# HYDROLOGICAL AND EROSIVE CONSEQUENCES OF FARMLAND ABANDONMENT IN EUROPE –A REVIEW

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**Abstract**

Farmland abandonment is a major problem in parts of Europe, particularly in mountain areas and semiarid environments. In such places, farmland abandonment represents a significant land use change from cropping to a complex of plant successions. The present study assesses the hydromorphological effects of land abandonment in Europe, and the consequences thereof with respect to water resource availability and soil erosion. The evolution of abandoned fields depends on (i) the time of abandonment; (ii) climatic conditions in the abandoned area; (iii) particular characteristics of the fields; (iv) the land management regimen following abandonment; and, (v) the role played by government policy. Throughout most of Europe, vegetation on abandoned farmland has evolved into dense forest or shrub. The expansion of vegetation explains, in part, the perceived decline in water resources, reductions in soil loss and sediment delivery, and the progressive improvement of soil characteristics. Such evolution has resulted in changing stream morphology, featuring narrowing and incision, and a decline in sedimentation level in Mediterranean reservoirs. The abandonment of bench terrace fields coincided with an increase in the occurrence of small landslides in the steps between terraces, as well as changes in the spatial organization of saturated areas. Plant colonization is slower in semiarid areas, increasing the development of soil crusts that reduce infiltration and increase overland flow. Land policies with detailed capability are necessary to remediate the consequences of farmland abandonment in various European environments.

**Key words:** farmland abandonment, runoff generation, soil erosion, bench terrace fields, semiarid areas, Europe

## 1. Introduction

Land use change is the main characteristic of rural areas in Europe during the 20th century (Cernusca *et al*., 1996; Debussche *et al*., 1999; Rabbinge and Van Diepen, 2000; Taillefumier and Piégay, 2003; Palang *et al*., 2005; Rounsevell *et al*., 2006; García-Ruiz, 2010). This occurred because of (i) changes in population density in rural areas, mainly attributable to migration to the cities; (ii) development of mechanization and novel agricultural techniques; (iii) low productivity in some rural areas (Duarte *et al*., 2008); (iv) regional, national, and international market forces; (v) an increasing effect of regional and national governmental initiatives, which subsidize some crops to the detriment of others, and have financed very expensive infrastructure including reservoirs and canals; (vi) effects of the Common Agricultural Policy (CAP) (Lasanta *et al*., 2000; Boellstorff and Benito, 2005); and, (vii) socioeconomic and political factors, including marked transformations of rural landscapes in post-communist eastern Europe (Kuemmerle *et al*., 2008). The agrarian landscapes of Europe have changed dramatically, particularly with respect to plot size; the types of crops planted; and the relative spatial distributions of fields, shrubs and forests. Today, these parameters bear little resemblance to those pertaining at the beginning of the 20th century.

These observations are particularly valid for mountainous and certain semiarid regions of Europe, where the characteristics of past landscapes are now almost unrecognizable, particularly because of the large expansion of regions characterized by farmland abandonment. In mountainous areas, physical constraints together with population ageing and small farm sizes have reduced competitiveness (Ruiz-Flaño, 1993; MacDonald *et al*., 2000), and farmland abandonment has thus occurred despite centuries of intensive human use of steep slopes. In semiarid areas, abandonment has resulted in declining productivity following continued cultivation of poor soils, and, more recently, CAP implementation, which has enhanced withdrawal of land from cultivation.

Farmland abandonment occurred throughout Europe during the second half of the 19th century, as a consequence of population movements from mountains to the cities. This was initially evident in the most industrialized countries (the United Kingdom, Germany, the Netherlands, Belgium, Switzerland, and France), next in Italy, and finally in Spain, Portugal, the Balkans, and the Carpathians. Lowland areas were also affected by depopulation, but farmland abandonment was not immediately evident because individual farm sizes increased as farms were amalgamated. In semiarid areas, farmland abandonment has been relatively recent, associated not with population movements, but rather with problems of water scarcity and the low soil quality of large flat fields (Oñate and Peco, 2005). It is noteworthy that land abandonment can co-exist with intensification of land use (Douglas *et al*., 1994; Van Eetvelde and Antrop, 2004; Mottet *et al*., 2006; Chauchard *et al*., 2007). This has occurred in some mountainous areas, where slopes have been increasingly subjected to abandonment although valley bottom cultivation has intensified, featuring the use of meadows for production of livestock feed and the construction of agricultural buildings and other infrastructure.

Two types of farmland abandonment can be distinguished in Europe. The first is a form of spontaneous abandonment affecting all European mountain areas, driven by either a progressive or sudden collapse of mountain societies. This process, which has occurred in the Pyrenees, resulted in restriction of cultivation to valley bottoms and some smooth hillslopes, with little agricultural effort being devoted to mountainous areas (Lasanta, 1988, 1989). This process also affected some semiarid areas in southeast Spain, as a consequence of soil deterioration following irrigation in the 1970s, and the progressive scarcity of water resources. Induced abandonment, prescribed by national or European Community policies designed to regulate markets for particular agricultural products (Baudry, 1991), has also been important. Such abandonment has been controlled by the CAP, and affects only some agricultural land, mainly in plains and piedmonts. The CAP has encouraged the withdrawal (termed "set-aside") of cultivated land, to reduce food surpluses and to limit the huge cost of agricultural subsidies under European Union commitments. Farmers that produce more than 92 tonnes of cereal per year are obligated to cease cultivation on part of their property, although the portion set aside can vary from year to year, in both rainfed and irrigated areas (Walford, 2002). Farmers can designate withdrawn land as unseeded or seeded fallow (Boellstorff and Benito, 2005). Unseeded fallow land is most common in semiarid regions, where soil moisture is a major factor limiting crop productivity. Seeded fallow is more common in relatively humid temperate areas, where the fields are planted with grasses or leguminous plants for at least 1 year after a cereal harvest. In both instances, the objective is to improve soil humidity, fertility, and organic matter content. Seeded fallow efficiently protects soil against erosion.

Farmland abandonment is an important cause of changes in landscape and wildlife communities, and has resulted in a loss of biodiversity (MacDonald *et al*., 2000) and lower levels of open areas. Environmentally, the most obvious consequence of land abandonment is plant recolonization. Regardless of abandonment type, a more- or-less complex plant colonization process occurs on abandoned fields, conditioned by soil and climate characteristics. Several years after abandonment, such fields are covered by grasses, shrubs, and trees. In many European regions, forests cover slopes that were under cultivation some decades ago, and this process has been accompanied by substantial environmental changes. Farmland abandonment during periods of social upheaval (*e.g.,* during the Black Death; AD 1347−1352) and war has been well-documented (Yeloff and Van Geel, 2007), and such events have been associated with expansion of forests (mainly of *Betula* and *Corylus* trees), based on results obtained from pollen records.

The hydrological and geomorphological effects of farmland abandonment and the consequent changes in land cover have been extensively examined, particularly in the Mediterranean region (Llorens *et al*., 1992, 1997a; Ruiz Flaño *et al*., 1992; Ruiz-Flaño, 1993; Gallart *et al*., 1994; Cerdà, 1997; Lasanta *et al*., 2000, 2006; Piégay *et al*., 2004; Cammeraat *et al*., 2005; Koulouri and Giourga, 2007; Lesschen *et al*., 2007, 2008; Romero-Díaz *et al*., 2007; Bakker *et al*., 2008; López-Moreno *et al*., 2008; Seeger and Ries, 2008; Nunes *et al*., 2010). Key issues related to land abandonment in Spain, Portugal, and France include the effects of such action on (i) soil hydrology, (ii) runoff generation, (iii) the extent of areas contributing to runoff, (iv) the nature of sediment sources, (v) soil erosion and evolution thereof after land abandonment, and, (vi) fluvial channel adjustments. These issues are particularly important in Europe, and especially in the Mediterranean region, where water resources are sourced almost exclusively from mountain headwaters, which behave either as water towers (Vivirioli *et al*., 2003, 2007) or as humid islands surrounded by subhumid or semiarid lands. The scarcity of water resources and spatial and temporal variabilities of discharge have necessitated the introduction of complex water management procedures, including construction of large reservoirs. Consequently, any land cover changes in mountains potentially threaten the delicate balance between water resource availability, reservoir management, ecological flows, and water use in lowlands. In particular, changes in plant cover will affect sediment sources and the connectivity between them and stream channels, which in turn will alter sediment yields, thus affecting reservoir silting and water quality.

The present report reviews our current knowledge on the hydromorphological evolution of abandoned fields in various European environments. Our main objective is to identify the principal factors affecting water resources and soil erosion, through a comparison of different types of abandoned fields in mountainous and semiarid areas.

## 2. The extent of farmland abandonment

Farmland abandonment has not been random from either a temporal or spatial viewpoint (Lasanta, 1988, 1989; Ruiz-Flaño, 1993; Douglas *et al*., 1994; García-Ruiz *et al*., 1996a). Such abandonment initially affected countries that became industrialized in the 19$^{th}$ century. From the middle of that century, populations in mountainous areas of the United Kingdom, Germany, Switzerland, northern Italy, and France migrated extensively to the cities, thus reducing the pressure on cultivated lands (Walther, 1986). In these countries, the main episode of population migration, and hence farmland abandonment, was largely complete by the first decades of the 20$^{th}$ century. In Mediterranean countries, the principal period of industrialization and population migration occurred in the middle of the 20$^{th}$ century (in the 1960s and 1970s), although a decrease in population in agricultural areas was already evident at the beginning of the century, particularly in Spain and Italy. Thus, farmland abandonment in Mediterranean countries was quite prolonged (extending over 60-70 years).

According to Lasanta (1988), Ruiz-Flaño (1993), and García-Ruiz *et al*. (1996b), field abandonment initially featured the steepest slopes of the highest areas, and both straight and convex slopes, particularly in regions remote from villages. In general, shifting agriculture fields were first abandoned because of marginal location and low productivity. Thereafter, abandonment affected both bench terraces and sloping fields, even those with relatively shallow gradients (10-20%). Abandonment was associated with difficulties in the use of modern agricultural machines on concave slopes and even on perched flats that were relatively distant from villages. Lasanta (1988) suggested that physical factors (altitude, exposure, and gradient) were the most influential in the first stages of abandonment, whereas, at later stages, human-related considerations (distance from a village, limited opportunities for mechanization) played a more decisive role. At present, only the valley bottoms in most European mountainous areas are cultivated, for example in the Alps, together with some shallow slopes cultivated with cutting meadows. Farmland abandonment was also significant in eastern European countries during the 1990s because of political changes that followed the fall of communist regimes. In semiarid regions, abandonment first affected non-irrigated rainfed fields with poor yields, and those degraded by irrigation (Romero-Díaz *et al.*, 2007).

Various studies have reported the relative extent of farmland abandonment throughout Europe. Figure 1 shows the spatial distribution of studies dealing directly or indirectly with the hydrological and geomorphological consequences of farmland abandonment (please see Table 1 also). The concentration of studies in the Mediterranean region (and Spain in particular) is noteworthy, as are the numerous reports on the Pyrenees, the Iberian Range, and the Mediterranean coast. France (the Prealps of Provence, the Central Massif), Italy, Portugal, Greece, and Slovenia have also been the focus of a range of studies. In the remainder of Europe, isolated reports have come from Belgium, Germany, Switzerland, Austria, Hungary, Latvia, and Estonia, and from the area between Poland, Ukraine, and Slovakia.

Land abandonment in European Mediterranean countries is concentrated in mountainous areas and some semiarid regions, particularly in Spain and Portugal. Lasanta (1989), Ruiz-Flaño (1993), and Poyatos *et al.* (2003) reported abandonment of most fields on hillslopes in the Pyrenees and the Iberian Ranges. García-Ruiz *et al.* (1996a, b) noted that the maximum size of the farmed area in the Pyrenees was probably attained in the middle of the 19th century, which coincided with the greatest population density of the region. A period of land abandonment followed, which was directly attributable to migration (primarily between 1950 and 1970), the failure of cereal crops produced on mountain hillslopes to be economically competitive, and the limited opportunities available for using the new machinery that was elsewhere (in the valley bottoms) increasing productivity. Lasanta-Martínez *et al.* (2005) and Lasanta and Vicente-Serrano (2007) noted that abandoned fields represented 22% of the total area of the central Spanish Pyrenees. Poyatos *et al.* (2003) estimated that grasslands and crops represented 28.3% of the total area of the Cal Rodó catchment (eastern Pyrenees) in 1957, but only 18.1% in 1996. In the same period, the area occupied by dense forests increased from 16.9% to 45.3%. Abandonment was also extensive in the southern Spanish mountains (the Betic Ranges), although many fields are still cultivated on relatively steep slopes (Faulkner, 1995). Land abandonment also progressed in semiarid areas of southeastern Spain (Romero-Díaz *et al.*, 2007) and central-southern Portugal (Van Doorn and Bakker, 2007; Nunes *et al.*, 2010) because of the low productivity of dry farming systems, where 1 year of cereal cultivation alternated with 2 or more years of fallow. In southern Portugal, the decrease in arable land resulted in a rise in afforestation, regeneration of *montado* open forests, and an expansion of shrub cover (Van Doorn and Bakker, 2007).

In France, most marginal lands were abandoned in the Malay Massif (southern French Alps) after the middle of the 19th century, resulting in an expansion of shrubland and forests, and a decrease in semi-natural open habitats (Chauchard *et al*., 2007). In 1842, forests covered 56% of the Plaine de Malay, but the plain is now entirely covered with *Pinus sylvestris, Abies alba,* and *Fagus sylvatica* forest. Land use changes since the first third of the 19th century have been described in the southern French Prealps. Taillefumier and Piégay (2003) noted that this area experienced a substantial increase in grassland (from 14% to 34.6%) between 1828 and 1956, and a large fall in the extent of ploughed land (from 36.4% to 12.1%). A marked expansion of forest (from 31.9% to 51.2%) and shrub areas (from 17.1% to 24%) was noted between 1956 and 1991, and, by 1991, ploughed land represented only 6.3% of the total area. In this latter period, forest increased at the expense of grasslands. Taillefumier and Piégay (2003) also reported that the landscape became simplified after the middle of the 19th century, changing from a varied mosaic of traditional farming areas to large homogeneous expanses of forest, shrubs, and grassland. Debussche *et al*. (1999) compared postcards showing Hérault (southern France) at the beginning of the 20th century, to the modern landscape, and confirmed the disappearance of land devoted to crops and pasture and the development of forests from the end of the 19th century, caused by rural depopulation and the almost complete disappearance of livestock. The cited authors also noted a decline in the area of bench terraces, which were rapidly invaded by shrubs and trees because the soil was deep and well preserved.

Several reports have appeared on the extent of land abandonment in Italy, and the recolonization of abandoned cultivated fields by forests and shrubs, particularly during the second half of the 20th century. Abandonment occurred throughout the country, including the Alps (Renzi *et al*., 2002; Surian *et al*., 2010), and in the central (Surian *et al*., 2010) and southern regions (Garfi *et al*., 2007; Duarte *et al*., 2008).

In Greece, land abandonment has affected many of the terraces constructed on steep slopes, both on the mainland and the Aegean Islands (Kizos and Koulouri, 2006; Koulouri and Giourga, 2007), and this has led to an expansion of shrubs. For example, Koulouri and Giourga (2007) reported that shrubs occupy 64% of early-abandoned plots on Lesvos Island.

Farmland abandonment has also been significant in the Swiss and Austrian Alps. Gellrich *et al*. (2007) found that abandonment in the Swiss mountains involved mainly former subalpine grasslands; and agricultural land on steep slopes, stony ground, and in colder regions. Rapid forest regrowth followed. Farmland abandonment in the last few decades has largely been restricted to areas with a higher proportion of part-time rather than full-time farmers. This suggests that, in recent times, land abandonment has not been affected by migration, in contrast to the pattern seen some decades ago (Gellrich and Zimmermann, 2007). Tasser *et al*. (2007) studied land use changes in the eastern Alps, and found that 8-67% of formerly cultivated areas had been abandoned over the past 150 years; forest regrowth has occurred in most instances. Farmland abandonment has continued in the years since 1980. In the same area, Tasser and Tappeiner (2002) noted that abandonment has also affected larch meadows and the less intensively used fields of the subalpine and alpine belts.

Studies on farmland abandonment in eastern European countries have revealed that the phenomenon is recent. For example, Kozak *et al*. (2004) noted that one-third of the cultivated area of the Beskid Maly Mountains (Carpathians, southern Poland) was abandoned between 1965 and 1997, and the process is continuing. Kuemmerle *et al*. (2008) studied the Carpathian Mountains in the triangle bounded by the borders of Poland, Slovakia, and the Ukraine, from 1986 to 2000. Since the breakup of the Soviet Union in 1989, 13.9% of farmland in the Polish sector has been abandoned, 20.7% in Slovakia, and 13.3% in the Ukraine.

Abandonment was greater at higher elevations. Reforestation was extensive in Slovakia, particularly at higher altitudes (up to 80% at elevations above 700 m). The reasons for land abandonment were related to the major economic and political changes caused by the transition from centralized to market-oriented economies in eastern Europe after 1989, resulting in the liberalization of prices and greater competition from foreign producers. Land abandonment was even more extensive in Latvia; in some regions 50% of the land under cultivation prior to 1989 had been abandoned by 1999 (Nikodemus *et al*., 2005). A similar study of Estonia's agricultural sector concluded that a very rapid process of abandonment occurred between 1990 and 1993, affecting about 30% of all cultivated land (Peterson and Aunap, 1998). Van Dessel *et al*. (2008) compared various land cover maps of the Lake Balaton catchment (Hungary), from

1981, 2000 and 2005, and concluded that there had been extensive conversion of arable agricultural land and vineyards to grassland and forest.

## 3. Plant colonization in abandoned fields

The process of plant colonization after land abandonment has been widely studied in various parts of Europe. From a hydromorphological point of view, the characteristics of plant colonization (rate and plant composition) affect infiltration rates, runoff generation, and soil detachment and sediment transport. It is thus essential to understand the various colonization stages and the factors controlling colonization.

Plant colonization in abandoned fields has been defined as a process of secondary succession (Pugnaire *et al.*, 2006), the complexity of which depends on multiple natural and human-induced factors including the depth and fertility of the soil; hillslope aspect; climate (average annual precipitation, evapotranspiration) (García-Ruiz *et al.*, 1996b; Teira and Peco, 2003); the distance from bordering vegetation; the floristic composition of vegetation at the borders; and external interventions after the land has reverted (Bunce, 1991).

In general terms, plant colonization involves an increase in vegetation density and soil protection, as well as a progressive rise in the complexity of plant associations. Nevertheless, the abandonment of mountain meadows and colonization of the meadows with scrub or trees may represent a decrease in biodiversity (MacDonald *et al.*, 2000) and homogenization of the landscape (Fig. 2). Various scenarios of land abandonment are evident (Fig. 3): (i) fields abandoned after 2-3 years of cereal cultivation under shifting agricultural practices, leaving an impoverished soil with open stubble; (ii) sloping or terraced fields (that had typically been cultivated once every 2 years), which when abandoned had a relatively dense stubble cover that was commonly grazed by sheep; and, (iii) fields which had been meadows producing livestock feed, which were frequently grazed by cattle after abandonment (Fig. 3). In addition, in the Mediterranean region, orchards and vineyards may have been established in fields abandoned for several years.

Abandoned sloping and terraced fields with stubble typically develop a relatively dense herbaceous cover in less than 10 years, at least in humid and sub-humid environments, and become grazing meadows. If livestock pressure remains relatively high, such fields may function as grazing meadows for decades, retarding the transition to shrubs and trees; in less heavily grazed fields the vegetation will progress quickly toward a shrub association (González-Bernáldez, 1991; Tasser *et al*., 2007; Tzanopoulos *et al*., 2007; Verburg and Overmars, 2009). For this reason, many villages in Mediterranean mountain areas are set in a very simple landscape, with grazing meadows around the village and a more distant surrounding belt of shrubs and forests that have colonized fields abandoned a long time ago (Vicente-Serrano *et al*., 2004; Lasanta *et al*., 2009). Tzanopoulos *et al*. (2007) noted that grazing affects vegetation succession in various ways. Grazing can delay the transition between vegetation communities because grazing inhibits shrub growth, but can facilitate shrub colonization of grazing meadows because grazing affects the competing herbaceous vegetation. Irrespective of the effects seen, the interactions between plant colonization and grazing seem to be very complex, as emphasized by Chauchard *et al*. (2007) in a study in the southern French Alps.

The rate of shrub colonization depends largely on the availability of shrub species in areas surrounding or adjacent to abandoned fields, and it is very common to note a circumferential pattern of plant colonization until the plot is fully covered by shrubs (Fig. 4). The persistence of a dense shrub cover will depend on the frequency of fires and on soil quality (Dunjó *et al*., 2003). Fire usually takes the plant colonization process back to the beginning, and this process was very common in Mediterranean environments, where fires were deliberately started by shepherds to eliminate thorny shrubs and to improve the quality of grasslands (Ruiz-Flaño *et al*., 1992). Turning to soil quality, plant colonization occurs quite rapidly on deep soils rich in organic matter. If a forest is close to an abandoned field with soils of this type, a young forest can develop in the field in 20 years or less. This has occurred in many continental and Atlantic areas of Europe, where fields that were cultivated until abandonment in the middle of the 20$^{th}$ century have now become dense forests (Nelson, 1990; Cernusca *et al*., 1996; Debussche *et al*., 1999; Lach and Wyzga, 2002; Poyatos *et al*., 2003; Taillefumier and Piégay, 2003; Andréassian, 2004; Cosandey *et al*., 2005; Keesstra *et al*., 2005; Chauchard *et al*., 2007; Gellrich *et al*., 2007; Tasser *et al*., 2007; Kuemmerle *et al*., 2008). In contrast, a dense shrub cover can remain for decades in abandoned fields with thin, poorly structured, eroded soils, even if precipitation is sufficient to support forest development and forest lies relatively close to the abandoned field (Verburg and Overmars, 2009). Under such conditions, the succession of shrubland to forest may not occur, or is very slow (Pueyo and Beguería, 2007). This has been noted at some sites in the central southern Pyrenees, where a dense cover of *Genista scorpius* developed in abandoned fields after 20-25 years, but the advance toward more mature stages of plant colonization then ceased. This was interpreted as a consequence of soil degradation after decades or centuries of shifting agriculture (Lasanta *et al*., 2006), so that only a plant as hardy as *G. scorpius* was able to adapt to the resulting soil conditions. Nunes *et al*. (2010) noted that plant colonization in abandoned fields in central Portugal was relatively slow because of the low organic matter content of thin soils. After 4-5 years of abandonment, a sparse graminaceous herbaceous cover developed. Two decades later, perennial shrub communities of *Cytisus multiflorus* and *Lavandula sampaioana* prevailed, whereas growth of stands of *Q. pyrenaica* was associated with a longer period of abandonment (approximately 30-40 years).

The influence of soil fertility on plant colonization after farmland abandonment was analyzed by Lasanta *et al*. (2000). In a field set aside under the CAP in a semiarid environment close to Zaragoza (northeast Spain), the incorporation of fertilizer (inorganic or organic) had spectacular effects on plant cover, at least during the first years following fertilizer application. Fertilized plots showed a rapid increase in the percentage of plant cover (to approximately 75-80%), whereas plots without added fertilizer had only limited plant colonization (approximately 40% cover). Such differences in colonization demonstrate that average precipitation is not the main limiting factor in the development of plant cover. In fact, the years in which these experiments were conducted were very dry, with annual precipitation of about 200-250 mm. Lasanta *et al*. (2000) therefore concluded that the low level of nutrients in the soil was probably more important in control of growth than was scarcity of water.

Lesschen *et al*. (2008) studied the spatial heterogeneity of plant cover in abandoned fields of southeast Spain, a semiarid environment with low average annual precipitation. The cited authors found that vegetation recovery was slow, particularly on marl substrata, because of a low infiltration rate. In general, where precipitation is scarce, plant colonization develops as patches of vegetation alternating with regions of bare soil (Bergkamp *et al*., 1996; Puigdefábregas *et al*., 1998; Puigdefábregas, 2005), resulting in non-uniform hydrological processes attributable to spatial structuring. Haase *et al*. (1997) and Pugnaire *et al*. (2006) noted that cessation of agriculture in southeast Spain led to development of a patchy landscape with almost monospecific stands of early colonizing species, particularly *Anthyllis cytisoides* L. and *Retama sphaerocarpa* Boiss, even several decades after abandonment. Pugnaire *et al*. (2006) concluded that colonization of abandoned lands may be restricted mainly by seed availability and climatic variability, and observed that agricultural practices over centuries may have limited the seed availability of some perennial species. The occurrence of marked climatic variability in semiarid environments can reduce the time required for seed germination under favorable conditions (Fig. 5).

## 4. Hydromorphological evolution of abandoned lands: a general perspective

As explained above, farmland abandonment can occur in a variety of situations, with differing hydromorphological consequences. Nevertheless, some common effects are evident regardless of climate or type of abandoned field.

In most instances, an increase in the density of plant cover has been observed following farmland abandonment, which has a direct influence on rainfall partitioning (evapotranspiration, throughfall, infiltration, and runoff) (Haria and Price, 2000). The presence of dense shrub communities and forests on past grasslands or in fields previously cultivated with cereals is associated with marked changes in the main components of the hydrological cycle. In general, a reduction in runoff and a drop in runoff-generating area are evident. It is well known from experimental catchment studies throughout the world (Bosch and Hewlett, 1982) that expansion of forest cover at the expense of cereal crops or meadows causes a decrease in runoff, primarily because of a rise in rainfall interception. In addition, Gallart *et al*. (2002) and Serrano-Muela *et al*. (2008) demonstrated the importance of water consumption by forests in summer, which reduces the water content of the soil and limits the hydrological response at the catchment level during severe summer rainstorms. For example, Gallart *et al*. (2002) recorded several instances of the lack of a hydrographic response even after summer rainfall of approximately 50 mm. García-Ruiz *et al*. (2008) compared the hydrological response in three catchments with different types of plant cover (forest, abandoned land with shrubs and grazing meadows, and badlands). No hydrological response was evident in the forest catchment in summer, despite the occurrence of severe rainstorms, a sudden increase in discharge was evident in the badlands, and a moderate increase was recorded in the abandoned catchment.

Andréassian (2004) studied the hydrological effects of forests in the evolution of discharge by comparing deforested and reforested catchments. The main conclusion was that deforestation increases annual flow whereas reforestation results in a fall. However, the results of studies in different environments worldwide are extremely varied, making runoff unpredictable under changing land use/land cover scenarios. With respect to floods, it appears that the flow effects of forests are restricted to less intense hydrological events (*i.e.,* floods corresponding to a return period lower than 5 years or so) as demonstrated by Cosandey (1990) in southern France and by Robinson *et al.* (1991) in Germany. The cited authors concluded that the impact of reforestation was either slight or nonexistent with respect to more extreme flood events. Thus, the impact of reforestation is more pronounced when flows are low, and hence is especially notable in summer. Despite this evidence, Andréassian (2004) concluded that information on the long-term consequences of reforestation is inadequate, because of changes associated with aging of forest stands.

Cosandey *et al*. (2005) undertook a detailed hydrological study of the impact of Mediterranean forests in various catchments of the Central Massif (Mont Lozère) and in southeast France (Draix and Réal Collobrier). The catchments studied included dense forest environments established after land abandonment, as well as deforested and clear-felled environments. One catchment was affected by a forest fire. The main findings were: (i) forest cover raised the threshold amount of rain needed to initiate flow; (ii) peak flows occurred later in forested catchments than in deforested areas; (iii) peak flows were significantly less in forested catchments; (iv) hydrographs in forested catchments showed a slower rising limb and, notably, a very slow recession limb, relative to the extreme reactivity of streams in deforested catchments; (v) the presence of forest slightly decreased annual flooding, but had no effect on decadal flooding; and, (vi) forest logging did not result in significant hydrological changes during heavy flood events, because the soils were highly permeable. These findings suggest that the main factors determining differences in hydrological behavior among catchments are soil depth and permeability, and the presence of bare areas, which in turn are related to the history of land use and land cover.

At a regional scale, Beguería *et al*. (2003) studied the evolution of streamflow in the Spanish Pyrenees over the last 50 years (the period of major land use/land cover changes) using data from gauging stations upstream of the main reservoirs, and water abstraction figures. The results demonstrated a change in the relationship between annual precipitation and discharge, with discharge clearly declining from the beginning of the study period, and particularly from the start of the 1970s. Such changes were not attributable to a temperature increase (which would enhance evapotranspiration) or to a decline in precipitation, but rather to a generalized expansion of shrubs and forests following farmland abandonment. Modeling to predict discharge in response to evolution of precipitation and temperature demonstrated that the predicted discharges were lower than those observed during the second half of the study period, highlighting the fact that discharge is progressively decreasing (by about 30 ± 4% over 50 years). Moreover, monthly runoff decreased significantly in February, March, April, June, and September. As there was a decrease in discharge in almost every month, and no negative temporal trend in precipitation (except in March) or positive trend in temperature (except in January and February), the development of dense shrub and forest cover after land abandonment (an important nonclimatic change) was suggested to explain the changing pattern of runoff. Studies in the eastern Pyrenees have shown that interception of runoff by young forests colonizing abandoned fields represented approximately 24% of annual precipitation (Llorens *et al*., 1997b). It is noteworthy that 22% of the territory in the central Pyrenees was cultivated in the past; in the time since farmland abandonment that area has become forest (68%), shrublands (25%), and grazing meadows (7%) (Vicente-Serrano *et al*., 2004), which explains the influence of land cover changes on streamflow. In another study of the Iberian Peninsula, Morán-Tejeda *et al*. (2010) noted that most of the headwater basins in the Duero River basin show more marked negative trends for runoff than for precipitation, consistent with the recent expansion of forests and shrubs in this area.

Gallart and Llorens (2004) performed a similar analysis in tributaries of the Ebro River, northeast Spain. The results indicated that a decrease in water yield was determined by a rise in forest cover, confirming that water resources cannot be assumed to be stationary over time under a scenario of land use change (Table 2). Gallart and Llorens (2001) found much evidence of declining water resources in various Spanish river basins over the period 1921−1999, and considered that this could be explained not only by increased water consumption for irrigation, or climate variability, but also by a causal relationship between increasing forest cover and a falling water yield. The application of a hydrological model in the Krofdorf mountain catchment (Germany) indicated that afforestation of abandoned lands with spruce could lead to a reduction by about 50% of the catchment discharge over a few decades. Groundwater recharge will fall to only 60% of the present rate because of a rise of about 35% in evapotranspiration (Meuser, 1990).

At a more detailed scale, Nunes *et al*. (2010) used rainfall simulation tests to assess the effects of various land covers (corresponding to different stages of plant colonization following farmland abandonment) on hydrological behavior in central

Portugal. Four types of land cover were selected: cereal crops, herbaceous cover (that grew after recent abandonment), scrubland (15–20 years after abandonment) and *Q. pyrenaica* forest (30–40 years after abandonment). Ploughed land had the most rapid and greatest response to precipitation, whereas recently abandoned fields showed the highest variation in runoff yield. The scrubland and (in particular) small patches of *Q. pyrenaica* yielded very low or no overland flow, such that infiltration capacity exceeded the simulated rainfall intensity (53-55 mm $h^{-1}$). The hydrological behavior of different forms of land cover reflects a trend toward a decrease in runoff due to plant colonization, and the highest values of organic matter content were found in scrubland and *Q. pyrenaica* patches.

A similar trend was observed at the Aísa Valley Experimental Station, where runoff and soil erosion were studied under various conditions, including (i) cereals on sloping fields; (ii) shifting agriculture with cereals; (iii) fallow land; (iv) recently abandoned AL1 land (abandoned for about 16 years following 4 years of cereal cropping), with 100% herbaceous cover and 60% shrub cover superposed; (v) recently abandoned AL2 land (abandoned for about 13 years after 4 years of shifting agriculture), with 100% herbaceous cover and 15% of shrub cover, superposed; (vi) grazing meadow (about 30-40 years after abandonment); and, (vii) dense shrub cover (about 35-40 years after abandonment) (García-Ruiz *et al*., 1995; Lasanta *et al*., 2006, 2010). These land covers represent various traditional cultivation systems, and different stages of, and alternatives to, land abandonment. It was interesting to note that recently abandoned AL1 land underwent rapid plant colonization, so that 65% of the soil was protected during the first year. However, recently abandoned AL2 land showed a slower colonization process. In addition, progression toward a dense shrub cover was faster on AL1 land, confirming that shifting agriculture yields poor soils. In the case of the plot with dense shrub cover, the long observation time of the study allowed assessment of progressive degradation of shrub stands caused by senescence; shrub cover declined from 100% in 1996 to 65% in 2008, with replacement by grasses. These results show that cultivated land (land growing cereals, land used in shifting agriculture, and temporarily fallow land) yields the highest runoff coefficients, and that abandonment results in a clear and progressive decrease in annual runoff yield because of gradual plant colonization and the growth of shrub stands. Figure 6 shows the negative trend of residuals obtained after analysis of relationships between annual precipitation and runoff coefficient after farmland abandonment, confirming the reduction in runoff as plant colonization progresses (Lasanta *et al*., 2010). The lowest values of runoff were recorded in plots with dense shrub cover, wherein increases in soil moisture content were also found (Errea *et al*., 2001). Plots with dense shrub cover did not show any temporal trend in runoff, although senescence changed the relationships among precipitation, infiltration, and runoff generation (Lasanta *et al*., 2010).

The progressive increase in plant cover density following farmland abandonment results in a general decrease in soil erosion. Most field experiments and regional studies throughout Europe have reached similar conclusions (García-Ruiz, 2010). This is a logical consequence of the protective effect of vegetation against rain splash and particle detachment. In addition, soil characteristics tend to improve some years after abandonment, and approach those prevailing prior to cultivation (Martínez-Fernández *et al*., 1995). Even a short period of abandonment (4-10 years) appears to result in significant increases in soil organic matter content, aggregate stability, hydraulic conductivity, and water holding capacity (López-Bermúdez *et al*., 1996). On Lesvos Island (Greece), Kosmas *et al*. (2000) obtained similar findings in studies on fields with slopes of gradient 18-25%, which had been abandoned for 40-45 years prior to the study. For soils developed on lava, the soil organic matter content increased in abandoned fields relative to fields under cultivation (2.36% and 0.92%, respectively), whereas for soils developed on schist the values were 3% and 1.87%, respectively. In the Maestrazgo Ranges near the coast of Valencia (eastern Spain), Ruecker *et al*. (1998) noted that 20 years after abandonment soil organic matter levels had recovered in revegetated fields. Aggregate stability was also greatly affected by farmland abandonment, with a remarkable increase in aggregate size. Trimble (1990) has also stressed that an improvement in infiltration capacity and a decrease in erosion potential occur after abandonment.

The first studies on soil erosion in abandoned fields were performed in the Iberian Ranges (García-Ruiz *et al*., 1988) and at the Aísa Valley Experimental Station, central Spanish Pyrenees, by scientists at the Pyrenean Institute of Ecology. These projects initially involved experimental plots about 3 $m^2$ in size (Ruiz-Flaño *et al*., 1992; Ruiz-Flaño, 1993), and, later, plots of 30 $m^2$ (García-Ruiz *et al*., 1995; Lasanta *et al*., 2006, 2010). The experimental plot studies have been supported by work involving geomorphic transects in fields abandoned for varying periods, and studies of the characteristics of soil in fields at different stages of land abandonment. The geomorphic transects (Ruiz-Flaño *et al.*, 1992; Ruiz-Flaño, 1993) showed that the greatest geomorphic activity occurred during the first years following abandonment, after which soil erosion was negligible because shrubs covered the soil (about 25-30 years after abandonment). However, severe erosion processes were evident in fields abandoned for 80-100 years, involving the undermining of shrub stands, rilling, and the development of a stone pavement following soil removal. The evolution of geomorphic micro-environments in abandoned fields of the central Pyrenees showed a clear decrease in the proportions of mild and severe sheetwash erosion during the first 50 years following abandonment, coinciding with a rise in the extent of rill erosion (Fig. 7). Nevertheless, the occurrence of erosion-related micro-environments (stone pavement, accumulations, and rills) tended to be greater in fields abandoned for very long periods. This was interpreted as the result of frequent human-induced fires during the stage of shrub cover development, when fields that had been abandoned for long periods were covered by thorny shrubs. Because such shrubs restricted grazing by sheep, shepherds burnt the scrubland to improve grassland quality. This was a recurrent process; the shrub cover returned within a few years and was burnt again, which resulted in increased soil erosion for some months. Figure 8 shows the hypothetical evolution of sediment yield and surface stoniness in abandoned fields affected by recurring fires lit by humans. The use of fire to improve the quality of grasslands almost ceased during the 1970s, when livestock numbers were reduced to very low levels, and the practice was later prohibited. Firing could thus explain why the oldest abandoned fields have the worst soil and plant cover conditions, whereas fields abandoned 40-60 years ago show dense shrub cover without any evidence of soil erosion. It is also noteworthy that the oldest abandoned fields were those with the worst soil quality and topographic conditions (straight and convex hillslopes), and were abandoned after decades under shifting agriculture; this probably made plant colonization difficult. In the same area, Navas *et al.* (2005) recently used $^{137}$[Cs] measurements to investigate the occurrence of soil redistribution processes following farmland abandonment, and found that south-facing slopes (*i.e.,* those most affected by cultivation and fires) had the highest erosion rates, and were consequently slow to achieve plant colonization.

In summary, Figure 3 provides a general and simplified overview of the relationships between time after farmland abandonment, and runoff and erosion, in three types of fields: those under shifting agriculture, sloping or terraced fields, and cutting meadows. In general, abandoned fields tend to show an increase in plant cover density, reducing runoff and soil erosion, which can be close to zero if shrub or forest cover is dense. Runoff and soil erosion also fall in grazing meadows. Shifting agriculture tends to result in evolution toward a stone pavement with a relatively open shrub cover. Recurrent fires in sloping abandoned fields disturb plant succession, and cause an increase in soil erosion that sometimes leads to stone pavement development.

The study of farmland abandonment at the catchment scale provides useful information on the processes involved (García-Ruiz *et al*., 2008). For example, a shrinkage in the area of sediment sources has been noted in the Arnás catchment, central Pyrenees, because most of the catchment is now covered with dense shrubs and small forest patches 30-40 years after land abandonment (Lana-Renault and Regüés, 2009; Lana-Renault *et al*., 2007). Lorente *et al*. (2003) reported that the occasional occurrence of debris flows on old cultivated steep hillslopes had almost no effect on sediment load in the main stream, as the runout distance was relatively short as a consequence of the presence of tree and shrub stands downslope of the debris flow scar. According to the SHETRAN model, this is the main reason for the small role played by debris flow on sediment load in old farmed basins in the Ijuez region (Bathurst *et al*., 2007).

The use of modeling to estimate sediment yields has confirmed the positive effects of farmland abandonment on soil erosion and sediment transport. Bakker *et al*. (2008) studied sediment yield in four areas of Europe. Three of the regions were selected because land use intensity had fallen in the recent past (abandoned cultivated lands in Alentejo, Portugal; the French Alps; and Thessalonika, Greece), whereas Hageland (Belgium) was selected as an intensively cultivated area, which included some grasslands that had been converted into arable land. Land use changes since the middle of the 20$^{th}$ century were analyzed, and sediment export was modeled using the WATEM/SEDEM model. Table 3 summarizes the estimated sediment outputs for the four areas. A marked reduction is evident in abandoned areas, and a slight increase is noted for Hageland. The conversion of grassland into arable land at the latter site had occurred principally on flat areas close to the stream network, which facilitated connectivity between sediment sources and rivers. Connectivity is always a major issue, as has been demonstrated in the Lake Balaton catchment, Hungary (Van Dessel *et al*., 2008), where a significant move to extensive agriculture followed the breakup of agricultural collectives in the 1990s. This resulted in an increase in the proportion of grasslands and forests at the expense of arable land. However, these changes had little impact on the sediment volume entering Lake Balaton because of the poor connectivity between areas affected by farmland abandonment and the stream channels.

The WATEM/SEDEM erosion model was also applied to various land use scenarios in the 47.2 $km^2$ Rogative basin (Murcia, southeast Spain) (Boix-Fayos *et al.*, 2008). From 1956 to 1997 the area of forest cover in the basin increased 3-fold, and that of cultivated land fell 2.5-fold. Up to 58 check-dams were constructed in the 1970s, accompanying reforestation works. The model showed that in a scenario without check-dams, farmland abandonment and reforestation would have caused a progressive decrease (54%) in sediment yield. The construction of the check-dams resulted in an additional decrease of 34% in sediment yield.

On the regional scale, farmland abandonment was considered to be the main factor causing reduction in the sedimentation of reservoirs in the Spanish Pyrenees (García-Ruiz *et al.*, 2010), and also the principal cause of extensive wildfires (Moreno *et al.*, 1998; Debussche *et al.*, 1999; MacDonald *et al.*, 2000; Pardini *et al.*, 2004; Nunes *et al.*, 2010). Cleared fields in the best topographic positions (concavities, and lower parts of hillslopes) acted as fire breaks, increasing the availability of food for livestock (Molinillo *et al.*, 1997; Lasanta *et al.*, 2009) (Fig. 9).

The influence of fields set aside under the CAP on soil hydrology and erosion is different, as such fields usually do not evolve into scrubland or forests. If financial support is to flow from the CAP, farmers are obliged to use the fields as seeded fallow land growing nonfood crops (*e.g.,* energy crops), or to frequently plough the fields to avoid plant colonization (unseeded fallow land). The former use is more common in Atlantic and continental Europe, whereas the second use is generally employed in the Mediterranean region, as soil water content is improved under this management regimen (Boellstorff and Benito, 2005). The hydromorphological outcomes of the two alternatives can be very different. Van Rompaey *et al.* (2001) calculated that a set-aside percentage of about 10% of land in the southern part of the Flemish Bravant province (central Belgium) reduced total soil erosion by 10%, as erosion in set-aside fields is close to zero. However, the selection of fields for set-aside is not random; farmers usually choose steep fields that are more susceptible to erosion, and, for this reason, the reduction in soil erosion may be much greater.

Studies of the value of set-asides in the Mediterranean region are more controversial. Boellstorff and Benito (2005) reported an increase in grain yield when wheat was cultivated after some years of unseeded fallow cultivation. Soil water measurements taken immediately before autumn planting were significantly higher in unseeded than in seeded fallow land. However, studies in experimental plots demonstrated that fields managed as unseeded fallow yielded about twice the amount of sediment of fields under cultivation. Boellstorff and Benito (2005) concluded that unseeded fallow lands showed considerably greater hydrological responses, and suffered from more soil erosion during intense rainstorms, than did control fields managed in an alternative manner. This suggests that the CAP set-aside policy has led to an increase in the amount of land that is at risk of high-level erosion. Lasanta *et al*. (2000) reached an opposite conclusion in work with experimental plots in the central Ebro basin, where cereal crop and set-aside land (unseeded fallow, and fertilized fallow to accelerate plant colonization) were compared. The highest sediment concentration was seen in the cereal plot, whereas the set-aside land surprisingly showed the lowest values, probably because a resistant soil crust impeded particle detachment and favored high runoff level. These results emphasize that complexity is the most outstanding feature of Mediterranean land environments.

Changes in plant cover following farmland abandonment have been very extensive in some areas of Europe, resulting in major channel disturbances. Piégay *et al.* (2004) estimated that the Drome River (in the French Prealps) transported a great deal of sediment in the early 20$^{th}$ century, because the river flowed through a deforested environment prone to erosion and frequent intense floods. Channel aggradation was observed in some fluvial stretches of the river between 1835 and 1945. As a result of spontaneous reforestation following land abandonment, sediment supply (particularly bedload) fell, resulting in channel degradation. Similar patterns have been observed in other southeastern French rivers. Thus, Liébault and Piégay (2001) reported three major phenomena in the Roubion River and tributaries thereof: (i) bed degradation, (ii) development of bed armoring in incised reaches; and (iii) channel narrowing accompanied by development of alluvial forests. These changes were attributed to an overall decrease in sediment delivery across the entire Rhône basin, caused by land use changes. In a review of fluvial changes in southeastern France, Liébault and Piégay (2002) observed a general trend toward channel narrowing, attributed to both climatic changes after the end of the Little Ice Age and basin reafforestation caused by flood control works and rural depopulation, which decreased both bedload supply and peak flows. Various human activities (sediment mining, reafforestation, and flood control works) have been identified as the major causes of channel changes (narrowing and incision) in Italian rivers, including a movement from braiding toward single-thread channels (Surian *et al*., 2010). A progressive trend of fan inactivation has been reported in the Sila Massif (of southern Italy) following the expansion of natural vegetation cover at the expense of cultivated lands (Garfi *et al*., 2007). Channel adjustments related to farmland abandonment have also been found in the central Spanish Pyrenees, where rivers crossing the Flysch Sector have tended to narrow in the second half of the 20$^{th}$ century, during which time fluvial bars have become progressively covered by alluvial forests (Beguería *et al*., 2006). Simultaneously, alluvial fans have shown reductions in active areas and have incised historical sediments (Gómez-Villar and García-Ruiz, 2000). López-Moreno *et al*. (2006) suggested that fluvial adjustments, including a reduction in peak flows corresponding to low return periods, were mostly related to land cover changes.

Similar studies have been undertaken in other Mediterranean areas. For example, Keesstra *et al*. (2005) and Keesstra (2007) analyzed the evolution of the Dragonja River floodplain (in southwest Slovenia), where farmland abandonment after 1945 was followed by natural reafforestation (to 31% in 1954, 63% in 1985, and 73% in 2002). Such afforestation resulted in restriction of flood plain sedimentation to events associated with large peak flows. The main consequence was that the river narrowed and incised the river bed. Between 1945 and 1975, this process created a terrace elevated about 1.5 m above the bed. After 1975, an additional terrace of 0.5-1.0 m developed above the river bed.

In the Upper Wisloka River (southern Poland), forest cover increased from 30% in 1938 to 67% in 1995 following rural depopulation and farmland abandonment during the 1940s. Such reafforestation significantly limited sediment delivery to the stream channel, causing bed scouring and an incision more than 2 m in depth (Lach and Wyzga, 2002).

## 5. Hydromorphological effects of farmland abandonment under particular conditions

Above, we present the general and usually relevant hydromorphological consequences of farmland abandonment. Nevertheless, particular conditions in abandoned fields can result in very different effects that require separate study. This is particularly true in the case of abandoned bench terrace fields, and when relatively flat areas in drylands are to be investigated.

*5.1. Bench terrace fields*

The effects of farmland abandonment in bench terrace fields are largely conditioned by disturbance of the topography and soil characteristics established during terrace construction. It is noteworthy that terraces introduce significant topographic changes, including a flat sector and an almost vertical step, the height of which depends on the gradient of the hillslope and the width of the flat sector. In general, the construction of terraces involves re-organization of the drainage network and redistribution of soil, which becomes thicker close to the steps and thinner in the inner part of the terrace. In extreme cases, terraces are narrow bands that follow contour lines. The step can be covered by a wall made of stones, or by herbs, shrubs, and even trees. Many bench terrace fields were abandoned during the 20$^{th}$ century, particularly the narrowest terraces that were impossible to work with machinery, and those that could only be cultivated with cereals or as meadow. The principal reason for abandonment was that construction and maintenance of bench terraces represented major manpower investments that could only be justified if highly profitable or subsidized crops (*e.g.,* olive trees, vineyards) were to be grown.

Although terraces continue to be cultivated, the main geomorphic problem with respect to conservation is that terraces tend to be affected by small mass movements in steps, resulting in scars that need to be repaired. The earlier abundance of manpower in rural areas allowed reconstruction of steps, even when soil had to be carried from the valley bottom or nearby areas. Farmland abandonment had an immediate effect on terraced hillslopes, because repair of mass movement scars became impossible (Fig. 10). This is true of many countries/regions including Greece (Kizos and Koulouri, 2006; Koulouri and Giourga, 2007), the Iberian Range in Spain (García-Ruiz *et al*., 1988; Lasanta *et al*., 2001), and the Pyrenees (Clotet-Perarnau *et al*., 1989). The abandonment of agricultural terraces caused landscape degradation and soil erosion, because scars are frequently affected by gullying and livestock trampling (García-Ruiz *et al*., 1988). For example, 85% of terraces on Lesvos Island (Greece) have been destroyed (Kizos and Koulouri, 2006). The principal factors controlling mass movement in abandoned terraces are slope (which in turn determines step height), and hillslope shape. In a study of 86 terraces in the Jubera Valley (Iberian Range), Lasanta *et al*. (2001) confirmed that the most important geomorphic process affecting abandoned terraces was wall collapse caused by small landslides (average volume: 3.3 $m^3$); the average landslide volume was

38.8 $m^3$ 100 $m^{-1}$. Landslide frequency was higher on concave hillslopes, particularly in the lowest parts thereof, where water tended to accumulate and the soil was saturated. After landslides, all of livestock trampling, splash effects, and overland flow facilitated the erosion of landslide scars. García-Ruiz *et al*. (1988) showed that the density of landslides in terrace walls was positively correlated with hillslope gradient, and negatively associated with the density of plant cover. Lasanta *et al*. (2001) demonstrated that erosion was barely discernible on the flat portions of terraces, although intensive grazing trebled both the runoff coefficient and suspended sediment concentration, compared to data from non-grazed terraces. Lesschen *et al*. (2008) reported that all of potential drainage area, loamy texture, the presence of trees on terraces, and the growth of shrubs on terrace walls, were significantly correlated with terrace failure. Cammeraat *et al*. (2005) found that plant recolonization was very rapid following terrace abandonment in the Alcoy basin of southeast Spain, and was sufficient to reduce landsliding and creep processes. The main problem was that soil permeability decreased rapidly with depth, and potential failure planes were found 1–2 m down, at the level of contact between regolith and unweathered parent material. In such instances, anchoring by root systems failed to prevent mass movement. Llorens *et al*. (1997a) noted that failures in terrace steps after land abandonment in the eastern Pyrenees were rare, and had little effect on erosion or landscape degradation because of dense plant cover of the topsoil at terrace edges. However, overflowing water was perceived to be a major erosion hazard in concave areas, because natural drainage pathways were occupied by terraced fields, which were not adequately maintained.

The importance of terracing failure as a contributor to erosion after farmland abandonment was investigated by Lesschen *et al*. (2008), who compared data from the current and 1984 versions of the Digital Elevation Model (DEM). Soil losses were estimated after subtracting terrace failure levels from the 1984 DEM data. The average net reduction in surface level since abandonment was 13.8 cm, representing an erosion rate of 87 Mg $Ha^{-1}$ $y^{-1}$; this is greater than that reported in some semiarid badlands (Cantón *et al*., 2001).

A marked increase in the connectivity between hillslopes and the stream network has been detected following terrace abandonment. For instance, Meerkerk *et al*. (2009) reported that the progressive deterioration of terraces following land abandonment in the Cárcavo basin (southeast Spain) caused an increase in the area contributing sediment to the river system by 3.2-fold between 1956 and 2006, and the cited authors estimated that if all terraces were removed the contributing area would increase by a factor of 6.0 compared to that in 2006. The formation of gullies connecting different terraces can establish important links between hillslopes and channels (Oostwoud Wijdenes *et al*., 1999; Bellin *et al*., 2009). In addition, failure to maintain network ditches tends to produce reorganization of the drainage system, through incision of new channels across terraces and re-establishment of the natural drainage network (Gallart *et al*., 1994). For this reason, stream channels frequently become the most important sediment sources in abandoned areas (Llorens *et al*., 1992).

The abandonment of old cultivated terraces also has a significant effect on runoff generation. Gallart *et al*. (1994) demonstrated that the intersection of the water table with the topography in the Cal Parisa basin (eastern Pyrenees) led to saturation of the inner parts of terraces during the wet season, increasing overland storm flow. Seeger and Ries (2008) found clear signs of hydromorphism on the slope-facing sides of abandoned terraces in the central Pyrenees, and the soils appeared to be saturated for long periods.

Finally, terrace abandonment enhances piping if particular conditions are met, thus contributing to land degradation and desertification. Steep hydraulic gradients between terraces encourage sub-superficial erosion at the terrace edge, particularly if the soils are dispersive and are sensitive to contraction and swelling with respect to hydration conditions (Fig. 11). An impervious layer in the lower soil horizon favors lateral drainage. The enlargement of desiccation cracks explains surface collapse and hole development (Solé-Benet *et al*., 2010); these features contribute to a chaotic landscape that evolves into a badland. Such processes are particularly active in extremely degraded soils, of high sodium content, in southeast Spain, as evidenced by the work of López-Bermúdez and Torcal (1986) and Romero-Díaz *et al*. (2007). Piping also occurs in terraced fields that remain under cultivation (García-Ruiz *et al*., 1997), but, in such instances, pipes are usually destroyed upon annual ploughing. In the absence of soil restoration, terrace abandonment leads to rapid development of piping.

*5.2. Abandoned fields in dryland areas*

Scarce and irregular precipitation in combination with particular soil characteristics can hinder plant colonization in abandoned fields located in semiarid areas. Relatively high temperatures, an average annual precipitation less than 400 mm, and long dry periods present major obstacles to the development of dense plant cover. Dry periods can last for up to 8 months a year in the central Ebro basin, and up to 10-11 months a year in southeast Spain. Few opportunities for seed germination exist under such conditions, and vegetation succession is slow, especially where infiltration is restricted by formation of a soil surface crust.

Such crusts are common in semiarid abandoned lands, mainly because of the low density of plant cover during the first years after abandonment. Crust formation results from a complex mix of factors. Structural crusts probably develop initially as surface seals caused by rain splash, but calcium carbonate dissolution and high evaporation rates following the wet season contribute to a rapid increase in both the thickness and strength of the microcrust (Gutiérrez-Elorza *et al*., 1995; Lasanta *et al*., 2000). In other instances, surface crusts are of sedimentary origin, being attributable to sheetwash erosion and deposition of fine particles forming a near-impervious layer in flat areas. Both types of crust, structural and sedimentary, have been found in abandoned lands of the Ebro basin (Ries and Hirt, 2008), where the crusts both reduce infiltration rate (by about 50% for sedimentary crusts) and considerably increase surface runoff (Ries and Langer, 2001), resulting in rill and gully erosion. Sedimentary crusts occupied 70% of abandoned fields 5 years after the land was left fallow.

Lasanta *et al*. (2000) also reported that plant cover density in the Ebro basin decreased after the second year of abandonment because of the development of a microcrust, which reduced infiltration and enhanced overland flow. A fall in infiltration is one of the most important factors constraining the evolution of plant cover. Poor nutrient conditions also affect such evolution, as plant cover readily develops if organic or chemical fertilizers are added. Cammeraat and Imeson (1999) reported lower infiltration rates in abandoned fields of the Upper Guadalentín basin (southeast Spain), attributed to the presence of a dense salty crust.

A decrease in soil infiltration, at least during the first years following abandonment, is crucial in development of soil erosion, although other factors also play important roles. Thus, Lesschen *et al*. (2008) noted that abandoned fields on marls were intrinsically very vulnerable to erosion, attributable to the dispersion of clay minerals. Lesschen *et al*. (2007) reported an increase in gully erosion in abandoned fields of the Cárcavo basin, compared to cultivated fields. Such erosion was attributed to the greater runoff concentration caused by crust development. Sauer and Ries (2008) investigated soil erosion in the Ebro basin, comparing erosion in a recently abandoned field (where cultivation ceased about 15 years ago) to that in a field abandoned about 75 years prior. In both instances, the predominant erosion process was sheet wash erosion in both cases. The most important difference between the two fields was the presence of rills in the field abandoned more recently, and the expansion of deep gullies with very active head-cuts in the field abandoned in the distant past. Nevertheless, studies on relatively evolved and structured soils have shown that plant colonization is organized in temporal bands that act as sediment traps, thus reducing sediment delivery to streams (Cammeraat and Imeson, 1999). Puigdefábregas *et al*. (1998) and Puigdefábregas (2005) studied soils on schists, and found that runoff coefficients could be locally high, but were (overall) usually low because of spatial discontinuities in runoff, because vegetation patches acted as sinks.

## 6. Conclusions

The area affected by farmland abandonment in Europe represents thousands of square kilometers, and is particularly concentrated in mountainous areas where depopulation and difficulties associated with the use of modern agricultural machines caused most fields on steep slopes to be abandoned. A large proportion of studies has focused on the Mediterranean region, probably because of variability in the types of abandoned land in this area, and in some instances also because of impediments to rapid plant colonization. Abandonment has also affected hilly areas in western Europe and many regions in eastern Europe, where the transition from centralized to market-oriented economies has resulted in unequal competition from foreign producers.

Farmland abandonment is an extremely complex process affected by a variety of factors. First, abandonment occurred at different epochs, commencing from the middle of the 19th century, and continued until recently. Second, abandoned fields are located in regions that differ in climatic conditions (ranging from humid to semiarid), resulting in a variety of plant colonization processes. Third, land abandonment affects many types of fields, including sloping, bench terrace, and shifting agriculture fields. Fourth, land management following farmland abandonment has varied, ranging from total abandonment to more-or-less extensive livestock grazing. Finally, during the 19th and most of the 20th century, land abandonment was generally a result of spontaneous personal decisions, which contrasts with the last two decades of the 20th century, during which abandonment has been dominated by set-asides under the CAP.

Throughout most of Europe, plant colonization evolved rapidly into formation of dense forests or shrub communities, with some fields becoming transformed into grazing meadows. Usually, vegetation densities approach 100%. Under such conditions, interception, infiltration, and water consumption by plants are encouraged and runoff decreases, whereas soil protection increases. In many European regions, expansion of forests and shrub communities explains all of the decline in water resources, the reduction in soil loss and sediment delivery, and the progressive improvement of soil quality (as estimated by measurements of soil aggregate and organic matter content). From a regional perspective, changes in plant cover level, runoff generation, and soil erosion have altered stream morphology, and have caused narrowing and incision of alluvial plains. The evidence also points to a reduction in sedimentation in some Mediterranean reservoirs. The generalized expansion of forests and shrubs may increase the frequency of wildfires affecting large areas, given the homogeneity and continuity of many landscapes. The clearing of shrubs and forests on concave areas with deep soils, and the transformation of such areas into cutting meadows and facilitating grazing, must be recommended, to increase landscape diversity, to improve livestock grazing conditions, and to reduce the risk of extensive wildfires.

Bench terrace fields in mountain areas also evolve into dense forests, although small mass movements frequently occur in the steps between terraces. Terrace abandonment and subsequent lack of maintenance has resulted in changes to the spatial organization of saturated areas and drainage networks.

Plant colonization is slower in semiarid areas (*i.e.,* those of southeast Spain), and this enhances the development of structural and sedimentary crusts, which reduce infiltration and increase overland flow and soil erosion, particularly on poorly structured soils developed on marly substrata. On well-structured soils (*i.e.,* soils on schists), the extent of plant colonization is such that overland flow is possible only after extreme rainfall events.

In summary, farmland abandonment has had very important consequences for all of landscape structure, water resources, soil erosion, stream dynamics, and reservoir silting. The extent of such effects depends on diverse factors (*e.g.,* field type, climate, rate and characteristics of plant colonization, and soil features). To develop effective policies for the management of marginal lands in Europe under future land cover predictions, it is essential to understand the diversity of factors affecting abandoned lands, and the hydromorphological effects thereof.

## Acknowledgments

Support for this research was provided by the projects PROBASE (grant no. CGL2006-11619/HID; Consolider), financed by the Spanish Commission of Science and Technology; ACQWA (grant no. FP7-ENV-2007-1), financed by the European Commission; and PI032/08, financed by the Aragón Regional Government. The authors also acknowledge support from the Program of Research Groups of the Aragón Regional Government, and from RESEL (the Spanish Ministry of the Environment). N. Lana-Renault was the recipient of a research contract (under the I+D+I 2008-2011 National Program) funded by the Spanish Ministry of Education and Science.

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**Figure captions**

Figure 1. The hydromorphological effects of farmland abandonment in Europe. Location of the sites reviewed. Please also see Table 1.

Figure 2. Evolution of land cover after farmland abandonment in a Mediterranean catchment (Cal Rodó, Vallcebre basin, Eastern Pyrenees). Source: Poyatos *et al*. (2003). Originally published in *Mountain Research and Development*, vol. 4, no. 4.

Figure 3. Evolution of runoff and erosion development after farmland abandonment under three scenarios: abandonment after use for shifting agriculture, sloping or terraced fields, and cutting meadows.

Figure 4. Plant colonization in an abandoned field in the Arnás experimental catchment, central Pyrenees. The colonization strategy features progressive colonization of the field from the borders. Shrub stands in the middle of the field are the result of seed dispersal by birds.

Figure 5. Abandoned fields in Cuenca de Mula (Murcia, southeast Spain). As precipitation is scarce and irregular, and because the soil is of poor quality, plant colonization is restricted.

Figure 6. Annual trends of the residuals obtained in analysis of relationships between annual precipitation and runoff coefficient. AL1: Abandoned sloping field. AL2: Abandoned shifting agriculture field. Both fields had been previously cultivated with cereals. Source: Lasanta *et al*. (2010).

Figure 7. Evolution of the presence (%) of geomorphic micro-environments in abandoned fields of the central Pyrenees, based on information from Ruiz-Flaño *et al*. (1992).

Figure 8. Hypothetical evolution of sediment yield and surface stoniness in abandoned fields affected by recurrent fires. Source: Ruiz-Flaño *et al*. (1992).

Figure 9. Old abandoned fields in Jubera Valley (La Rioja, northern Spain), where shrubs had been cleared to develop grazing meadows.

Figure 10. Small landslides at the border of abandoned bench terrace fields in Maestrazgo (northeast Spain). Most landslides occurred in concavities, in which water tended to concentrate during rainy seasons.

Figure 11. Piping and badland development in an abandoned field in Cuenca de Mula (Murcia, southeast Spain).

Table 1
Click here to download Tables: Table 1.doc

Table 1. General information on the studies dealing directly or indirectly with the hydrological and geomorphological consequences of farmland abandonment in Europe (Code refers to Figure 1).

| Code | Location (Study site) | Country | Climatic area | Reference | Spatial scale | Aim |
|---|---|---|---|---|---|---|
| 1 | Flemish Brabant | Belgium | Atlantic | Van Rompaey *et al.* 2001 | regional | Impact of set aside programs on soil erosion risk |
| 2 | Hageland | Belgium | Atlantic | Bakker *et al.* 2008 | large basin | Erosion and sediment export to past land use changes; importance of land use change patterns |
| 3 | Scottish uplands (Cairngorm mountains) | UK | Atlantic | Haria & Price 2000 | plot | Changes on evapotranspiration from natural pine woodland regeneration |
| 4 | Vitzeme Uplands | Latvia | Boreal | Nikodemus *et al.* 2007 | regional | Causes of land abandonment and its impacts on landscape structure |
| 5 | Bavaria (FM/N,S catchs.) | Germany | Continental | Robinson *et al.* 1991 | small catchment | Hydrological effects of different land uses |
| 6 | Bavaria (KM catch.) | Germany | Continental | " | " | " |
| 7 | Bavaria (UM catch.) | Germany | Continental | " | " | " |
| 8 | Hesse (Krofdorf catch.) | Germany | Continental | Meuser *et al.* 1990 | small catchment | Effects of afforestation on runoff |
| 9 | Lake Balaton | Hungary | Continental | Van Dessel *et al.* 2008 | large basin | Impact of land cover changes on landscape connectivity |
| 10 | Carpathian Mts. | Poland, Slovakia, Ukrania | Continental | Kuemmeler *et al.* 2008 | regional | Extension and effects of land abandonment |
| 11 | Carpathian Mts. (Wisloka River) | Poland | Continental | Lach & Wyzga 2002 | regional | Changes in channel geometry and flows following catchment reafforestation |
| 12 | Alps (Lauteret) | France | Sub-alpine Continental | Bakker *et al.* 2008 | large basin | Erosion and sediment export to past land use changes; importance of land use change patterns |
| 13 | Alps | Italy and Austria | Sub-alpine Mediterranean and Alpine | Tasser *et al.*. 2007 | regional, plot | Mechanisms and effects of natural reforestation |
| 14 | Alps and Apeninnes | Italy | Sub-alpine Mediterranean | Surian *et al.* 2010 | regional | Land use change and channel adjustments |
| 15 | Alps and Prealps (15 large river basins) | France | Sub-alpine Mediterranean | Liébault & Piégay 2002 | regional | Channel narrowing and its relation to natural and human factors |
| 16 | Prealps (Bauvières plain) | France | Mediterranean | Piégay *et al.* 2004 | regional | Trends in sediment yield and channel disturbances in relation to afforestation |
| 17 | Prealps (Upper Roubion River) | France | Mediterranean | Liébault & Piégay 2001 | regional | Channel adjustment in response to a decrease in long-term bedload supply linked to land use change |

| Code | Location (Study site) | Country | Climatic area | Reference | Spatial scale | Aim |
|---|---|---|---|---|---|---|
| 18 | Draix (Brusquet catch.) | France | Mediterranean | Cosandey *et al.* 2005 | small catchment | The effect of plant cover on catchment hydrology |
| 19 | Draix (Laval catch.) | France | Mediterranean | " | " | " |
| 20 | Réal Collobrier (Rimbaud catch.) | France | Mediterranean | " | " | " |
| 21 | Réal Collobrier (Valescure catch.) | France | Mediterranean | " | " | " |
| 22 | Mont Lozère (Cloutasse catch.) | France | Mediterranean | " | " | " |
| 23 | Mont Lozère (Latte catch.) | France | Mediterranean | " | " | " |
| | | | | Cosandey 1990 | small catchment | " |
| 24 | Eastern Lesvos island | Greece | Mediterranean | Koulouri & Giourga 2007 | plot | Soil evolution and vegetation recovery following land abandonment |
| 25 | Lesvos island | Greece | Mediterranean | Kizos & Koulouri 2006 | regional | Changes in the Lesvos agricultural landscape |
| | | | | Kosmas *et al.* 2000 | plot/transects | Effect of parent material on soil evolution and vegetation recovery following land abandonment |
| 26 | Thessalonika (Lagadas) | Greece | Mediterranean | Bakker *et al.* 2008 | large basin | Erosion and sediment export to past land use changes; importance of land use change patterns |
| 27 | Prealps (Mella river basin) | Italy | Mediterranean | Renzi *et al.* 2002 | large basin | Impact of land use change on floods |
| 28 | Calabria (Mucone River basin) | Italy | Mediterranean | Garfi *et al.* 2007 | large basin | Land use change and fan morphodynamics |
| 29 | Drangonja basin | Slovenia | Mediterranean | Keesstra *et al.* 2005 | large basin | Response of fluvial morphology to large-scale land abandonment |
| | | | | Keesstra 2007 | large basin | " |
| 30 | Alentejo (Amendoiera) | Portugal | Mediterranean, atlantic influence | Bakker *et al.* 2008 | large basin | Erosion and sediment export to past land use changes; importance of land use change patterns |
| 31 | Central Portugal (Coâ basin) | Portugal | Mediterranean, atlantic influence | Nunes *et al.* 2010 | plot | Effects of land abandonment on runoff and sediment yield |
| 32 | Main river basins in Spain | Spain | Mediterranean, Continental, Atlantic | Gallart & Llorens 2001 | regional | Relationships between land cover change and streamflow |
| 33 | Central Spain (Torrijos) | Spain | Mediterranean continental | Boellstorff & Benito 2005 | regional | The impact of set aside program on erosion risk |

| Code | Location (Study site) | Country | Climatic area | Reference | Spatial scale | Aim |
|---|---|---|---|---|---|---|
| 34 | Duero River basin | Spain | Mediterranean continental | Morán-Tejeda *et al.* 2010 | regional | Role of climate evolution and land use changes on the regional trends of discharge |
| 35 | Almería (Cautivo) | Spain | Semiarid Mediterranean | Cantón *et al.* 2001 | micro catchment | Factors controlling runoff generation and sediment production |
| 36 | Almería (Rambla Honda) | Spain | Semiarid Mediterranean | Puigdefábregas *et al.* 1998 | plot | Hydrological connectivity of hillslope elements |
| | | | | Puigdefábregas 2005 | plot | A review of the role of vegetation patterns in structuring runoff and sediment fluxes |
| | | | | Solé-Benet *et al.* 2010 | plot | Soil erosion and controlling factors in different types of abandoned terraces |
| 37 | Almería (Sierra de Gata) | Spain | Semiarid Mediterranean | Oostwoud Wijdenes *et al.* 2009 | micro catchment | Gully head morphology as indicator for gully development on abandoned fields |
| 38 | Central Ebro basin | Spain | Semiarid Mediterranean | Gutiérrez-Elorza *et al.* 1995 | plot | Soil erosion in semiarid environments |
| 39 | Central Ebro basin (Barranco Las Lenas) | Spain | Semiarid Mediterranean | Ries & Langer 2001 | plot | Runoff generation in abandoned fields |
| | | | | Ries & Hirt 2008 | plot | Consequences of crust formation on surface runoff and soil erosion in areas of fallow land |
| | | | | Sauer & Ries 2008 | plot | Interdependence of geomorphodynamics and vegetation cover on abandoned fields |
| 40 | Central Ebro basin (Peñaflor) | Spain | Semiarid Mediterranean | Lasanta *et al.* 2000 | plot | Changes in runoff and soil erosion after farmland abandonment |
| 41 | Murcia | Spain | Semiarid Mediterranean | López-Bermúdez & Torcal 1986 | regional | Erosion by piping in abandoned fields |
| | | | | López-Bermúdez *et al.* 1996 | plot | Soil erosion under different land covers |
| | | Spain | Semiarid Mediterranean | Trimble 1990 | regional | Soil erosion under different land covers |
| 42 | Murcia (Upper Guadalentín basin) | Spain | Semiarid Mediterranean | Cammeraat & Imeson 1999 | plot | Soil-vegetation patterns and landscape dynamics |
| 43 | Murcia (Carcavo basin) | Spain | Semiarid Mediterranean | Bellin *et al*.., 2009 | small catchment | Soil water conservation structures and implications of their abandonment |
| | | | | Lesschen *et al.* 2007 | large basin, plot | Indentification of vulnerable areas for gully erosion using different scenarios of land abandonment |
| | | | | Lesschen *et al.* 2008 | large basin, plot | Extent and causes of erosion and terrace failure on abandoned fields |

| Code | Location (Study site) | Country | Climatic area | Reference | Spatial scale | Aim |
|---|---|---|---|---|---|---|
| | | | | Meerkerk *et al.*., 2009 | small catchment | Effect of terrace removal and failure on hydrological connectivity and peak discharge |
| 44 | Murcia (Mula Basin) | Spain | Semiarid Mediterranean | Martínez-Fernández *et al.* 1995 | transects | Soil-vegetation and land use relationships |
| | | | | Romero-Díaz *et al.* 2007 | plot | Factors contributing to the piping process in abandoned terraces |
| 45 | Murcia (Rogativa basin) | Spain | Semiarid Mediterranean | Boix-Fayos *et al.* 2008 | large basin | Effectiveness of land use changes and check-dams to control sediment yield |
| 46 | Alicante (Alcoy basin) | Spain | Sub Mediterranean | Cammeraat *et al.* 2005 | plot | Role of vegetation succession on landslide activity in abandoned terraced |
| 47 | Maestrazgo (Morella) | Spain | Sub Mediterranean | Ruecker *et al.* 1998 | plot | Soil development and vegetation recovery after land abandonment |
| 48 | Eastern Pyrenees | Spain | Sub Mediterranean, mountain influence | Clotet-Perarnau *et al.* 1989 | regional | Landslides in bench terraces due to extreme events |
| 49 | Eastern Pyrenees (Ca l'Isard catch., Vallecebre) | Spain | Sub Mediterranean, mountain influence | Gallart *et al.* 2002 | small catchment | Seasonal aspects on interception, soil water content, runoff generation and suspended sediment transport processes in abandoned catchments |
| 50 | Eastern Pyrenees (Cal Parisa catch., Vallecebre) | Spain | Sub Mediterranean, mountain influence | Gallart *et al.* 1994 | small catchment | Role of old agricultural terraces on runoff generation in a farmland abandoned environment |
| | | | | Gallart *et al.* 2002 | small catchment | Seasonal aspects on interception, soil water content, runoff generation and suspended sediment transport processes in abandoned catchments |
| | | | | Llorens *et al.* 1992 | small catchment | Role of old agricultural terraces on the hydrological response and sediment dynamics in a farmland abandoned environment |
| | | | | Llorens *et al.* 1997a | small catchment | Sediment budget and erosion rates in a farmland abandoned environment |
| | | | | Llorens *et al.* 1997b | small catchment | Rainfall interception by forest in a farmland abandoned environment |
| 51 | Eastern Pyrenees (Can Vila catch., Vallecebre) | Spain | Sub Mediterranean, mountain influence | Gallart *et al.* 2002 | small catchment | Seasonal aspects on interception, soil water content, runoff generation and suspended sediment transport processes in abandoned catchments |
| 52 | Central Pre-Pyrenees (Sabayés-Bentual del Rasal) | Spain | Sub Mediterranean, mountain influence | Seeger & Ries 2008 | plot | Understanding the degradation history and the future development of soils in abandoned areas |

| Code | Location (Study site) | Country | Climatic area | Reference | Spatial scale | Aim |
|---|---|---|---|---|---|---|
| 53 | Central Pyrenees | Spain | Sub Mediterranean, mountain influence | Beguería *et al.* 2003 | regional | Role of climate evolution and land use changes on the regional trends of discharge |
| | | | | Beguería *et al.* 2006 | regional | Consequences of land use change on fluvial dynamics |
| | | | | García-Ruiz *et al.* 2010 | regional | Hydrological and geomorphic effects of farmland abandonment at different spatial scales |
| | | | | López-Moreno *et al.* 2006 | regional | Temporal evolution of high flows in response to climatic factors and land use change |
| 54 | Central Pyrenees (Aísa valley) | Spain | Sub Mediterranean, mountain influence | Ruiz-Flaño 1993 | plot/transects | Geomorphological evolution of abandoned fields |
| | | | | Ruiz-Flaño *et al.* 1992 | plot/transects | " |
| 55 | Central Pyrenees (E.E.V.A.) | Spain | Sub Mediterranean, mountain influence | Errea *et al.* 2001 | plot | Soil moisture changes after land abandonment |
| | | | | García-Ruiz *et al.* 1995 | plot | Understanding the degradation history and the future development of soils in abandoned areas |
| | | | | Lasanta *et al..*, 2006 | plot | Geomorphic and hydrological effects of traditional shifting agriculture |
| | | | | Lasanta *et al..*, 2010 | plot | Sediment yield and runoff under traditional land uses and after land abandonment |
| 56 | Central Pyrenees (Arnás catch.) | Spain | Sub Mediterranean, mountain influence | García-Ruiz *et al.* 2008 | small catchment | Influence of different land covers on flood generation and sediment transport |
| | | | | Lana-Renault & Regüés 2009 | small catchment | Seasonal dynamics of suspended sediment transport in a farmland abandoned environment |
| | | | | Lana-Renault *et al.* 2007 | small catchment | Relationships between rainfall, discharge and suspended sediment transport |
| | | | | Navas *et al.* 2005 | small catchment | Erosion patterns in a farmland abandoned environment |
| | | | | Seeger & Ries 2008 | small catchment | Understanding the degradation history and the future development of soils in abandoned areas |
| 57 | Central Pyrenees (San Salvador catch.) | Spain | Sub Mediterranean, mountain influence | García-Ruiz *et al.* 2008 | small catchment | Influence of different land covers on flood generation and sediment transport |
| | | | | Serano-Muela *et al.* 2008 | small catchment | Hydrological behavior of a forested undisturbed environment |

| Code | Location (Study site) | Country | Climatic area | Reference | Spatial scale | Aim |
|---|---|---|---|---|---|---|
| 58 | Central Pyrenees (Ijuez basin) | Spain | Sub Mediterranean, mountain influence | Bathurst *et al.* 2007 | large basin | Effect of forest loss on landslide and debris flow incidence |
| 59 | Central Pyrenees (Upper Aragón and Gallego basins) | Spain | Sub Mediterranean, mountain influence | Lorente *et al.* 2003 | large basin | Characteristics and analysis of debris flow parameters in an area affected by land abandonment |
| 60 | Ebro basin | Spain | Sub Mediterranean, mountain influence | Gallart & Llorens 2004 | regional | Temporal changes in runoff in relationship to changes in precipitation, potential evapotranspiration and forest cover |
| 61 | Iberian Range (Jubera basin) | Spain | Sub Mediterranean, mountain influence | García-Ruiz *et al.* 1988 | plot | Geomorphological evolution of abandoned fields |
| 62 | Iberian Range (Oja and Najerilla basins) | Spain | Sub Mediterranean, mountain influence | Gómez-Villar & García-Ruiz 2006 | large basin | Factors influencing the presence /absence of tributary-junction fans |
| 63 | Iberian Range (Upper Leza and Jubera basins) | Spain | Sub Mediterranean, mountain influence | Lasanta *et al.* 2001 | regional, plot | Geomorphological evolution of terraced fields after cultivation |

**Table 2**
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Table 2. Water budgets in different Spanish rivers. Source: Gallart and Llorens (2001).

| River and location | Period (years) | Flow ($Hm^3$ $yr^{-1}$) | Gross decrease ($Hm^3$ $yr^{-1}$) | Gross decrease (%) | Consumption ($Hm^3$ $yr^{-1}$) | Consumption (%) | Precipitation ($Hm^3$ $yr^{-1}$) | Precipitation (%) | Residual ($Hm^3$ $yr^{-1}$) | Residual (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Duero at Carrascal | 1921-95 | 4440 | 1770 | 39.8 | 658 | 14.8 | 338 | 7.6 | 774 | 17.4 |
| Duero at Miranda | 1934-96 | 9190 | 5450 | 59.3 | 1080 | 11.8 | 1630 | 17.7 | 2740 | 29.8 |
| Ebro at Palazuelos | 1915-95 | 1670 | 619 | 37.1 | - | - | 112 | 6.7 | 507 | 30.4 |
| Ebro at Tortosa | 1940-97 | 12900 | 5760 | 44.7 | 1410 | 10.9 | 2140 | 16.6 | 2220 | 17.2 |
| Tajo headwater | 1940-96 | 1180 | 687 | 58.2 | - | - | 145 | 11.4 | 542 | 45.9 |

Table 3. Sediment outputs from four European areas with different land uses. Source: Bakker *et al.*, 2008.

| | Sediment export ($Mg\ ha^{-1}\ yr^{-1}$) |
|---|---|
| Amendoeira (Portugal) | |
| 1958 | 4.7 |
| 1990 | 2.9 |
| Lautaret (France) | |
| 1952 | 3.3 |
| 2001 | 0.9 |
| Lagadas (Greece) | |
| 1945 | 8.6 |
| 1993 | 6.9 |
| Hageland (Belgium) | |
| 1933 | 6.5 |
| 2001 | 7.3 |

Figure 1

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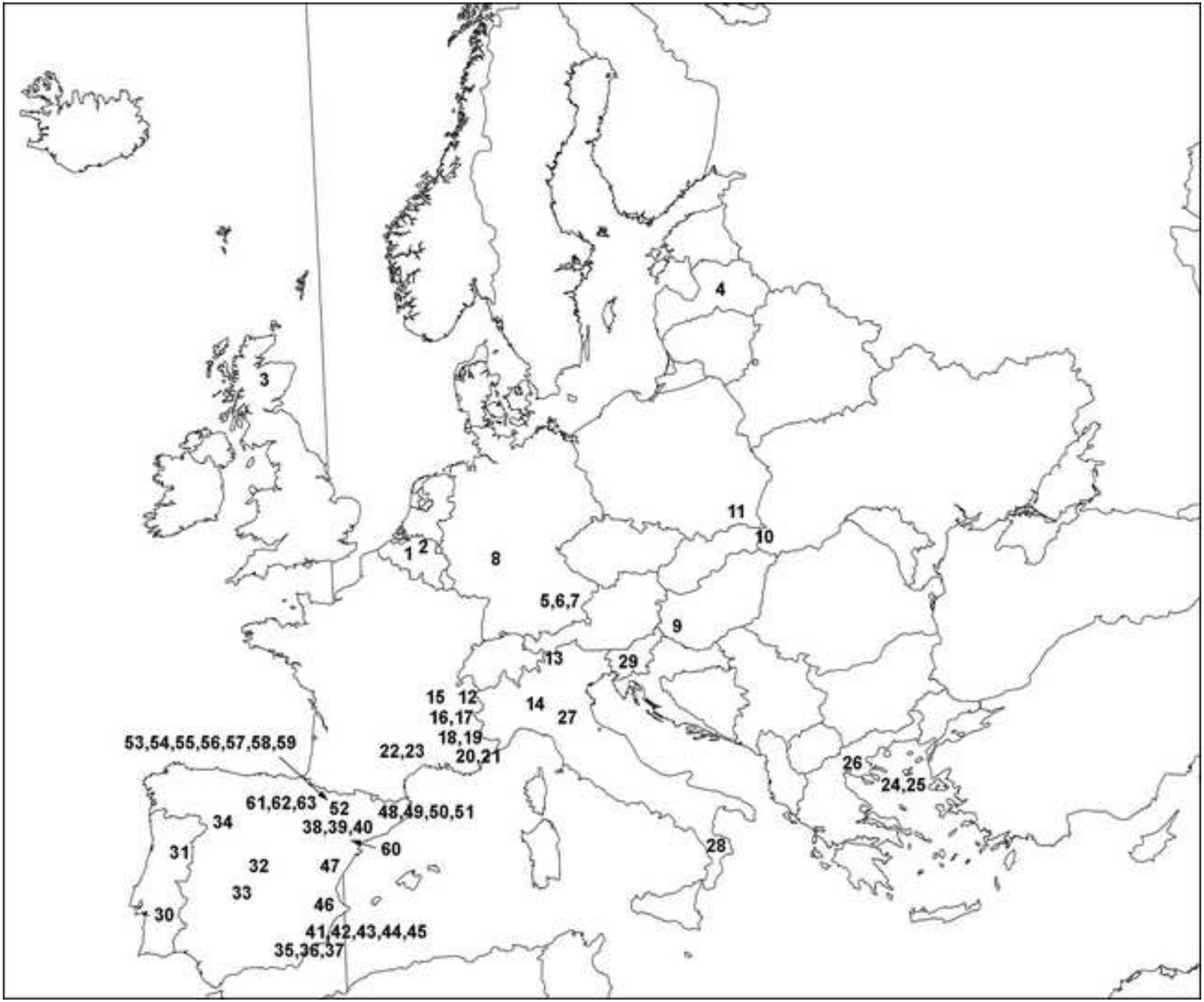

**Figure 2**
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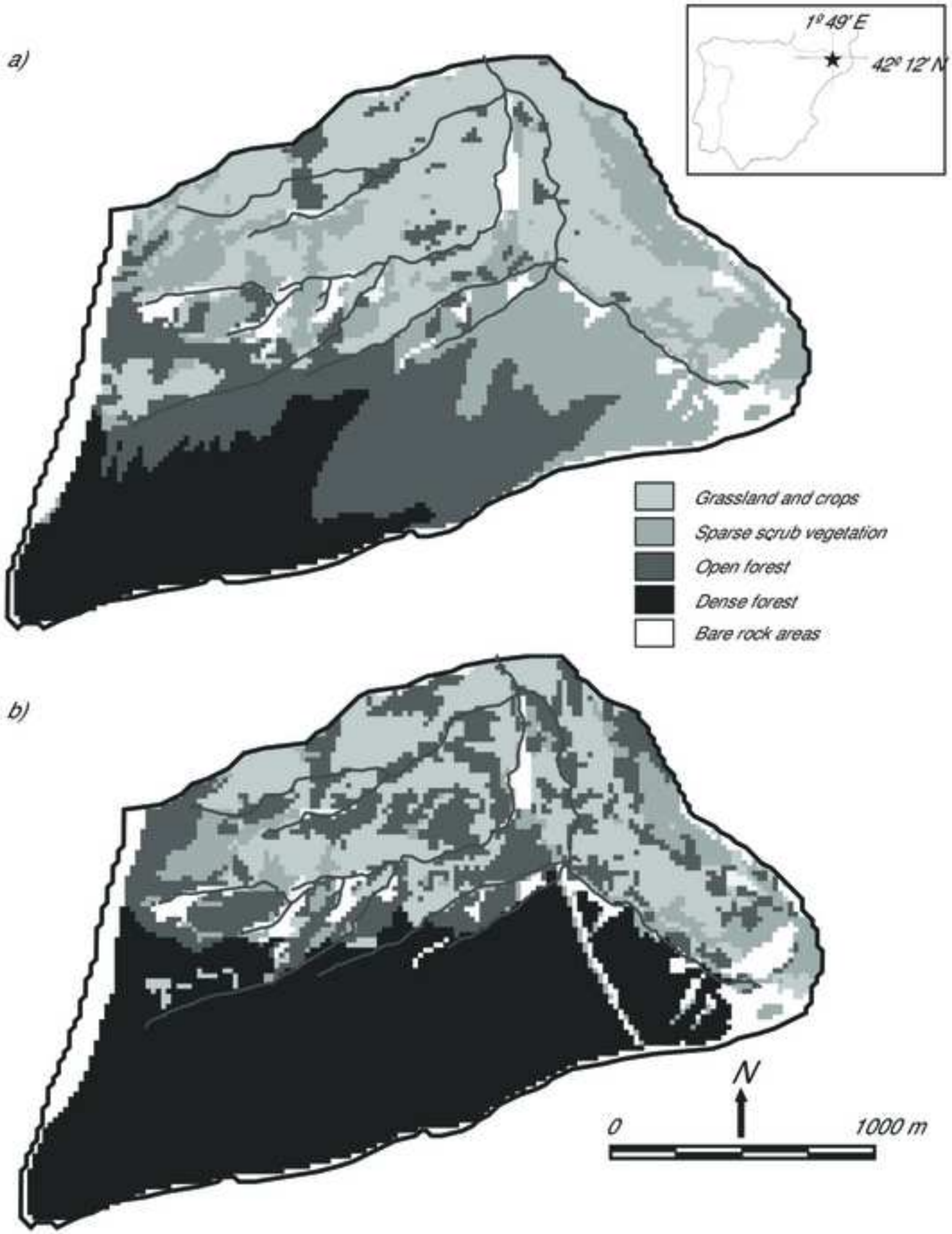

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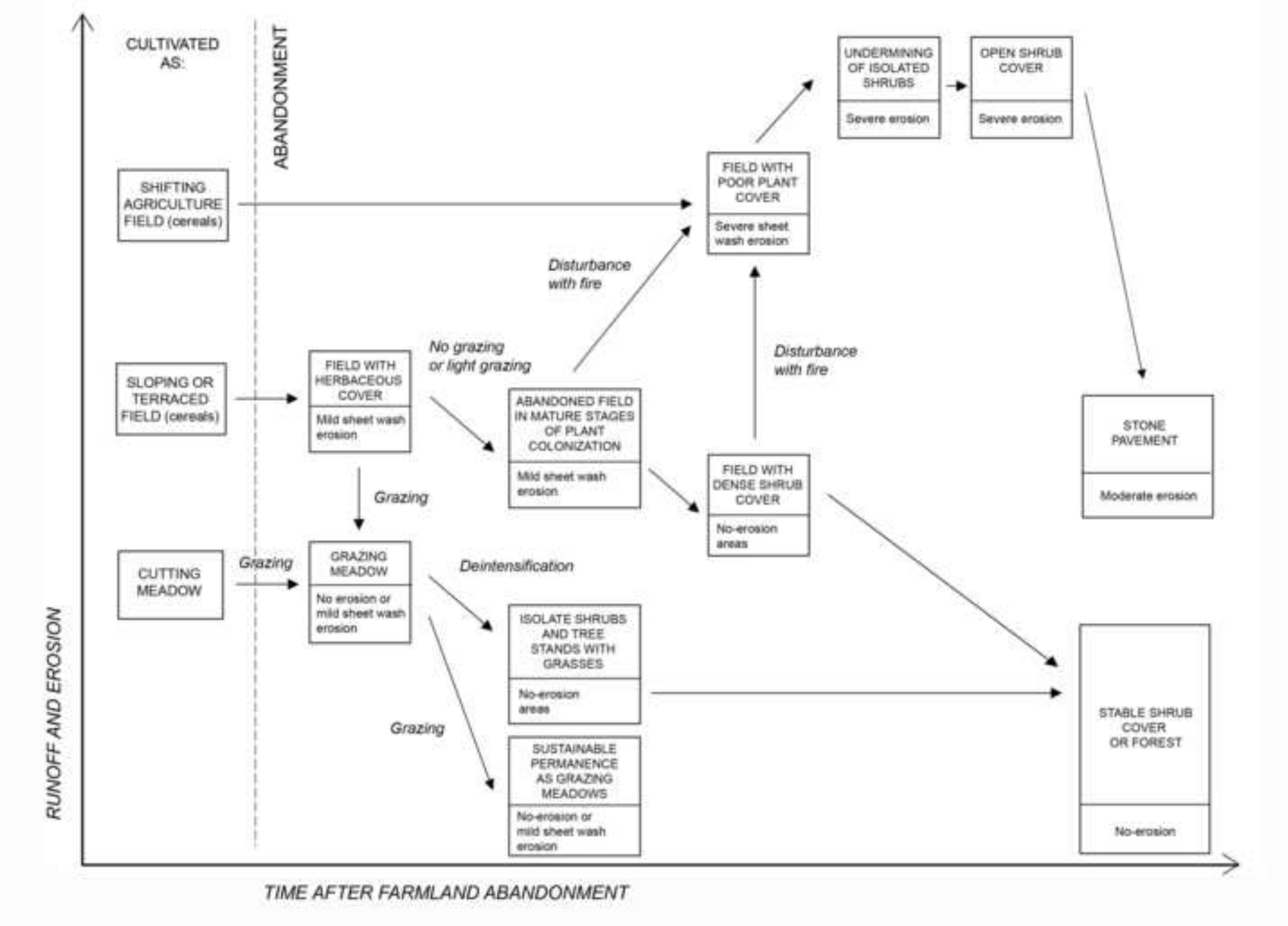

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Figure 6

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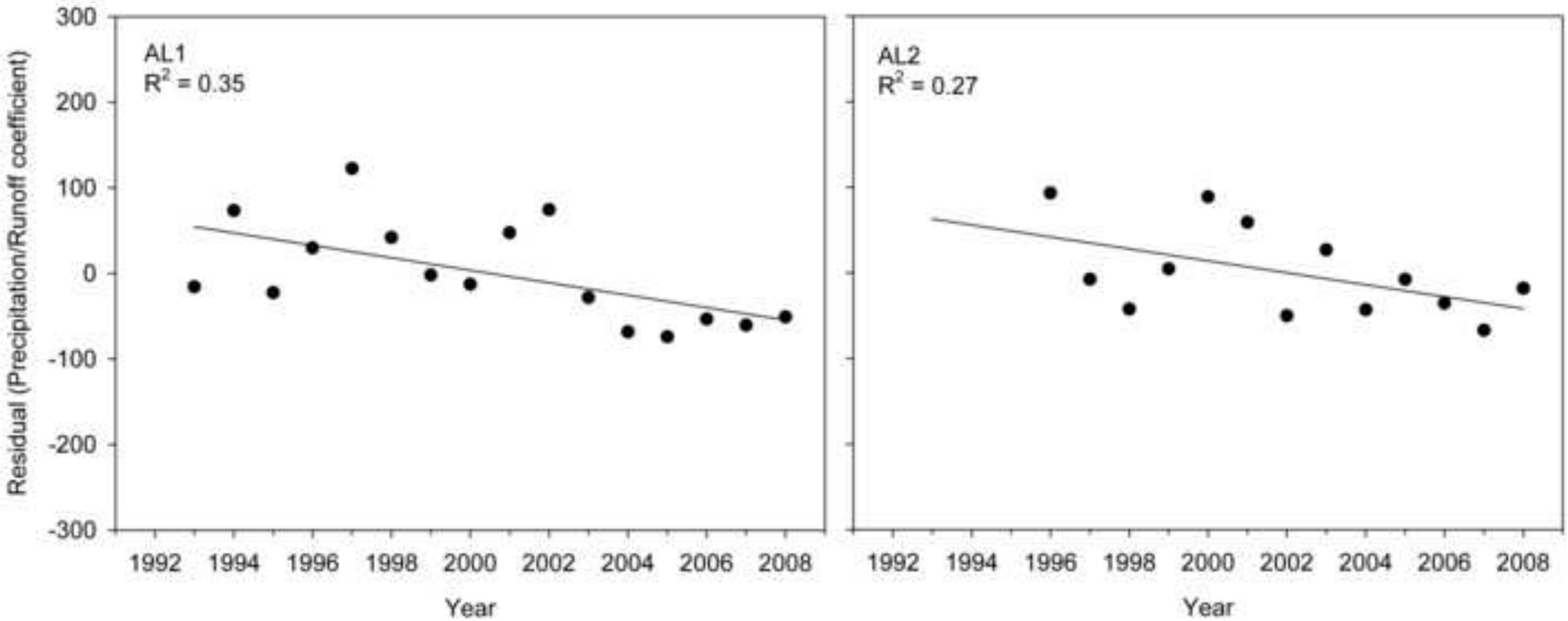

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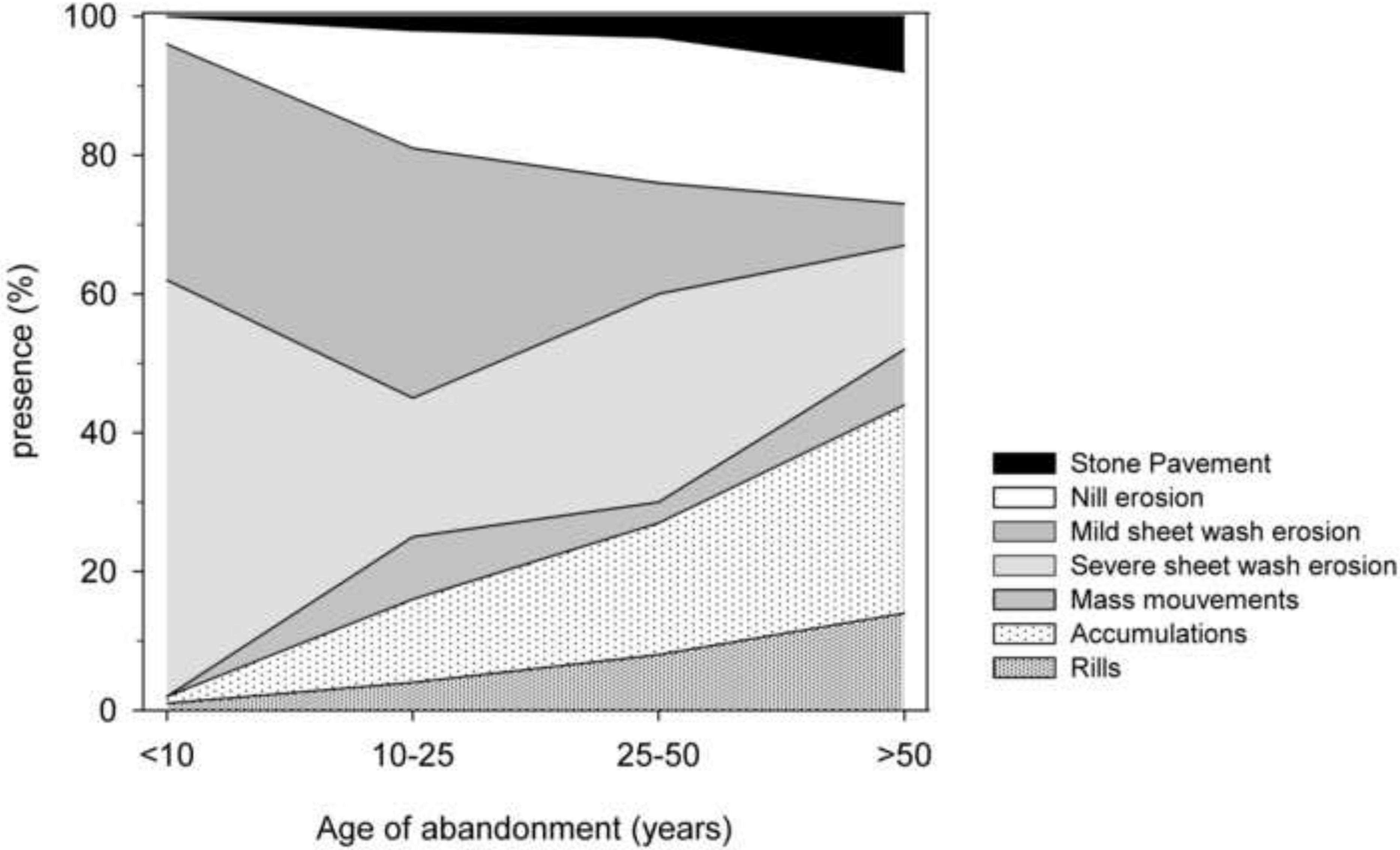

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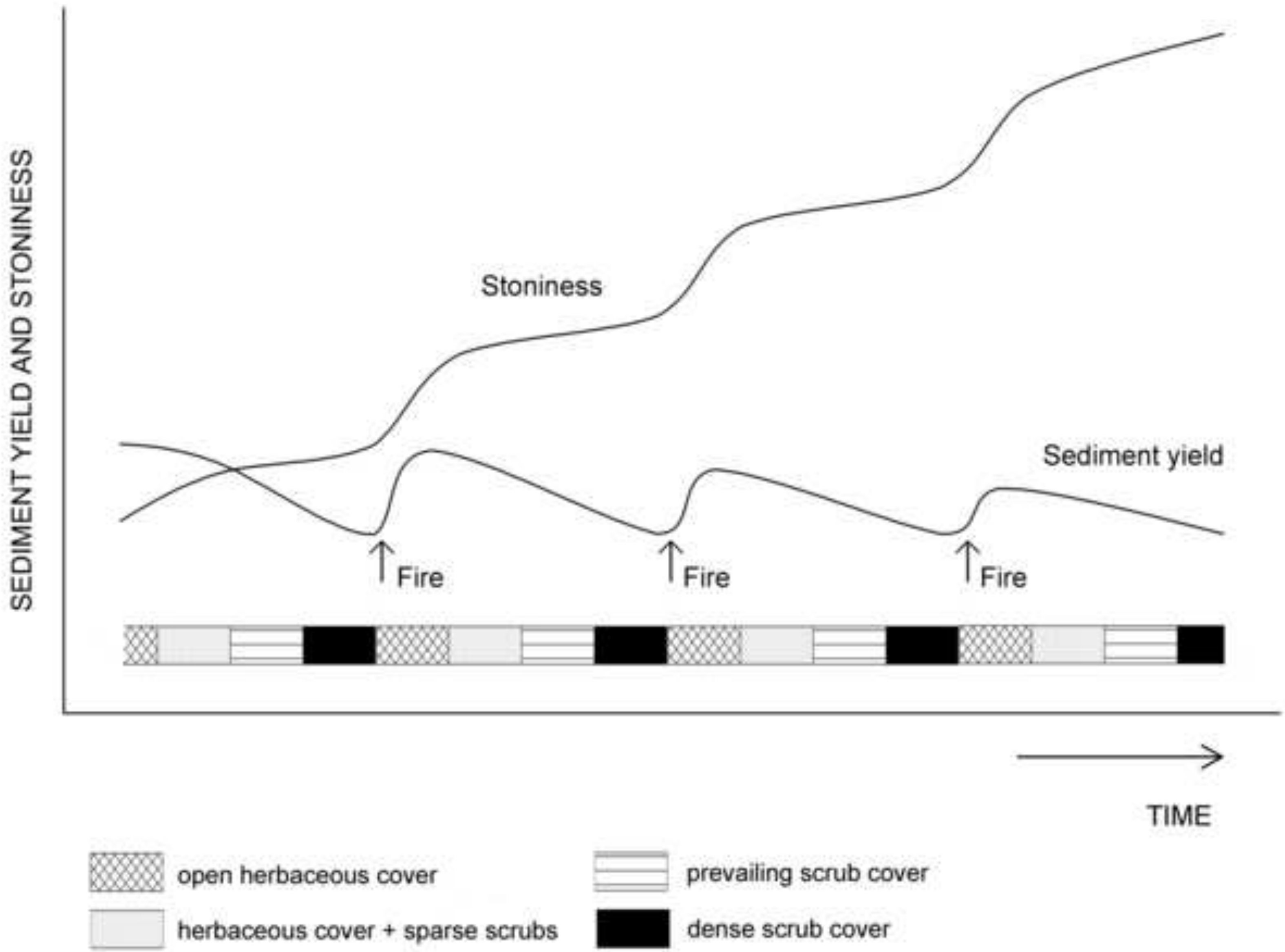

Figure 9
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