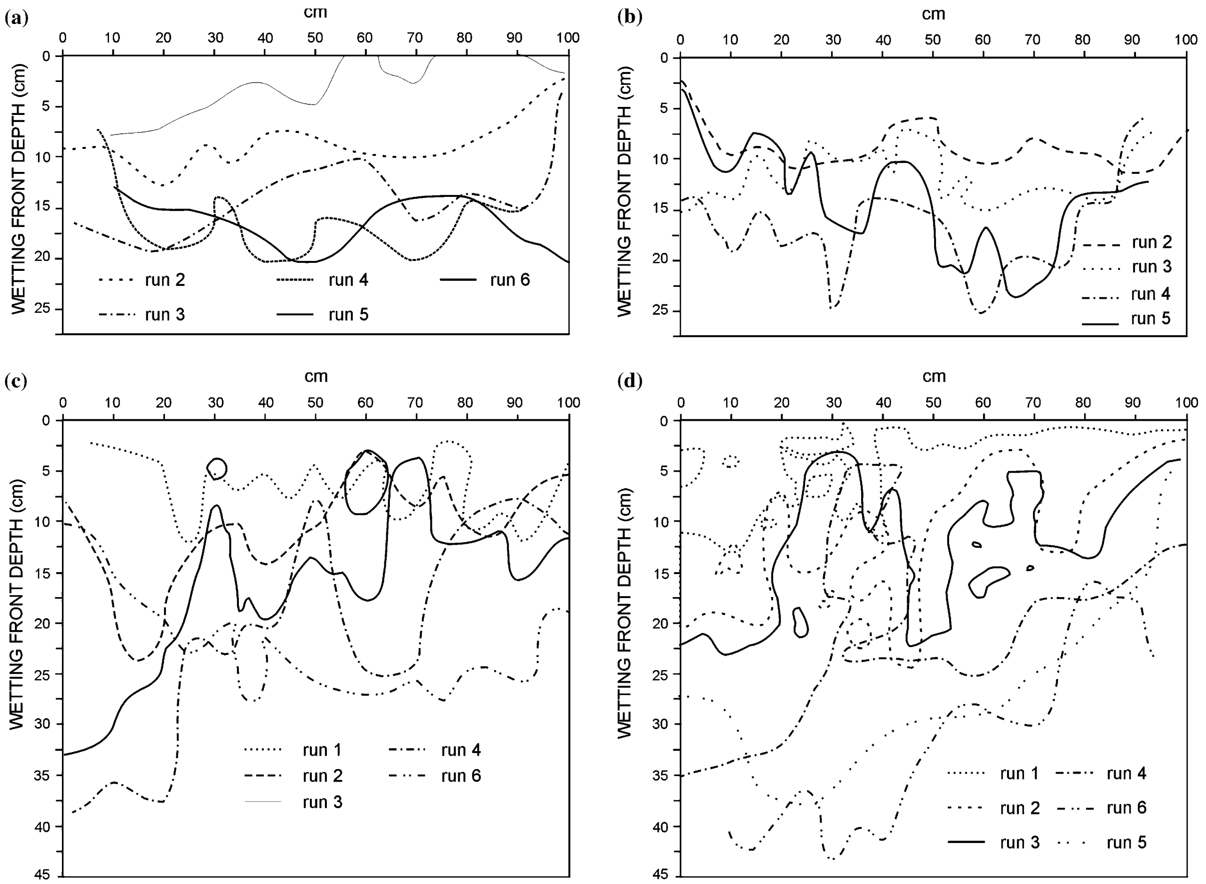

Figure 6. Wetting fronts immediately after four rainfall simulation experiments. (a) Cultivated land in cherry orchard; (b) Abandoned between 2001 and 1989; (c) Abandoned between 1989 and 1973 and (d) Abandoned before 1973.

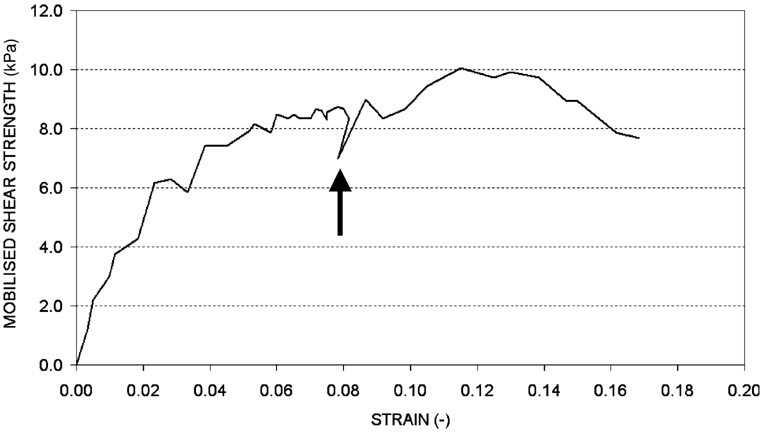

Figure 7. Stress-strain curve of in-situ direct shear test. Strain is expressed in displacement over length of shear box (-). Arrow indicates snapping of large root.

stress-strain curve can be observed (Figure 7). The mean root reinforcement is 3.9 kPa ± 6.3 when the soil shear strength, as calculated from the results of the laboratory direct shear tests, was subtracted. The mean root reinforcement values were 0.6 kPa ± 0.1 for herbs and

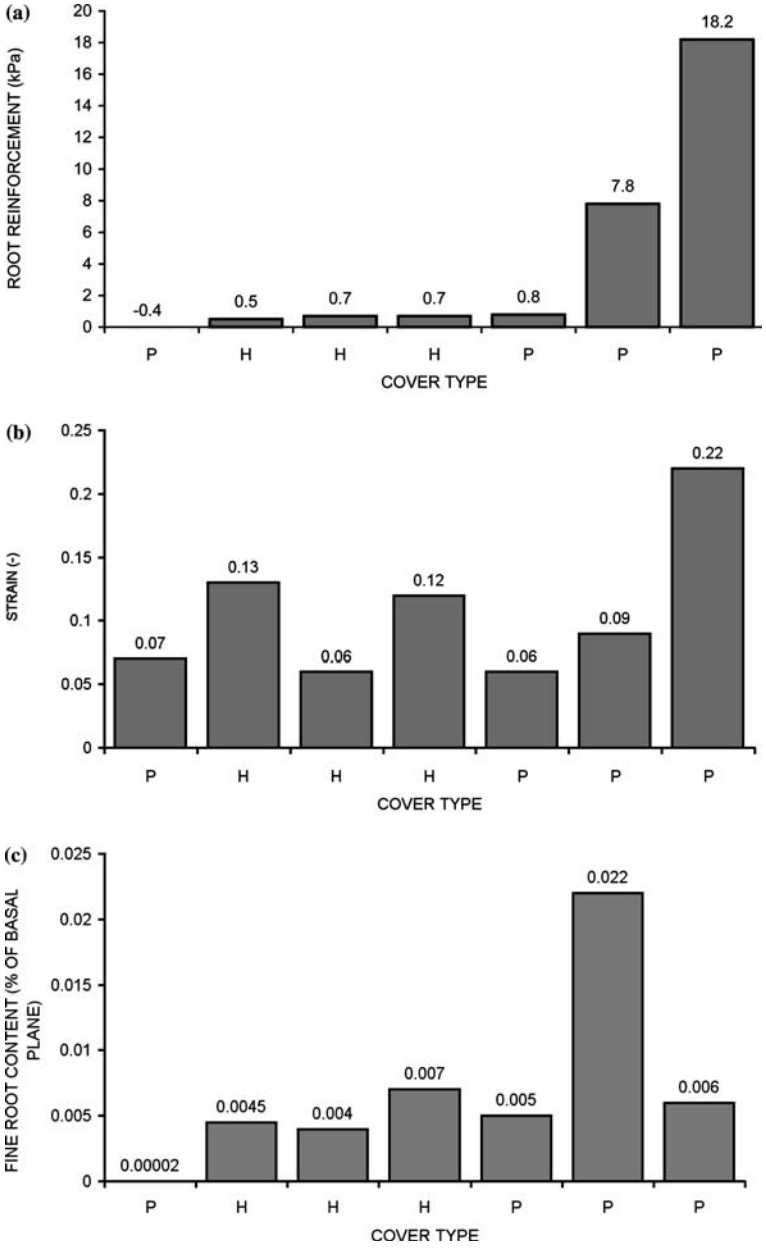

Figure 8a–c. Strain (a), reinforcement (b) and fine root content (< 1 mm) (c) for seven *in-situ* direct shear tests. H and P refer respectively to herbaceous cover and the presence of Aleppo pine trees.

5.9 kPa ± 7.5 for Aleppo pine respectively. The root reinforcement ranged from −0.4 kPa (no reinforcement) to 18.2 kPa. Figure 8 shows the strain, reinforcement and fine root content (< 1 mm) for seven in situ direct shear tests for both herbaceous and Aleppo pine covered soils. The eighth test was not incorporated as no root data were determined from this test. The seventh value was obtained from a test under dense forest cover of *Pinus halepensis* while a test on an 11-year-old sapling of the same species returned a root reinforcement of 7.8 kPa. When the largest reinforcement is excluded, related to large roots, a good correlation between the fine root content (< 1 mm) of the slip plane and the root reinforcement is found ($y = 117930x{-}1.1309$,

$R^2 = 0.96$, $P = 0.004$). Not enough observations have been made to make conclusive remarks on the role of larger roots.

Discussion

The results show that there is a clear effect of land-use change on the development of vegetation cover and type over the last 50 years. Several stages in the development of the vegetation can be recognized, both in the field and from sequential aerial photographs. With the development of biomass over time the incorporation of organic matter into the soil becomes important, as shown by the increasing organic carbon levels with vegetation succession. This is in agreement with studies carried out such as by Martinez-Fernandez et al. (1996), Martínez-Mena et al. (2002) and Ulery et al. (1995), who showed that vegetation removal or development affects the organic carbon levels of the soil. The increase in organic carbon levels over time was also reflected by the development of Ah and ecto-organic horizons in the soil. The high levels of $CaCO_3$ in all soils at all depths hamper the swell and shrinkage properties of clay (Lamas et al., 2002) and reduce the amount of macro-pores present. The porosity showed a clear decrease and bulk density increased with increasing depth. However in the regolith an inherited higher macro-porosity was found, which is related to the marl shards developing during the first phases of weathering of the marl.

Geomorphological processes such as overland flow and sheet wash acting directly on the surface decreased over time, which can be explained by the increased influence of vegetation cover. However these processes probably play an important role in the initiation of local mass wasting processes as flow concentration is typical in the first stage of abandonment. The increase in overland flow (sheet wash and rill flow) is related to several factors: Ploughing of the terrace surface will cease with abandonment, favouring soil crust formation and water concentration. The increase of vegetation cover increases surface roughness, and reduces the size of bare crusted – areas in between the vegetation. Interception by the vegetation reduces the amount of rainfall reaching the soil and the drop impact velocity on the soil (Morgan, 1995). Furthermore, infiltration rates will be higher under the vegetation (Cerda, 1997; Imeson et al. 1998; Pierson et al., 1994) compared with the surrounding, non vegetated areas. This higher infiltration is often associated with good soil aggregation and increased macroporosity (Cerda et al. 1994; Haynes and Swift, 1990). This latter aspect is clearly visible in the results from the rainfall simulations. The more irregular wetting front and deeper percolation of water into the soil over the 50 years since abandonment are evident. However, the effect of hydrophobic processes might be important, as many studies have shown that these are responsible for heterogeneous infiltration patterns (Doerr et al., 2000) but in this case water repellency tests showed that the effect of water–water repellency could be ignored.

Landsliding and creep processes on the contrary increased over time since abandonment, and became more prominent as the farmers stopped terrace maintenance. Together with the vegetation succession after land abandonment the below ground biomass will increase including larger roots (>5 mm). These roots can have a positive effect on soil strength (Wu et al., 1979) and will be effective in reducing landsliding as long as these roots also contribute to anchoring in the unweathered soil. Where roots increase the soil strength this might have a positive effect on soil creep only. Where this is not the case, there might not be a positive effect from vegetation development on slope stabilization at all (Gray, 1995). Roots might even induce adverse effects as they uptake water for transpiration and hence desiccate the soil, which can result in large macro-pores (desiccation cracks), which may transport water deep into the soil (Coppin and Richards, 1990).

The in-situ direct shear tests were performed on samples near pine trees as well as on samples where only grass, herbs or shrubs were present. However, root counts under pine returned higher numbers but the root numbers under both grass and pine decrease exponentially with depth, and virtually no roots, coarse or fine, are present below 0.6 m. The correlation between the fine root content and root reinforcement from the in-situ shear tests suggests that vegetation type is of minor importance to the actual reinforcement. However for larger roots such as pine taproots this might be the case when these have a high spatial density. With few trees and under wet conditions on a slope the soil might flow around the large roots as the fine roots do not have enough effect to supply sufficient strength to the soil.

Conclusions

Broad and fine scale research at the Valles de Alcoy revealed that:

(1) Mass wasting processes increased over time after abandonment with increasing cover of vegetation following natural succession and only after 40 years mass movement activity was reduced. This is opposite to common literature on root reinforcement on slopes (Coppin and Richards, 1990; Gray, 1995).
(2) Organic carbon levels in the upper 0.10 m of the soil increased significantly in the period of study.
(3) Rainfall simulations suggested that with increasing time since abandonment, infiltration becomes more heterogeneous and that macropore flow becomes important. This latter process might play an important role in the rapid transfer of water from the surface to potential slip planes, resulting in increased pore pressures at the failure plane, thus enhancing the risk of failure.
(4) The results show that the contribution of the root systems to soil shear strength is present, but limited (~4 kPa). The root system can reinforce the soil up to 40 cm depth, but this does not extend deep enough into the soil to prevent shallow mass wasting processes. These generally develop on potential slip planes at a depth of about 1m, coinciding with the weathering depth (C1 and C2 horizons) of the soil profile.
(5) Vegetation succession does not increase slope stability (no root anchoring) to such a degree that the decline of terraces by mass wasting processes is fully counterbalanced. Instability may be further decreased by developing preferential flow paths feeding potential failure planes in the soil. Eventually a decline in mass wasting processes was observed after 40 years of abandonment.

Acknowledgements

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