Erosion des sols en contexte agricole : état des connaissances

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Ce chapitre comprend essentiellement un article en préparation constituant *in extenso* le *§* I.2. Un résumé de cette synthèse bibliographique est proposé dans le *§* I.1.

I.1. Résumé de l'article

Le but de ce chapitre est, d'une part, de synthétiser les connaissances sur les redistributions de sol en contexte agricole et, d'autre part, de définir des thèmes peu traités dont l'étude permettrait d'avancer dans la problématique posée : déterminer les effets de la fragmentation spatiale, c'est-à-dire du parcellaire agricole, en tant qu'élément structural évolutif du paysage, sur les sols et leur redistribution à l'échelle paysagère. Cette étude bibliographique constitue un article en préparation intitulé : *« A review about assessment of soil erosion-deposition without monitoring in agricultural hillslopes - the case of Western Europe »*, présenté *in extenso* ci-après, et dont voici le résumé.

Dans **la première partie de l'article**, sont présentés **les processus de redistribution de sol** engendrés par les vecteurs dominant l'érosion récente en Europe, à savoir l'eau et le travail du sol. Cette présentation s'articule autour de deux échelles spatiales : l'échelle locale (intraparcellaire) et l'échelle paysagère (de quelques parcelles au bassin versant). L'approche des processus à l'échelle locale permet de souligner les mécanismes des redistributions et de déterminer leurs facteurs de contrôle. L'approche à l'échelle paysagère permet de définir le concept de paysage agricole et d'aborder l'influence des mosaïques d'occupation du sol et des types de bordures de parcelles associées sur les vecteurs eau et travail du sol. Cette première partie permet également d'aborder les conséquences spécifiques à l'action des différents vecteurs sur le sol, sur sa variabilité spatiale, et sur le relief dans le paysage.

La seconde partie de l'article propose une approche de la **caractérisation des processus de redistribution des sols par l'étude d'indicateurs (SEDI : Soil Erosion-Deposition Indicators)**. Ces indicateurs résultent de la redistribution de matière par l'eau et/ou le travail du sol ; ils persistent plus ou moins longtemps dans le sol. Un SEDI est une caractéristique physique ou chimique du sol, ou des éléments associés à son fonctionnement, dont l'étude permet de qualifier et/ou de quantifier l'érosion ou le dépôt de sol à différentes échelles spatiales et temporelles. Quatre catégories de SEDI sont définies : les indicateurs topographiques, pédologiques, biologiques et archéologiques. Les indicateurs appartenant à ces différentes catégories sont présentés selon les deux échelles spatiales abordées dans la partie précédente : l'échelle locale et l'échelle paysagère. Certains SEDI ont déjà été évoqués dans la première partie de l'étude bibliographique et sont détaillés ici, d'autres sont découverts dans cette partie de l'exposé. L'analyse aux deux échelles spatiales démontre que les SEDI étudiés à l'échelle locale témoignent plus particulièrement de processus hydriques non-concentrés et événementiels, alors que les SEDI à l'échelle paysagère permettent de souligner l'action des processus sur le plus long terme, notamment ceux liés à l'érosion et au dépôt d'origine aratoire.

L'étude de tels indicateurs pour approcher les processus de redistribution de sol fait apparaître des chemins prometteurs. La combinaison de quelques SEDI peut permettre de caractériser rapidement et efficacement les processus de redistribution de sols en cours ou passés sur un terrain donné. Les SEDI peuvent être choisis en fonction des échelles spatiales, mais également temporelles, définies selon la problématique posée. De plus, cette approche via l'étude de SEDI ne requière aucun suivi temporel de longue durée sur le terrain, élément positif pour des projets de recherches et travaux de thèse qui ne durent que quelques années.

A l'issue de cette revue bibliographique, il apparaît que certains aspects de l'érosion des sols en Europe de l'Ouest n'ont pas été pleinement traités. La caractérisation de ces aspects semble pourtant indispensable à la compréhension de l'état actuel des sols. En effet, bien que les sols et les paysages évoluent conjointement (Hall, 1983) sous l'effet des redistributions de sol et des activités humaines, **la mise en relation de l'histoire de l'occupation du sol et de ces conséquences sur l'épaisseur de sol n'a été que peu abordée** (Salvador-Blanes, 2002 ; Follain, 2005 ; Houben, 2008). De même, **alors que le relief est une variable prédictive utile pour établir la distribution spatiale des sols et de leur épaisseur** (par exemple, Huggett, 1975; Bourennane, 1997; Heimsath *et al.*, 1999; King *et al.*, 1999),

peu d'étude lient mathématiquement les variations morphologiques locales induites par les bordures de parcelles (par exemple les banquettes agricoles) à l'épaisseur des sols. Toujours d'un point de vue prédictif, il s'avère aujourd'hui nécessaire d'implémenter l'effet des éléments structurants du paysage et de leur évolution dans les modèles d'érosion fonctionnant à l'échelle du versant ou de petits bassins versants (par exemple : Van Oost *et al.*, 2000 ; Follain *et al.*, 2006). Cependant, des données de validation concernant les vitesses de réactivité des sols aux changements de parcellaire restent rares. Pour terminer, il apparaît que les travaux effectués en Europe de l'Ouest sur l'érosion des sols sont essentiellement concentrés en domaine loessique (nord-ouest de l'Europe) et en contexte méditerranéen (sud de l'Europe). Peu de travaux ont ainsi été effectués en domaine carbonaté soumis au climat tempéré en Europe. Les différentes approches développées dans les chapitres suivants visent à préciser ces différents aspects.

I.2. Article en préparation, à soumettre à « Catena »

A review about assessment of soil erosion-deposition without monitoring in agricultural hillslopes – the case of Western Europe

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1. Introduction

Mechanical soil erosion is a natural phenomenon which became a problematic issue for farmers and rural communities since it has been accelerated, i.e. when natural rate has been significantly increased by human activities. Since the second World War, agricultural practices are responsible for a significant acceleration of erosion in Western Europe, due to large changes such as mechanisation, new agricultural policies and rising consumer demand. Most concerns about accelerated soil erosion are related to its negative effects, e.g. water pollution, lower crop yields, reduction of water storage capacity or organic matter losses (e.g. Andraski and Lowery, 1992; Berger *et al.*, 2006; Boardman and Poesen, 2006; Papiernick *et al.*, 2009). The protection of soil as a crucial natural resource is an important challenge, which requires an identification of the major soil erosion-deposition processes involved the assessment the spatial variability of erosion-deposition rates.

Recent soil redistributions observed in croplands of Western Europe were mainly attributed to water processes. Soil erosion by water requires the detachment of soil particles and their transport by runoff water. However, it has been recently outlined that tillage erosion appears to generate significant soil redistribution in intensively farmed cropland (e.g. Lindstrom *et al.*, 1992; Govers *et al.*, 1994; Boardman et Poesen, 2006; Cerdan *et al.*, 2010). Tillage translocation corresponds to the displacement of soil during farming operations.

Soil erosion in agricultural hillslopes is controlled by numerous factors, especially soil properties (physical and chemical), erosivity of soil particle vectors (raindrop impact, runoff and tillage implements), hillslope morphology (slope, slope- and curvatures), landscape fragmentation and associated various landuses and managements (Morgan, 2005; Verheijen *et al.*, 2009). However, these factors present different degrees and patterns of spatial variability from regional scale (climate) to in-field scale (soil surface properties, landuse and management). Their interactions through space induce that the predominant erosion-deposition processes, their intensities, and their variations could radically differ within a field, a hillslope, and from one hillslope to another. Quantifying soil erosion in agricultural landscapes, outlining its driving processes, and specifying its spatial varaibility, appears then to be particularly difficult.

In addition, data about middle-term soil redistribution are sparse for Western Europe. Research projects and Ph.D. works are predominantly contractual and limited to a few years. Therefore, experimental approaches of soil translocation with regular data recording in-field are time-restricted. Experiments do not allow appreciating the entire temporal and spatial variability of the erosion processes involved. Nowadays, study of soil erosion requires rapid and efficient techniques to characterize soil translocation in areas subject to accelerated erosion since the last few decades.

This paper reviews the dominant processes (water and tillage-induced processes) causing soil losses and gains in cultivated hillslopes of Western Europe, and the factors which control these processes. Two spatial approaches are considered, the local and the landscape scale, to highlight the influence of landscape fragmentation and various landuses and managements on soil erosion-deposition intensities and patterns. We then suggest a list of Soil Erosion-Depostion Indicators. These indicators are intended to qualify and/or quantify rapidly one or both of the dominant processes involved on soil redistribution in cultivated areas without any experimentation.

2. Soil erosion-deposition processes

2.1. Soil erosion-deposition at local-scale

2.1.1. Water processes

Soil material displacement by water has been widely studied on agricultural context. Its appearance requires two important phenomenons: the detachment of soil particles and their transport by water throughout the hillslope.

2.1.1.1. Detachment of soil particles

The detachment of soil particles requires first the destruction of soil aggregates, and consequently depends mainly on aggregate stability (Kemper and Rosenau, 1986; Farres, 1987). The main characteristics controlling aggregate stability are texture, organic matter content, clay-mineral composition, and the nature and content of cations and Fe-Al oxydes (Wischmeier and Mannering, 1968). However, the organic matter content appears to be the most influential parameter for soil-aggregate stability on cultivated temperate lands of western Europe (Monnier, 1965; Haynes and Swift, 1990).

Soil desaggregation by water occurs through different physical and physico-chemical mechanisms, which affect aggregates at different levels - from the micro-scale (clay particle) to the macro-scale. Four mechanisms of desaggregation have been identified (Le Bissonnais, 1996). Their relative intensity appears to be controlled by soil physical/chemical properties, and by the rain event nature:

- the **slaking** consists on aggregates break-down by compression of the entrapped air when aggregates are rapidly wetted (Panabokke and Quirk, 1957; Emerson, 1967) .

- the **mechanical desaggregation under raindrop impact**: aggregates are fragmented, and particles are eventually taked off from the surface of aggregates depending on the kinetic energy of the raindrops (Al-Durrah and Bradford, 1982; Nearing *et al.*, 1987). The short-distance lateral displacement of the pre-detached particles that could occur then is called the splash effect (Ellison, 1945).

- the **desaggregation by differential swelling** corresponds to the cracking of aggregates because of an alternation of swelling/drying phases of the clayey particles (Kemper and Rosenau, 1986).

- the **physico-chemical dispersion** comes from the reduction of attraction strengthes between colloïds during swelling (Emerson, 1967).

Moreover, detachment of soil particles could occur through runoff flow traction, when flow shear stresses exceed aggregates shear strengthes. Detachment rate then depends on various parameters such as aggregate stability, aggregate size, flow shear stress or flow velocity (Nearing *et al.*, 1991; Kuznetsov *et al.*, 1998).

2.1.1.2. Transport of soil particles

The transport of soil particles requires the intervention of active agents, raindrop impact and runoff energy, which produce the next four processes: splash erosion, sheetwash, rill erosion and gully erosion. Among these transport processes, we dissociate non-concentrated erosion processes (splash and sheetwash processes, i.e. interrill erosion) where raindrop energy is the principal agent of transport, and concentrated erosion processes (rill and gully erosions) where soil particles transport is predominantly induces by runoff energy (Bryan, 2000; Cerdan, 2001). The interrill processes occur intermittently on the whole hillslope area, whereas rill and gully erosions, which are linear processes, can be randomly or systematically distributed over the hillslope area.

<u>- Non-concentrated erosion:</u>

As mentioned above, splash erosion consists is the detachment of bare soil particles and their lateral transport by raindrop. The splash effect is caused by the kinetic energy produced by the raindrop impact on a soil surface: it depends mainly on raindrop characteristics, themselves linked to rainfall nature and intensity – i.e. rainfall erosivity (Ellison, 1945; Park *et al.*, 1983). Depending on its shape and density, the vegetal cover protects the soil surface from raindrop impact and sealing (Foley *et al.*, 1991), and reduces the energy of the drops which reach the soil surface (Smith and Wischmeier, 1957). The splash effect defines the first vector of soil particles displacement before runoff begins.

Consecutively to soil desaggregation and splash effect, surficial processes of structural reorganization could occur, as illuviation, collapse and sedimentation within micro-concavities (Mc Intyre, 1958; Loch, 1994). These phenomenons can lead to the crusting of soil surface that declines considerably soil infiltrability (McIntyre, 1958; Bradford *et al.*, 1987). The structural evolution of soil by crusting emboldens the formation of water excess in the surface and its flowing (water runoff). Crusting appears to be lower on steep slopes than on gentle slopes. Indeed, the energy of raindrop impact appears lower and the consecutive detached particles are continuously removed by sheet wash on steep slopes when compared to gentler slopes (Poesen, 1986). Aggregate stability is then often considered as an indicator of soil susceptibility to erosion and crusting (Le Bissonnais *et al.*, 1996; Barthès and Roose, 2002).

The formation of a water excess on the soil surface leads to the appearance of new processes allowing the transport of suspended particles. This water excess occurs (i) when the rate at which water infiltrates the soil is lower than the rainfall intensity (Horton, 1933), or (ii) when the soil porosity becomes saturated by water (Hewlett et Hibbert, 1967). The consecutive water excess runs on the soil surface as a “sheetflow”. Sheet erosion drives to the removal of a more or less uniform layer of fine particles which consist mainly in the richest part of the soil (high organic matter and nutrient contents; Fullen and Brandsma, 1995).

A relation exists between the runoff energy and the charge of transported particles which depends greatly on soil nature and initial wetting conditions. The runoff energy reflects flow discharge and hydraulics which are strongly influenced by soil surface properties, microtopography and vegetation, and are therefore highly variable in space and in time (Römkens *et al.*, 2001; Le Bissonnais *et al.*, 2005). For example, raindrop impact modifies gradually the soil surface roughness during an event, and from an event to another. Moreover, the raindrop impact brings energy to sheetflow, rising its transport capability (Bryan, 2000), and improves the charge of particles through its action on particles detachment (Proffitt and Rose, 1991).

Both splash and sheetflow translocation tend to happen on whole areas of cultivated hillslopes. In addition to a high temporal and spatial variability of interrill erosion induced by various parameters such as aggregate stability, roughness, vegetation, rain erosivity, the transport of soil particles by sheetwash is also influenced by general hillslope morphology. So, interrill processes can be favoured on specific sections of the hillslopes. Experiments showed that interrill erosion tends to increase with the slope gradient (Poesen, 1984; Kinnel, 1990; Fox *et al.*, 1997), and on convex profile curavture landforms. When slope arises, a runoff acceleration and an increase of the particle charge happen too (Chaplot and Le Bissonnais, 2003; Cerdan, 2001). In such conditions, deposition occurs when the transport capacity of runoff flow strongly decreases, i.e. when slope gradient decreases (concave profile curvature areas).

<u>- Concentrated erosion:</u>

The apparition of rill and gully erosions requires the concentration of runoff flows, justifying the expression of “concentrated erosion”, and the transport of soil particles. Rill and gully erosions are threshold-dependant processes, and are controlled by a wide range of parameters.

Rill erosion defines the development of random, small, intermittent concentrated flow paths, of only several centimeters deep, which work as both soil particles source and delivery systems (Cerdan *et al.*, 2006, Govers *et al.*, 2007). The consecutive small incised channels are called rills, and can be randomly or systematically distributed. These features can be easily removed by tillage operations. Gully erosion produces features larger than rills, and unlike rills, gullies can reappear at the same location after their possible removal by tillage (Poesen, 1996; Casalí, 2000). Gullies can indeed be too large and deep for being removed by tillage practices, and then interfere with the trafficability of the land (Souchère *et al.*, 1998). In agricultural landscapes, rill and gully erosions appear either in natural drainage ways or along linear anthropogenic landscape elements (such as field boundaries, roads...) (Foster, 1986; Vandaele, 1996), both constituting preferential ways of runoff flowing. Natural drainage ways are distinctive convergent linear landforms defined by concave planform curvature and minimal slope gradient.

Conditions for water concentration are mainly controlled by topographical properties of the cultivated hillslope and soil surface properties, such as a low roughness or a lack of vegetal cover (Cerdan, 2001). Steep slopes tend to enhance runoff velocity and then to favour rill and gully initiation than lower slopes. However, under favorable conditions, low slopes favour soil crusting, and can then severely lower the slope gradient threshold for rill/gully initiation (Valentin *et al.*, 2005). Moreover, for a given slope, a critical drainage area is needed to produce sufficient runoff to concentrate water, and initiate rill erosion in preferential ways of flowing. Thus, flow concentration alone does not necessarily cause rill/gully incision (Dunne and Dietrich, 1980). Indeed, rill/gully initiation seems linked to the threshold tractive force of the flow for particle entrainment and transport, which depends on both flow conditions and soil surface properties (Horton, 1945; Bull and Kirkby, 1997). In spite of many works, concentrated erosion processes appear still unclear (Nearing *et al.*, 1997; Polyakov and Nearing, 2003; Wirtz *et al.*, 2011)

Compared to interrill erosion, concentrated processes are not likely to occur at any location on cultivated hillslopes. The need for flow concentration and sufficient flow shear strengths to the detachment of particles induce that concentrated erosion processes would happen preferentially on mid- and footslope parts of cultivated hillslopes, especially for most intense gullying. As in case of the interrill processes, deposition occurs when the transport capacity of runoff flow strongly decreases. Sediment fans can be observed at the downslope extremities of rill and gully features, preferentially on footslope areas, or on midslope depressions (Boardman and Robinson, 1985; Evans, 1995).

2.1.2. Tillage-induced processes

Tillage has not been taken into account as a direct factor of erosion in cultivated areas until late 1980's and early 1990's. It was generally defined as an indirect factor of erosion due to its action on physical soil properties, like porosity, roughness, structure (Burwell *et al.*, 1963 ; Zobeck and Onstad, 1987; Lipiec *et al.*, 2006). Research about soil erosion focused on water because of its frequencies and intensities. Concentrated water erosion leads to greater soil losses at shorter time-scale than tillage-induced processes, and creates spatial patterns (rills and gullies) which appear more remarkable than those of tillage. Field experiments were also mostly of "short-term nature", the tillage effect was then difficult to observe (Van Oost *et al.*, 2005). Moreover, Govers *et al.* (1999) suggested that the development of the USLE and first physically based models of erosion have focused scientists of the discipline on sheet and rill erosion modelling especially. Nevertheless, tillage was subsequently identified as a direct factor of erosion; especially thanks to the formation of specifical related features as lynchets (Mech and Free, 1942; Papendick and Miller 1977) and later through the presence of shallowed lightened soils on slopes shoulders (Lindström *et al.*, 1990; Revel *et al.*, 1993). Soil translocation by tillage appeared to be not spatially homogenous, and to involve soil erosion and accumulation at various locations in cultivated land.

2.1.2.1. Soil movements during tillage

Movements of soil induced by the use of an implement (mouldboard plough, harrow, disc…) can be decomposed into two types (Lindström *et al.*, 1992). First of all, the primary movements are directly linked to the passage of an implement through the soil (mechanical movements). From a purely physical point of view, the kinetic strengths due to the movement of an implement involve inevitably a movement of the soil thickness crossed by the implement. Soil aggregates are pulled up and move within the implement until leaving it or being ejected. Aggregates then slide, roll, constituting the secondary type of movements (gravitational movements).

The result of these two types of movements is generally expressed as a mass of soil moved by unit of in a specific direction (Govers *et al.*, 2006). The intensity of this transport depends on many factors. As explained by Lobb *et al.* (1999) and Van Muysen *et al.* (1999), the primary movements are mainly governed by the geometry of the tool, the depth and the speed of the implement passage, as well as the initial physical conditions of the soil. These authors also observed that the secondary movements are induced by gravity, and that their intensity is then dependent on slope gradient.

2.1.2.2. Topographical control of tillage translocation

In many studies (Lindström *et al.*, 1990; Govers *et al.*, 1994; Montgomery *et al.*, 1999; Van Muysen *et al.*, 1999) the slope gradient was identified as the most important factor influencing the intensity of soil translocation by tillage. This relation, positive and generally linear, has also been observed in the case of manual plowing (Turkelboom *et al.* 1997; Quine *et al.*, 1999; Kimaro *et al.*, 2005). In these experiments, agricultural practices were made either perpendicularly and/or along elevation contour lines. When the soil is tilled perpendicularly to contour lines, the intensity of soil translocation in the downslope direction is more intense than in the upslope one. Revel *et al.* (1989) measured that upslope tillage compensated only 60% for downslope tillage (slope of 18%). The alternation of downslope and upslope tillage inevitably induces a movement of soil material downward the slope. Concerning tillage along the elevation contour lines, Lindström *et al.* (1992) and Van Muysen *et al.*, (1999, 2002) have demonstrated that soil translocation intensity depends also on the main slope gradient, the soil being turned up- or downslope. But, compared to contour lines tillage, up- and downslope practice is more erosive (Van Oost *et al.*, 2006).

As soil translocation by tillage depends on slope gradient, erosion and accumulation occur when slope gradient varies. Hence, some field experiments and mathematical simulations demonstrated that net soil loss is controlled by curvature (Quine and Walling, 1993; Revel *et al.*, 1993; Lobb *et al.*, 1995, Poesen *et al.*, 1997). Erosion occurs on convex slope, accumulation on concave slopes, and a simple translation happens on linear slopes (Lindström *et al.*, 1992; Govers *et al.*, 1996). The spatial variability of tillage erosion is therefore controlled by topography, and movements by tillage appear to be an important geomorphic processes in a long-term application, mainly in levelling relief (Lobb and Kachanovski, 1999; De Alba *et al.*, 2004). Figure 1 illustrates the effect of tillage erosion on relief.

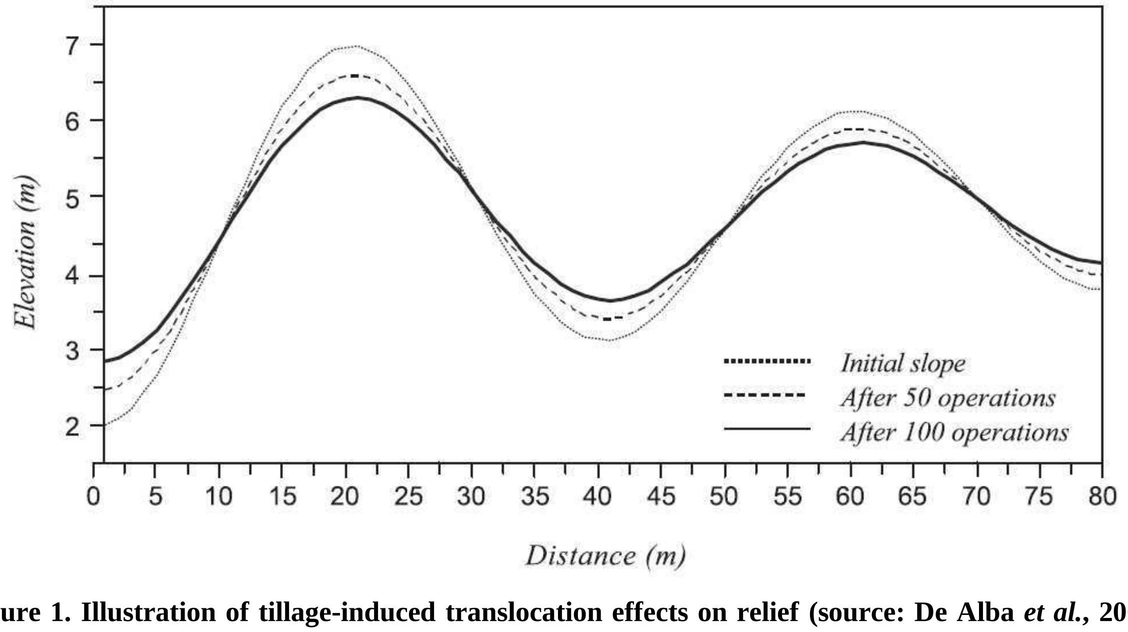

Figure 1. Illustration of tillage-induced translocation effects on relief (source: De Alba *et al.*, 2004).

To summarize, the different factors controlling locally water and tillage-induced processes of soil erosion-deposition in cultivated hillslopes are indicated in the following Table 1. Their respective effects on the different processes are detailed in the third column entitled “Effect”.

Table 1. Factors controlling water and tillage-induced processes of soil erosion-deposition in cultivated hillslopes, and their respective effects.

Processes		Factor	Effect
Water	Splash Effect	Rain erosivity	defines raindrop size, kinetic energy of raindrop impact and time length of rain event
		Aggregate stability	controls aggregate shear strength against raindrop and flow shear stresses
		Vegetation cover	intercepts raindrop and reduces kinetic energy of raindrop impact
		Slope	reduces kinetic energy of raindrop impact
	Interrill erosion	Microtopography (Roughness)	improves the temporary storage capacity of water, and hydraulic resistance
		Porosity	controls water infiltration in the soil
		Vegetation cover	improves porosity (stems provide preferential infiltration paths)
		Slope	increases flow shear stress
	Rill and gully erosion	Microtopography (Roughness)	improves the temporary storage capacity of water, and hydraulic resistance
		Vegetation cover	improves porosity (stems provide preferential infiltration paths)
		Planform curvature	convexities contribute to flow concentration
		Drainage area and slope length	control amount of runoff needed to concentrate water
		Slope	enhances runoff velocity
Tillage-induced		Implement geometry Tillage depth	influence volume of soil displaced
		Tillage speed	enhances tillage translocation
		Slope	controls intensity of gravity-induced movements of soil particles
		Curvature (profile and planform)	convexities enhance soil erosion / concavities enhance soil deposition

2.2. Soil erosion-deposition at landscape-scale

2.2.1. Concept of agricultural landscape

Spatial organisation of Earth surface, and inherently of agricultural areas, started to be studied and described thanks to the emergence of landscape ecology in the 1980’s. This science aims to quantify heterogeneity of landscapes and to investigate its causes and its consequences on ecological processes at different scales (Turner, 2005). Throughout the evolution of human needs and the emergence of landscape ecology, the term ‘landscape’ took another meaning. As observed by Longatti et Dalang (2007), the landscape as a “picture concept”, e.g. a visual and emotional experience tends to be perceived as “a physical location where biological processes take place”.

The determination of an area as a landscape is predominated by the asumption of a spatial heterogeneity (Turner *et al.*, 2001; Farina, 2006). According to Bolliger *et al.* (2007), spatial heterogeneity in landscape ecology is “usually referred to as landscape pattern or landscape structure”. This notion of heterogeneity, e.g. structuration or patterning, can be indirectly perceived in the different definitions of agricultural landscapes that can be found in litterature. For example, Meeus *et al.* (1990) defined them as areas where “management is manifest and the interaction of such factors as soil conditions, elevation, use, management and history are visible in the landscape and are expressed in its form and layout.” Bennet *et al.* (2006) define agricultural landscapes as “mosaics of different land-uses. Typically, land-uses such as cereal cropping, horticulture, tree plantations, or grazing pastures are interspersed with human settlements, roads, wetlands and streams”. The terms “management” and “land use” connote a notion of heterogeneity induced by human actions. Indeed, humans reorganise the natural land and improve its uses according to their needs, and it implies large recognized consequences on landscape spatial organisation (Antrop, 2005). So, concerning agricultural land, farmers became the principal managers of space (Poudevigne *et al.*, 1997; Gascuel-Odoux *et al.*, 2009) and allow the being of “agricultural landscapes” as physical areas.

In order to quantify landscape heterogeneity, structuration and patterning have been detailed by ecologists, creating a specific vocabulary and identifying a sort of landscape hierarchisation. The complexity of landscapes has induced the elaboration of discrete representations. Agricultural landscapes have been assimiled to “mosaics” or “patchworks” (Deffontaines *et al.*, 1995; Thomas, 2001; Bennet *et al.*, 2006), because what characterized the most the agricultural landscape patterning is the degree of fragmentation. We understand that a first order of fragmentation in agricultural landscapes is defined by the development of sites and settlements (villages, farms, factories...), and their linkage by linear infrastructures such as roads principally (Jaeger, 2000). This first order defines primary areas. These areas are themselves structured by the various agricultural systems (Baudry, 1993) - which determine land-uses (cereal-growing, farming, orchard...) - and the way in which these systems organise fields and farms in space (Deffontaines *et al.*, 1995). Then, agricultural systems determine a second order of fragmentation. This organisation can be summarized as the splitting up of primary areas with specifical landuses into smaller parts (secondary areas), e.g. plots, fields (Forman, 1995).

We retain from the above definitions that fragmentation of agricultural landscapes results from the determination of geometrical units (2D) limited and separated one by one by linear (1D) infrastructures. The geometrical units are fields, built up areas and wetlands. The linear infrastructures encompass actual field borders, which could be abstract (furrows) or material (as hedges, grass strips, roads, land tracks, stone walls). Material borders often provide other primary utilities than a simplistic delimitation of areas. Roads and land tracks are obviously used as communication networks between farms, fields, and settlments. Grass strips, hedges and stone walls can be part of soil conservation programms, used to stop soil fluxes along cultivated hillslopes. Grass strips and hedges improve water and biodiversity conservation, and are communication networks for local fauna. The properties, locations and spatial arrangment of these unidimensionnal and bidimensionnal components affect soil erosion all over the agricultural landscapes.

2.2.2. Consequences of spatial heterogeneity on soil erosion processes

Field defines the smaller geometrical unit of erodible land on agricultural landscapes. A field is characterized internally by its landuse, specific management (agricultural practices inherent to farmer’s management), and externally by its geometry and types of borders. All of these characteristics appear decisive considering the effects of both water and tillage processes and their interactions on soil translocation.

Landuse and management determine the degree of vegetal cover and its seasonal variability, depending on crop rotation, which are essential factors influencing soil protection against rainfall event erosivity (Morgan, 1995; Gomez *et al.*, 2009). In addition, vegetal cover improves soil structure, especially porosity, and consequently infiltration capacity. Agricultural practices, especially tillage, act on soil physical properties, such as porosity, roughness, structure, aggregate stability (Tebrügge and Düring, 1999; Pagliai *et al.*, 2004;

Strudley *et al.*, 2008), which affect greatly soil erodibility (Van Dijk *et al.*, 1996 a; Römkens *et al.*, 2001). Effects of tillage on soil erodibility are numerous, and present different time-scales of effectiveness (rainfall event scale, seasonal scale, long-term scale). For example, tillage improves immediately soil porosity and consequent infiltration capacity against next rainfall event erosivity, but long-term tillage decreases considerably aggregate stability in comparison to no-tillage management. Moreover, tillage induces surficial patterns which condition runoff variability all over the field (Souchère *et al.*, 1998; Takken *et al.*, 2001); especially linear features (wheel tracks, ridge-and-furrows...) especially favour the concentration of runoff water (Desmet et Govers, 1997; Vandekerckhove *et al.*, 1998). Finally, field management by the farmer determines the types of tillage implements and their annual frequency of use: these parameters affect directly the mean annual rate of tillage-induced erosion within a field (Van Oost *et al.*, 2006).

Linear infrastructures associated with landscape fragmentation (hedges, roads, furrows, grass strips...) play an important role on the spatial variability of erosion-deposition processes. Field borders indeed affect hydrological and sedimentological connectivities over hillslopes. Hydrological connectivity refers to the passage of water from one geometrical unit to another over the landscape, and is expected to cause runoff, whereas the sedimentological connectivity relates to the effective transport of particles through the landscape (Bracken and Crocke, 2007). Sedimentological connectivity refers originally to the transport of particles through water processes only. Here, we apply the concept of sedimentological connectivity also to tillage-induced translocation, as tillage is an effective vector of particles in cultivated landscapes. Besides, Hooke (2003) defines the concept of sedimentological connectivity as “the transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system”.

The effect of a linear infrastructure on hydrological and sedimentological connectivities depends on many parameters such as its nature, position, orientation on hillslopes, and the involved erosion-deposition process. Vegetated field borders (grass strips, hedges) tend to buffer soil water and trap sediments transported by runoff (Van Dijk *et al.*, 1996 b; Caubel *et al.*, 2003). Hence, vegetated borders inhibit flow concentration by reducing slope lenght (when oriented along contour-lines) and surface drainage areas, and acting as obstacles to runoff flows. On contrary, convex borders (for example furrows) act as anthropogenic drainage ways and favour flow concentration, and consequently sedimentological connectivity. Convex borders are especially efficient when oriented in the main slope direction. Compacted borders (roads, land tracks) have limited infiltration capacity which enhances runoff and hydrological connectivity (Wemple *et al.*, 1996; Forman and Alexander, 1998). In the case of tillage-induced process, all types of field borders act as lines of zero-flux, tillage extent being limited within the geometrical unit field (Guiresse and Revel, 1995; Dabney *et al.*, 1999; Van Oost *et al.*, 2000). Field geometry appears to dictate the orientation of tillage practices, tillage being predominantly carried out on field-lenght orientation. Tillage-induced deposition and erosion tend to occur, respectively, upslope and downslope field borders oriented in contour-line direction. Deposition could occur alongside field borders oriented closely in the main slope direction if tillage is carried out closely to contour-line direction in at least one adjacent field. This phenomenon is all the more marked when the main slope is relatively low: soil displacement by mechanical movements is then favoured compared to gravitationnal movements.

Agricultural landscapes are mosaics of numerous fields, each characterised by specific internal and external properties (landuse, management, borders and geometry). Table 2 summarizes the consequences of these characteristics of landscape heterogeneity on water and tillage-induced processes of soil erosion-deposition. The main factors controlling soil erosion-deposition processes (Table 1) are affected by landscape heterogeneity, especially by landuse and management. Tillage practices affect greatly the spatial variability of water erosion-deposition processes. Field geometry and borders appear to control hydrological and sedimentological connectivities. These results underline the strong influence of agricultural landscapes heterogeneity on erosion-deposition processes, and their respective rates and patterns. The degree of hydrological and sedimentological connectivities between the different fields are major parameters that will govern the apparition of some processes (as concentrated erosion) or some specifical erosion or deposition features (i.e. sort of soil erosion-deposition indicators). Consequently, the study of erosion-deposition in an agricultural context delivers different aspects of the processes involved when upscaling from an homogeneous plot, or field, to a landscape.

Table 2. Consequences of landscape heterogeneity (landuse and management; field geometry and borders) on water and tillage-induced processes of soil erosion-deposition.

Processes	Landuse and Management	Field geometry and borders
Water-induced	determines **vegetal cover** and its seasonal variability	vegetated borders buffer soil water and trap sediments
	tillage affects **roughness**, **porosity**, and **aggregate stability**	reduce **drainage area**, **slope length**
	tillage induces preferential ways of flowing (wheel tracks, furrows)	convergent borders (furrows) are preferential ways of flowing
	tillage deposition occurs on concave areas (reduces **planform curvature)**	compacted borders enhance runoff
	tillage fills rills	-
Tillage-induced	defines **tillage implements, depth** and **speed**	borders act as line of zero-flux
	defines annual frequencies of tillage	geometry determines tillage direction

3. Soil Erosion-Deposition Indicators (SEDI)

We propose to approach the assessment of erosion-deposition processes in agricultural hillslopes through the study of Soil Erosion-Deposition Indicators (SEDI) resulting from water and tillage-induced soil displacements. This approach does not require any experiments in the field, and can provide solutions for a rapid and efficient overview of erosion-deposition processes occuring in an area. The SEDIs are classified into four categories: topographical, pedological, biological and archaeological.

These SEDI will be presented through two different space-scales, the local and the landscape-scale. The differenciation between these two scales is based on their respective degree of heterogeneity (*cf.* *§* 2.2.1). The criteria chosen to characterise the degree of heterogeneity are topography, lithology and landuse which control greatly soil formation, erosion, and the way humans fragment the cultivated hillslopes. Referring to the principle of heterogeneity allows to highlight the importance of humans (especially farmers) as agricultural landscape managers and the inherent consequences on erosion-deposition processes (*cf.* *§* 2.2.2).

3.1. Definition and classification of the SEDI

Despite of a regular use of these terms in the worldwide literature (e.g.; Wallbrink and Murray, 1993; Hill and Schütt, 2000; Bòdnar and Hulshof, 2006; Okoba and sterk, 2006; Mathieu *et al.*, 2007), no accurate definition for erosion (or deposition) indicators exists to the best of our knowledge. According to the nature and uses of the various SEDIs identified in soil erosion studies, we qualified them as follows:

Soil Erosion-Deposition Indicators are physical or chemical characteristics of soil, or related components, the study of which enables to qualify and/or quantify soil erosion or deposition at different space and temporal scales.

SEDI are direct or indirect proofs of the action of one or several combined soil erosion or deposition processes. The being of a SEDI can be natural, i.e. the SEDI has always been observed on natural contexts, or human-induced, i.e. the SEDI appeared because of agricultural activities or other human actions. We identified various SEDIs. A simplistic classification was established to facilitate their presentation. The SEDIs have been classified into four types:

- The **Topographic SEDIs** correspond to remarkable soil surface features induced by soil material erosion or deposition. They exist at various levels, from the aggregate microtopography to hillslope morphology, depending on the nature of the soil erosion-deposition process(es) which created them.

- The **Pedological SEDIs** include the physical or chemical soil components which spatial variability and arrangement give evidence of soil modification by erosion or deposition processes.

- The **Biological SEDIs** define all the characteristics of vegetal cover being sufficiently affected by soil erosion or deposition to recognise and assess the soil redistribution.

- The **Archaeological SEDIs** refer to archaeological objects (artefacts, built foundations) which presence, state and/or spatial distribution testify of soil erosion or deposition since their introduction on the studied hillslope.

3.2. SEDI at local scale

Local scale defines here all areas observed in an agricultural context which do not present heterogeneity. The study area is then characterized by relatively uniform soil, substrate, topography and landuse. It presents an homogeneous landcover and no fragmentation by linear infrastructures. The dimensions of the area depend on its own pedological, morphological and lithological characteristics, and on their spatial variability. This area is not bigger than the smallest geometrical unit, i.e. a field. Local scale can then characterise all the spatial approaches carried out from the square-meter to the field scale, encompassing all the possible sizes of usual experimental erosion plots used in soil research.

The SEDIs observed at the local scale help particularly studying the effects of a specific landuse, landcover, and/or management on erosion-deposition processes in cultivated areas. The SEDIs presented in Table 3 are indeed predominantly present in natural erosive contexts although we study soil translocation in agricultural hillslopes entirely managed by humans. Many of the SEDIs at local scale can testify from impacts of agricultural practices on soil erosion.

Table 3. Soil Erosion-Deposition Indicators (SEDI) at local-scale.

Class of SEDI		SEDI	Natural (N) or Human-Induced (HI)	Erosion (E) or Deposition (D)	Processes	Possible quantification	References
Topographic		Eroded aggregates	N	E	Splash, desaggregation	No	Le Bissonnais *et al.*, 1989; Gollany *et al.*, 1991; Bergsma, 2001
		Sheetwash features	N	E	Sheet	No	Govers and Poesen, 1988; Bryan, 2000; Chaplot and Le Bissonnais, 2003
		Splash pedestal	N	E	Splash	No	Poesen *et al.*, 1994; Clegg *et al.*, 1999
Pedological	Physical	Sedimentary crust	N	D	Sheet, Splash	No	Bresson and Boiffin, 1990; Le Bissonnais, 1990; Valentin and Bresson, 1992; Shainberg and Levy, 1996
	Chemical	Radionuclides (vertical distribution)	N & HI	E & D	Tillage, Water	Yes	Walling and Quine, 1992; Wallbrink and Murray, 1993; Matisoff *et al.*, 2002; Porto *et al.*, 2003; Huh and Su, 2004; Smith and Dragovich, 2008
Biological		Roots/plants exposure and burying	N & HI	E & D	Sheet, Splash	Yes	Bodoque *et al.*, 2005; Gärtner, 2007; Brenot *et al.*, 2008; Casalí *et al.*, 2009
Archaeological		Buried artefacts/built foundations	HI	D	Tillage, Water	Yes	Brown *et al.*, 2003; Lang *et al.*, 2003; Ambers *et al.*, 2006

We observe that local scale SEDIs stem largely from non-concentrated water processes (Table 3). Concentrated water and tillage processes appear to produce little remarkable evidence at the local scale. The concentration of runoff flow requires a sufficient drainage area and a natural or human-induced preferential way of flowing. The SEDI created by concentrated flows cause huge changes on soils properties and topography. Then, the consecutive linear features tend to rise spatial heterogeneity. Regarding the tillage-induced erosion, many comments can be made. Any tillage operation leads to soil tilled-depth displacement (*cf. §* 2.1.2). The topography of a tilled area, which does not present spatial heterogeneity, would be then considered automatically as a SEDI at the local-scale. Moreover, tillage-induced translocation is far more important than splash or sheetflow translocations, and the application of tillage is nearly systematic in cultivated areas. The treatments differ from one field to another depending on the landuse and on specific managements. Tillage homogeneizes soil surface conditions (aggregation, roughness...) within a field. But at the local scale, we are not able to visualize a net soil loss or gain after tillage passage: this assessement would require field-experiments with the monitoring of artificial tracers displacement as described in Lindström *et al.* (1990) or Lobb *et al.* (1999).

3.2.1. SEDIs at the local scale: proofs of non-concentrated water erosion

At the local scale, the topographic and physical pedological SEDIs (Table 3) appear to be exclusively related to non-concentrated water erosion processes. The transport of particles caused by non-concentrated water is predominantly implied by raindrop impact energy: the two processes involved being splash effect and sheetwash erosion (*cf. §* 2.1.1). The size of a raindrop is millimetric, the transport of particles by splash is centimetric, and sheetwash is a more or less uniform thin water layer running on a high variable soil surface. The observation of splash effect and sheetwash erosion indicators in field is then necessarily carried out at small space-scale due to their “readibility”: it occurs obseving centimetric to metric transects or plots, considering surface microtopography and/or vertical cross-sections (Bresson et Boiffin, 1990; Gollany *et al.*, 1991; Clegg *et al.*, 1999). The three topographical SEDIs (*eroding aggregates*, *sheetwash* and *splash pedestal*) are only related to soil loss, whereas the pedological one (*sedimentary crust*) is related to consecutive deposition, and reorganisation, of soil particles by non-concentrated water erosion processes.

The two topographical SEDIs called *eroding aggregates* and *splash pedestal* are directly induced by the raindrop impact on the soil surface (Le Bissonnais *et al.*, 1989; Poesen *et al.*, 1994). Their respective morphologies are largely controlled by the original suface conditions, and the frequencies and intensities of raindrop impacts on soils. In the case of *eroding aggregate*s the morphology of aggregates results from the effect of spatial random impacts of raindrop on aggregates. Progressively, the detachment and transport of particles by splash effect and desaggregation lead to the elaboration of aggregates with predominantly convex form and rough surface (Bergsma, 2001). They are predominantly observable above the flow surface during events. In the case of *splash pedestal* the crater morphology observed on soil surface is due to repeated impacts of raindrops under a suffisant high vegetal cover, e.g. tree canopies or cereals (Poesen *et al.*, 1994; Clegg *et al.*, 1999). This repetition is implied by the presence of a leaf which intercepts several raindrops that are canalized and guided by the leaf morphology until they fall on the soil surface. These craters are often deeper than craters that could be observed on bare soil without such a vegetative cover.

Sheetwash refers to the flowing of non-concentrated water and the induced transport of fine particles on the soil surface (Govers and Poesen, 1988; Bryan, 2000). *Sheetwash* as topographic SEDI refers then to smoothed microreliefs: they are long and narrow flow paths as well as wider sheet flow surfaces (Fig. 2; Chaplot et Le Bissonnais, 2003; Okoba et Sterk, 2006). The sizes of *sheetwash* depend on pre-event microtopography and on the various obstacles that have been encountered. They are often paired with parallel flow marks of lag sediment (Bergsma, 2001). Contrarily to "s*heetwash*" that is mainly an erosive SEDI, the *sedimentary crust* witnesses the deposit of fine particles transported by splash and sheet erosions (Le Bissonnais, 1990; Shainberg et Levy, 1996). A *"sedimentary crust"* is a thin layer on the soil surface which sealed it after the deposition and sorting of soil particles and fragments under water excess conditions (Bresson et Boiffin, 1990; Valentin and Bresson, 1992).

All of these topographic and physical pedological SEDI give evidence of the importance of raindrop effect on aggregate breakdown and the changing on soil surface structure, roughness, which are of strong importance concerning soil infiltrability and erodibility. Unfortunately, a quantification of soil erosion-deposition by splash and non-concentrated runoff through their study appear difficult without any temporal recording, e.g. experimentation in field.

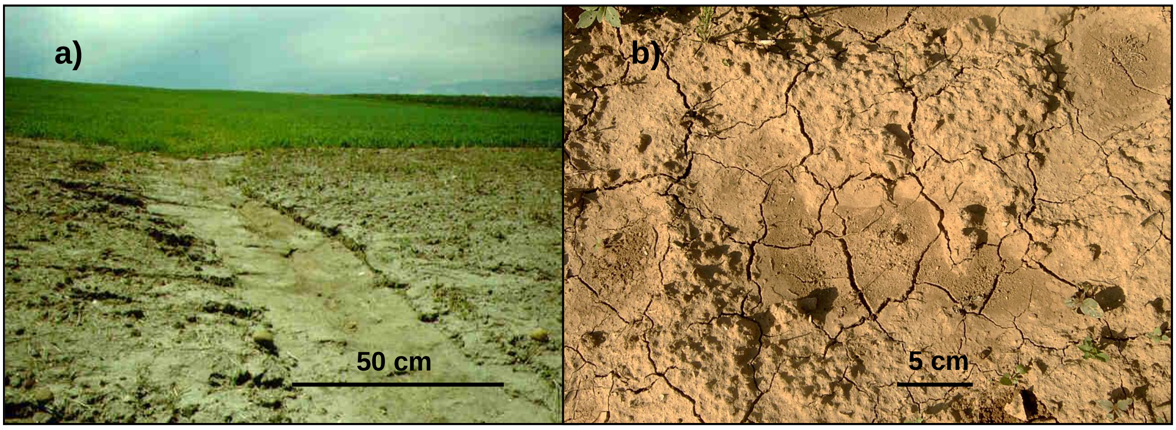

Figure 2. Illustration of the toopgraphic SEDI (a) “sheetwash” and (b) “”sedimentary crust”.

3.2.2. Advantages of radionuclides as tools for soil erosion-deposition study

Several *radionuclides* (^{7}Be; ^{137}Cs; ^{210}Pb; $^{239+240}$Pu) have been regularly used for the study of soil erosion-deposition since the 1960’s, especially ^{137}Cs (Rogowski and Tamura, 1965; Walling and Quine, 1992). Their uses have been extensively described and detailed in many publications as related to key assumptions, potential limitations and uncertainties that must be quoted in any application (Ritchie and McHenry, 1990; Walling and Quine, 1991; Blake *et al.*, 1999; Zapata, 2003; Huh and Su, 2004). At the locale scale, their inventories and vertical distribution are studied.

The main quality of these different *radionuclides* is to be strongly linked to soil particles, especially clays and organic matter (Tamura, 1964; Robbins, 1978; Olsen *et al.*, 1986). The detection of erosion or deposition through the study of a radionuclide activity is based on two major points:

- the knowledge of sources and inputs of the fallout radionuclide of interest (dates, frequencies, quantities). Fallouts mainly occured through rainfalls, and therefore are not spatially homogeneous.
- the assumption that measured radionuclide activities at undisturbed locations (no subject to erosion or deposition) called “references”, and located near the study area, are representative of the cumulative effect of each radionuclide input into soil.

Then, when a radionuclide activity measured at a location on study area (total inventory per unit area, usually Bq.m^{-2}) is compared to its related mean activity measured at the “references”, the difference observed between them reflects the total erosion or deposition that could have occurred at this point. If the activity measured in the field is higher than the "reference" activity, then soil material deposition occured at the study location since radionuclide fallout. Conversely, if the activitiy measured in field is lower than the "reference" activity, then soil material erosion occured at the study location since radionuclide fallout.

The use of *radionuclides* as a SEDI is particularly useful. Sampling of "references" and study location is carried out by drilling, and can be done in one day. The size of increments sampled along each profile can be adapted to more or less detailed vertical distribution of radionuclide through its specific activity ($Bq.kg^{-1}$). Sample preparation before activity measurement consists in drying a sample, sieving it to eliminate coarse particles, grinding it to a fine powder and weighting it. Finally, radioactivity counting is carried out thanks to spectrometry techniques (alpha or gamma) for each sample (Muramatsu *et al.*, 2000; Huh and Su, 2004).

Figure 3 illustrates the principle of radionuclide use as a SEDI through the vertical distribution of ^{137}Cs at "reference", erosion and deposition locations, extracted from a study carried out in Italy by Porto *et al.* (2003). The "reference" profile sampled in permanent grassland shows ^{137}Cs well mixed in the 15 to 20 first centimeters, and then radionuclide specific activity declines with depth. This vertical distribution suggests that "reference" area have been tilled at least once since radionuclide fallout: this illustrates the difficulty to find a location in cultivated areas where no erosion-deposition processes occured. The profile submitted to soil erosion (Fig. 2b) had a total activity (Cs_{tot} = 783.3 $Bq.m^{-2}$) lower than the "reference" activity ($Cs_{réf}$ = 2033 $Bq.m^{-2}$), and ^{137}Cs mixed only in the 20 first centimeters of the tilled layer suggesting soil depletion. The profile submitted to soil deposition (Fig. 3c) had a total activity (Cs_{tot} = 3918 $Bq.m^{-2}$) higher than the "reference" activity, and the vertical distribution of ^{137}Cs reflects the soil thickening related to progressive soil material deposition at this location.

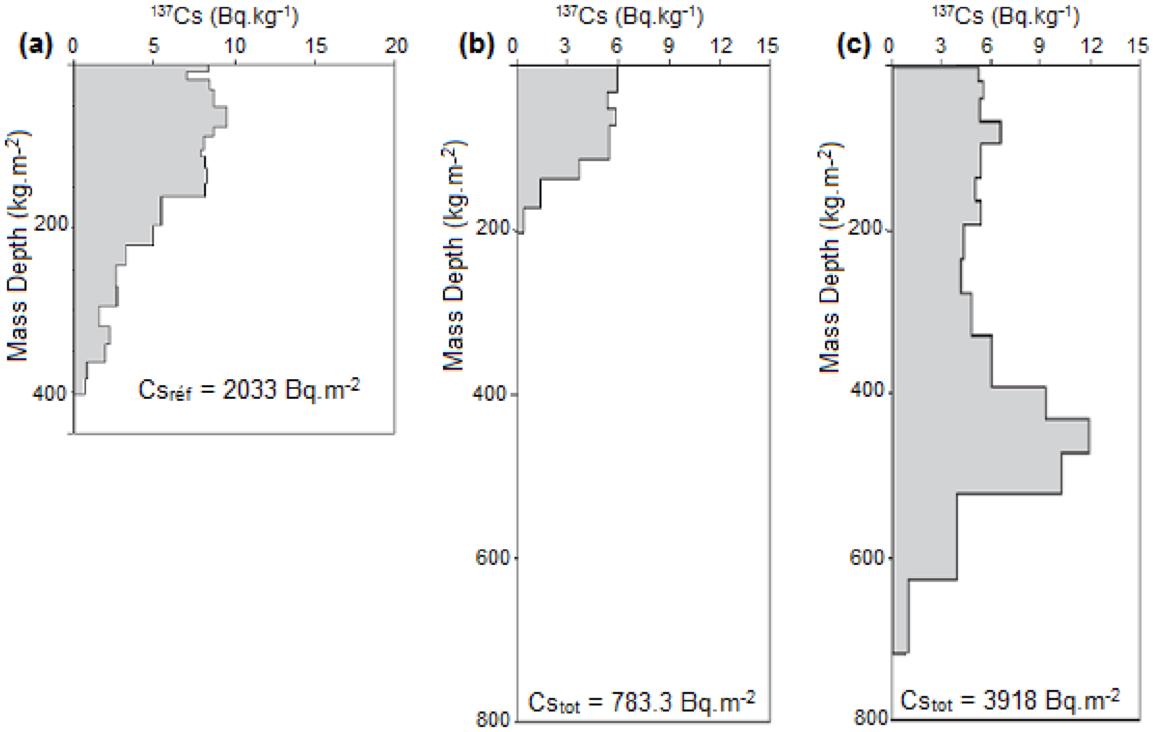

Figure 3. ^{137}Cs mass depth/vertical distribution associated with (a) a "reference" profile, (b) a profile submitted to erosion, and (c) a profile submitted to deposition (after Porto *et al.*, 2003).

The differences observed between inventories measured at "references" and study locations can be used to punctually assess mean erosion-deposition rates (t.ha^{-1}.yr^{-1} or mm.yr^{-1}) since radionuclide fallout. Several methods have been developped to convert radionuclide inventories into erosion-deposition rates, the more simplistic being the proportionnal method (De Jong *et al.*, 1983; Vanden Berghe et Gulinck, 1987; Walling and Quine, 1990). Unfortunately, a spatial modelling approach appears necessary to distinguish erosion from deposition processes which contributed to the mean rates at a study location.

Table 4 presents some basic information about main radionuclides used in soil erosion-deposition studies, i.e ^{7}Be, ^{137}Cs, ^{210}Pb and $^{239+240}$Pu.

Table 4. Main fallout radionuclides used as Soil Erosion-Deposition Indicators

Radionuclide	Natural (N) or Human-Induced (HI)	Type of fallout	Half-life	References
Be-7	N	Continuous	53 d.	Wallbrink and Murray, 1993; Blake *et al.*, 1999; Zapata, 2003
Cs-137	HI	Nuclear weapon test: mid 1950's to mid 1970's / Chernobyl accident: 1986	30.2 y.	Rogowski and Tamura, 1965; Ritchie and McHenry, 1990; Walling and Quine; 1992
Pb-210	N	Continuous	22.3 y.	He and Walling, 1996; Walling and He, 1999; Zapata, 2003
Pu-239+240	HI	Nuclear weapon test: mid 1950's to mid 1970's / (Chernobyl accident: 1986)	Pu-239: 24110 y. Pu-240: 6564 y.	Muramatsu *et al.*, 2000; Schimmack *et al.*, 2002

*d.: days; y.: years

Among the main *radionuclides* used as SEDIs some are produced naturally (^{7}Be, ^{210}Pb) whereas others are induced by specific human activies (^{137}Cs, $^{239+240}$Pu). ^{7}Be is produced by the bombardment of the atmosphere by cosmic rays which induce the spallation of nitrogen and oxygen atoms in the troposphere and stratosphere. ^{7}Be is then extremely short-lived (half-life of approx. 53 days) relative to the other radionuclides described here, ^{137}Cs, ^{210}Pb and $^{239+240}$Pu. ^{210}Pb is produced by the ^{238}U decay series, and has a half-life of 22.3 years. ^{210}Pb is derived from the decay of gaseous ^{222}Rn, which is the daughter of ^{226}Ra occuring naturally in soils and rocks. Then, its decay generates ^{210}Pb that appears to be in equilibrium with its parent. A small quantity of this ^{210}Pb is introduced into the atmosphere, and subsequent fallout induces then an input that is not in equilibrium with its parent ^{226}Ra (Robbins, 1978): this component is called “unsupported” or “excess” ^{210}Pb. The amount of unsupported ^{210}Pb in a sample is calculated by measuring both ^{210}Pb and ^{226}Ra and subtracting the supported activity. ^{7}Be and ^{210}Pb are continuously released all over the globe.

The human-induced *radionuclides* (^{137}Cs, $^{239+240}$Pu) were both produced by nuclear fission and released into the atmosphere through aerial nuclear weapons tests (1950’s to 1970’s) and/or through the Tchernobyl accident (1986). ^{137}Cs, ^{239}Pu and ^{240}Pu have a half-life time of 30.2 years, 24110 years and 6564 years, respectively. In comparison to ^{7}Be and ^{210}Pb, these releases were punctual and predominantly focused on the Northern Hemisphere.

Because of various half-lives, delivery rates, delivery histories, and land use, these radionuclides are distributed differently in the soil for a given location (Wallbrink and Murray, 1993). Figure 4 extracted from Mathisoff *et al.* (2002) depicts these phenomenons for

^{137}Cs, ^{7}Be and ^{210}Pb, $^{239+240}$Pu behaviour in the soil is relatively similar to ^{137}Cs. ^{7}Be has the shorter life-time, is continuously released, and falls frequently on soil surface through rainfalls: it is therefore mainly concentrated in the first 10 mm of soil depth (Wallbrink and Murray, 1993; Zapata, 2003). ^{7}Be has been mainly used to study interrill erosion. ^{210}Pb has a longer life-time than ^{7}Be (22.3 years and 53 days respectively): excess ^{210}Pb is mainly concentrated in the first 10 to 30 mm soil depth (He and Walling, 1996; Zapata, 2003). ^{137}Cs and $^{239+240}$Pu have medium and long life-time respectively and have been released momentarily. Their concentration in undisturbed soils often presents a peak, and is more or less mixed homogeniously in the soil thanks to the effect of bioturbation since their fallout. As illustrated in Figure 3, tillage tends to homogenize the distribution of most longer half-life time radionuclides in the tilled layer. The common study of these different *radionuclides* can help distinguish erosion processes, sediment sources, or detail historic soil erosion in cultivated hillslopes.

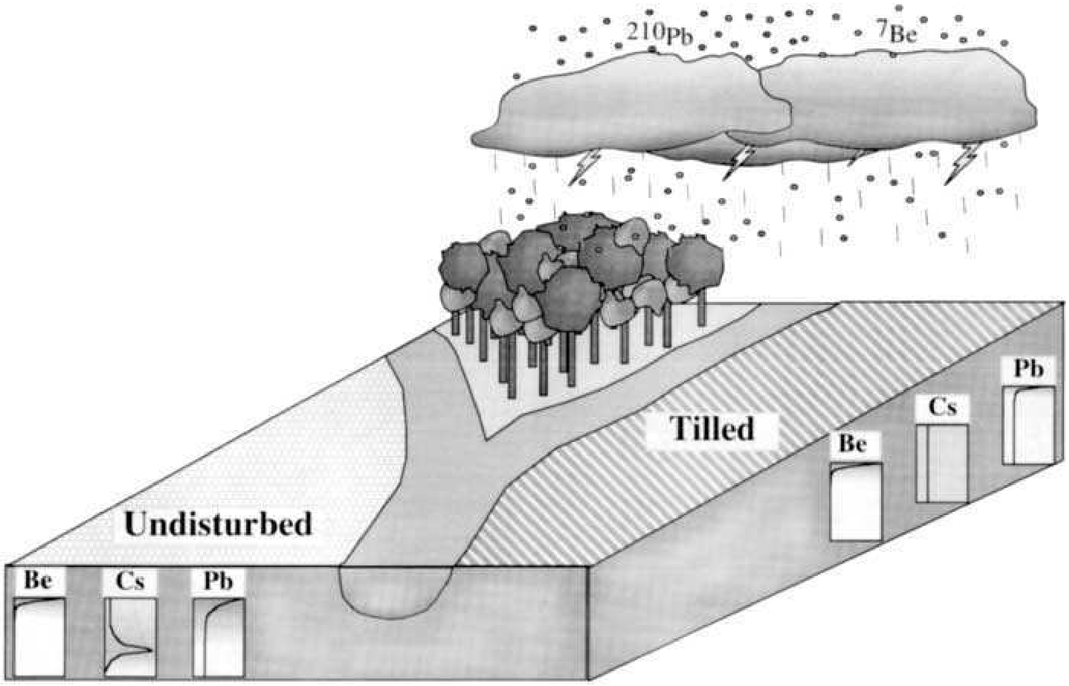

Figure 4. Illustration of 7Be, 210Pb, and 137Cs vertical distributions in soils under different soil managements (after Mathisoff *et al.*, 2002). Shading and sketches indicate radionuclide activity with depth in the 10- to 30-cm-deep soil profiles.

3.2.3. Biological and archaeological SEDIs: consequences of human activities

Both biological and archaeological SEDIs are undirect proofs of soil erosion and/or deposition processes, intentionally or unintentionally created by humans through their different historical uses of hillslopes presently cultivated.

Biological SEDIs define all the *roots/plants* which state of exposure or burying can be considered as a passive marker of soil erosion or deposition, respectively, since the date of plantation. The principle of erosion-deposition measurement is relatively similar in dendrogeomorphology and vineyard erosion studies. In dendrogeomorphology, the root axis is considered as the relative former position of soil layer, i.e. when tree was planted. The difference measured between the actual elevation of soil surface and the elevation of root axis at the tree location is then related to the age of the root defined by dendrochronology to quantify the amount of soil erosion over time (Bodoque, *et al.*, 2005; Gärtner, 2007). This technique is mainly used in erosive contexts. In case of grafted vine plants, the limit between underground roots and aerial scion is sharply distinguishable by a callus developped around the fused stems. This callus is defined as the marker of former soil surface position (Grenot *et al.*, 2008, Casalí *et al.*, 2009). Figure 5 extracted from Casalí *et al.* (2009) illustrates the principle of the use of graft vine plants as SEDIs. These techniques are used in vineyards and orchards, where tillage is not practised, biological SEDIs are used specifically for the quantification of interrill processes. Trees and vineyards can be used as markers of medium to long-term soil erosion or deposition. The use of crops as markers is also possible for a short-term assessment of soil erosion-depostion by non-concentrated water (Stocking and Murnaghan, 2001).

Archaeological SEDIs (*artefacts or built foundations*) can be used as markers of local soil deposition. Indeed, *built foundations* (e.g. walls) are obstacle to soil material flux and can be progressively buried. *Artefacts* can be displaced by tillage-induced and concentrated water erosion processes, or simply washed by non-concentrated erosion proceses, but can easily be buried by soil deposition. Buried *artefacts* and *built foundations* are then markers of ancient soil surface position, and help through their datation to constraint local deposition rates (Brown *et al.*, 2003; Lang *et al.*, 2003; Ambers *et al.*, 2006). Whereas *artefacts* are often accidentally found during soil prospections (trenches), *built foundations* can be located by geophysical approaches such as ARP (Automated Resistivity Profiling), electromagnetic, magnetic and GPR methods (Tabbagh, 1992; Piro *et al.*, 2000).

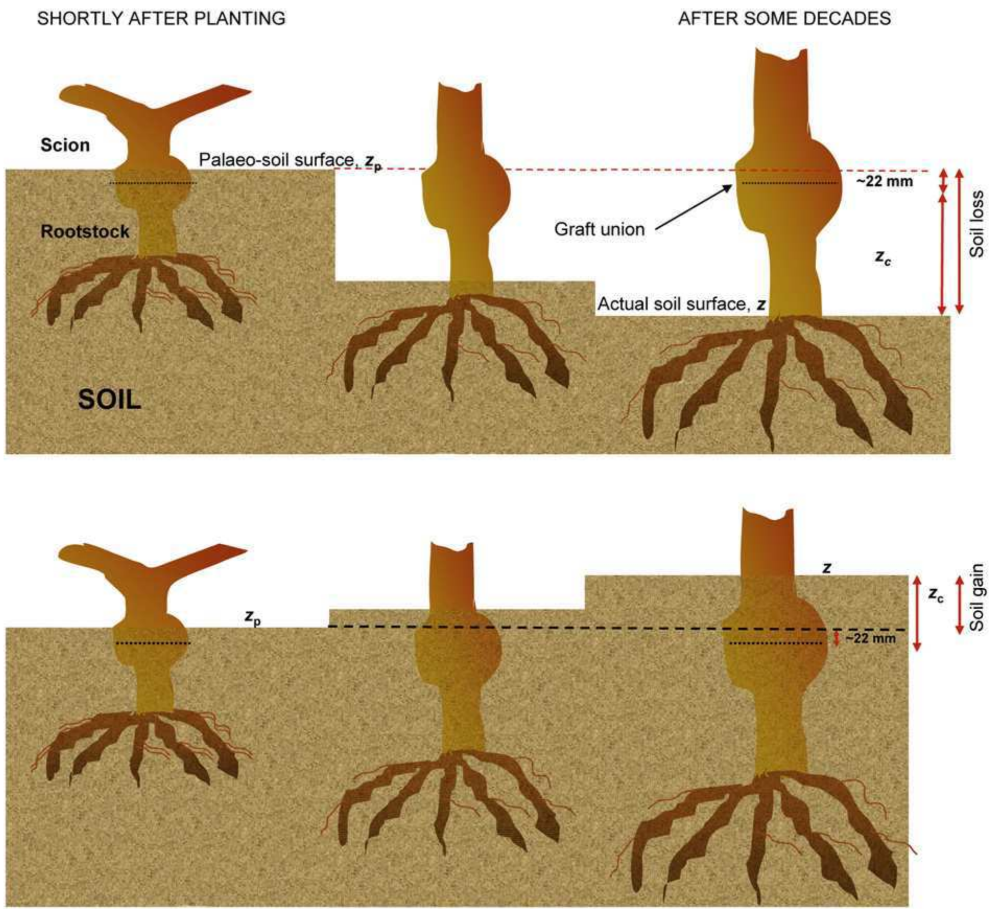

Figure 5. Illustration of the use of the grafting callus formed in a vine plant as SEDI, i.e. a palaeo-surface marker after the soil top layer has been eroded/deposited by erosion/deposition (after Casalí *et al.*, 2009)

3.3. SEDI at landscape scale

The term landscape can be applied to an area where heterogenity is present, i.e. structuration, patterning (*cf.* § 2.2.1). We would call landscape-scale all dimensions of an agricultural area which present necessarily different landuses (various fields and linear infrastructures) and a certain degree of spatial variability on topography, and optionnally differences in terms of lithology and soil types. So, landscape-scale can designate all study site composed of several fields as an hillslope or an agricultural watershed.

Landscape-scale exhibits SEDIs which give us informations about effects of landscape fragmentation and inherent changes on hydrological and sedimentological connectivities, on spatial variability of soil erosion and deposition (Table 5). Appearance and spatial occurrence of many SEDIs presented here are indeed largely dependent on the rate of fragmentation of agricultural landscapes, i.e. on the density and spatial repartition of linear infrastructures. Moreover, some of these SEDIs exist only in agricultural contexts induced by fragmentation (*lynchet*) or specific management (*angular rock fragment, crop yield*). SEDIs related to tillage-induced processes are more detectable at landscape-scale than at local-scale. Contrarily to water processes, tillage-induced processes spark rarely off their own SEDIs (expect *rock fragment cover*). The study of the spatial distribution of some SEDIs allows tracking soil translocation over landscapes.

Table 5. Soil Erosion-Deposition Indicators (SEDI) at landscape-scale.

Class of SEDI		SEDI	Natural (N) or Human-Induced (HI)	Erosion (E) or Deposition (D)	Processes	Possible quantification	References
Topographic		Rill	N	E	Concentrated water	Yes	Nearing *et al.*, 1997; Polyakov and Nearing, 2003; Wirtz *et al.*, 2011
		Gully	N	E	Concentrated water	Yes	Poesen *et al.*, 1996; Vandaele *et al.*, 1996; Casalí *et al.*, 2000; Martinez-Casanovas, 2003; Poesen *et al.*, 2003
		Lynchet	HI	D	Tillage, Water	Yes	Bolline, 1971; Papendick and Miller, 1977; Salvador-Blanes, 2006
		Sediment fan	N	D	Concentrated water	Yes	Boardman and Robinson, 1985; Evans, 1995; Øygarden, 2003
Pedological	Physical	Horizon morphology	N	E & D	Tillage, Water	No	Bolline, 1971; Nachtergaele and Poesen, 2002; Rommens *et al.*, 2007; Förster and Wunderlich, 2009; Reiß *et al.*, 2009
		Angular rock fragment	HI	E	Tillage	No	Poesen *et al.*, 1997; Poesen *et al.*, 1998; Van Wesemael *et al.*, 2000; Nyssen *et al.*, 2002
		Stoniness	N	E	Sheet	No	Favis-Mortlock *et al.*, 1991; Boardman, 2003; Navas *et al.*, 2005
		Magnetic susceptibility	N & HI	E & D	Tillage, Water	No	Thompson and Olfield, 1986 ; Dearing, 1994; Royall, 2001
		Soil colour/reflectance	N	E & D	Tillage, Water	No	De Jong, 1992; Mathieu *et al.*, 1998; Hill and Schütt, 2000; Stavi and Lal, 2011
	Chemical	Stable elements	N & HI	E & D	Tillage, Water	Yes	McGrath and Lane, 1989; Sibbesen *et al.*, 2000; Van der Perk *et al.*, 2004; Salvador-Blanes *et al.*, 2006; Rusjan *et al.*, 2007; De Gryze *et al.*, 2008; Fernández-Calviño et al, 2008;
		Radionuclides	N & HI	E & D	Tillage, Water	Yes	Walling and Quine, 1992; Blake *et al.*, 1999; Walling et He, 1999; Schimmack *et al.*, 2002; Van Oost *et al.*, 2005; Mabit *et al.*, 2009
Biological		Crop yield	HI	E & D	Tillage, Water	No	Jones *et al.*, 1989; Mokma and Sietz, 1992; Pierce et Lal., 1994; Papiernik *et al.*, 2009
Archaeological		Artefact cover	HI	E & D	Concentrated water, Tillage	Yes	Roper, D.C., 1976; Quine and Walling, 1992; Brown *et al.*, 2003

3.3.1. Linear infrastructures and consequences on occurence of topographical SEDIs

SEDIs specific to processes of concentrated-water erosion, e.g. rill and gully erosion (*cf.* § 2.1.1.2), are included in SEDIs usable at landscape-scale (Table 5). SEDIs related to concentrated processes are *rill*, *gully* and *sediment fans*: the two first are related to linear soil depletion features, the last to soil deposition which occurs at downslope extremities of the two first (Fig. 6). Concentrated-water processes are largely controlled by natural ways of water flowing (concave landforms predominantly oriented on slope direction) and parameters as slope gradient and slope-length. As mentionned in § 2.2.2, the presence of vegetated field limits (grass strips, hedges) over cultivated hillslopes buffers water flows, reduces slope-lenght, drainage area and the potential of concentration. Hence, the higher the degree of fragmentation, the less rill and gully erosion processes and consequent topographical SEDIs appear. However, the presence of linear features within a field such as tillage furrows can constitute artificial ways of potential water concentration.

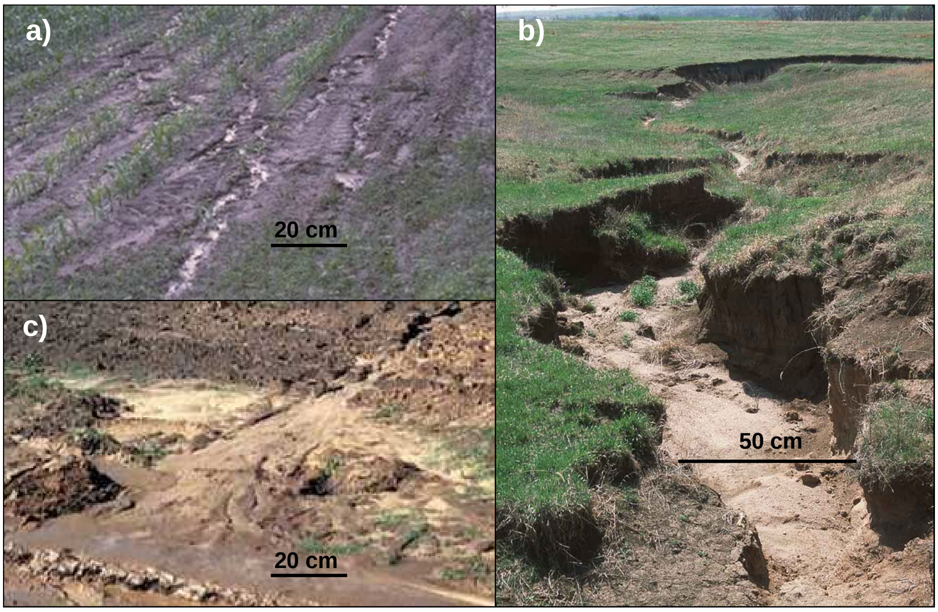

Figure 6. Illustration of the topographic SEDIs (a) rill, (b) gully, and (c) sediment fan.

Unlike the topographical SEDIs mentionned above and exclusively related to water erosion-deposition processes (Table 7), a *lynchet* is induced by the presence of a linear feature, whatever its nature, combined with water and/or tillage erosion processes. Lynchets are also known as terraces, soil banks or fence lines. They are locally called “rideaux” in northern France and Belgium. The field borders associated to *lynchet* formation are closely oriented perpendicularly to the main slope. A lynchet is predominantly shaped by the progressive accumulation of soil material by water and/or tillage translocation upslope of a field border (Bollinne, 1971; Papendick and Miller, 1977; Van Dijk *et al.*, 2005; Follain *et al.*, 2007). This phenomenon leads to the creation of a gentler slope than in the upslope field area and an associated break-in-slope below the field border (Fig. 7). Depending on the slope gradient upslope and the degree of development of the lynchet, the break-in-slope can range from several decimetres to a few meters high (Papendick and Miller, 1977; Salvador-Blanes *et al.*, 2006). Moreover, the benching effect tends to be amplified by erosion downslope of the break-in-slope (Van Oost *et al.*, 2000; Follain *et al.*, 2007). Although lynchets are of decametric width, they may store an important proportion of soil material on cultivated hillslopes because of their frequent occurrence (Macaire *et al.*, 2002). The higher the rate of landscape fragmentation is; the higher the potential presence of *lynchets* will be. *Lynchets* provide a perfect example of an anthropogenic landform resulting from agricultural practices.

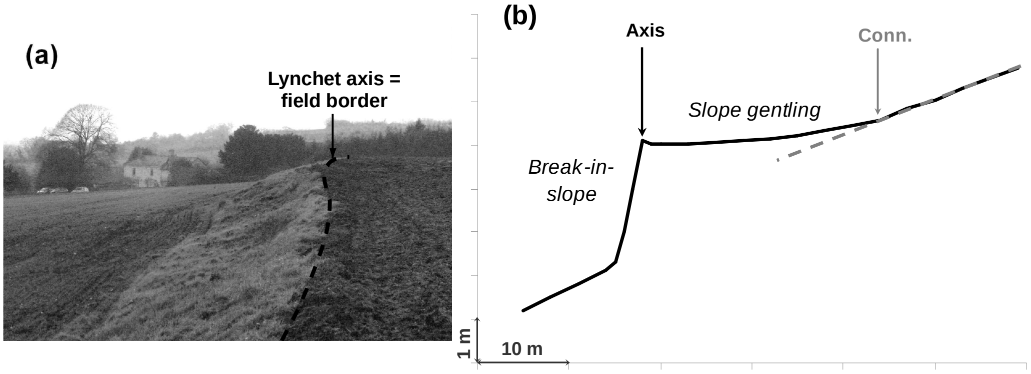

Figure 7. Topographical characteristics of a lynchet (SEDI): (a) view and (b) topographic cross-section of a lynchet (“conn.”: connection to upslope field area).

The nature and intensity of upslope erosion processes providing soil material to be accumulated along downslope field border, and then progressively forming a *lynchet*, depend on landuse, management, fragmentation, and nature of the linear infrastructures, of upslope area. The nature and intensity of accumulation processes along the downslope border would depend on the nature of the border, the landuse of the field, and intensity and nature of upslope erosion processes. Soil deposition through water runoff decreasing occurs upslope vegetated barriers (such as grass strips and hedges) which buffer water and reduce hydrological and sedimentological connectivities (*cf.* *§* 2.2.2). If the landuse and management of the field require tillage practices, soil deposition induced by tillage would happen at downslope field part whatever the nature of the border.

The advantages in the study of topographical SEDI at landscape-scale is that their morphological characteristics allow a quantification of soil material eroded (*rill, gully*) and deposited (*lynchet, sediment fan*). For this purpose, direct measurements in the field, DEM analyses, or photogrammetry, of these SEDI has successfully been applied, especially in rill and gully studies (Thomas *et al.*, 1986; Vandaele et Poesen, 1995; Casalí *et al.*, 1999; Poesen *et al.*, 2003).

3.3.2. SEDI at landscape-scale: a best visibility of tillage-induced processes

Landscape-scale appears more appropriate for the observation of the impact of tillage-induced processes. Firstly, a landscape-scale approach implies a higher spatial variability on topography: slope gradient is the most important characteristic which controls tillage erosion rate and its spatial variability, and consecutively its distinction (*cf.* *§* 2.1.2.2). Secondly, tillage erosion is a within-field phenomenon: each field border is acting as line of zero-flux, and thus the variability of tillage-induced soil erosion is strongly linked to landscape fragmentation. The *lynchet* - a SEDI induced by fragmentation - is one of the first SEDIs which allowed identifying tillage practice as an efficient vector of soil erosion-deposition (Mech and Free, 1942; Papendick et Miller, 1977). Unfortunately, all of the SEDIs likely to be used at the landscape scale and related to tillage-induced processes witness also for water processses, except *angular rock fragments*. They reflect the total soil erosion or deposition without process distinction, except in case one of them dominates largely soil displacement over a study area. But water and tillage-induced processes act differently in space because of different controlling factors and different responses to topographical changes (*cf.* *§* 2.1 and 2.2.2). Therefore, the study of location and spatial variation of these SEDIs has potential to distinguish dominant processes.

Topographical SEDIs treated previously are remarkable soil surface features induced by soil material erosion or deposition. The relative truncation (erosion) or thickening (deposition) of upper organo-mineral horizons is strongly expressed through the inherent morphology of the topographical SEDI (Bollinne, 1971; Nachtergaele and Poesen, 2002). But erosion or deposition processes do not necessarily create new soil surface morphologies characteristic of the process themselves. For example, rill or gully filling, or a footslope lynchet, are not necessarily distinguishable through topography without experimentation, i.e. multi-temporal study of elevation changes. The study of soil *horizon morphology* evolution, and consequently soil thickness, along trenches or through the construction of soilscape models appears useful for characterising erosion or deposition in the landscape (Rommens *et al.*, 2007; Förster and Wunderlich, 2009; Reiß *et al.*, 2009).

The SEDI *Angular rock fragments* defines soil cover and content of angular, pluri-centimetric to decimetric fragments of bedrock induced by tillage erosion (Poesen *et al.*, 1997; Fig. 8). *Angular rock fragments* tend to be more present on shallow soils predominantly eroded by tillage. When tillage implement depth is higher than depth of upper bedrock limit, rock fragments are regularly extracted by the implement and mixed in the tilled layer. *Angular rock fragments* are reflected through shallow and stony soils on topographic convexities, potentially in upslope-field parts (Poesen *et al.*, 1998; Van Wesemael *et al.*, 2000). This SEDI has been mainly studied on Mediterranean regions. The SEDI *Angular rock fragments* should not be confused with the SEDI *stoniness* which is related to sheet erosion. *Stoniness* corresponds to a small loose stones cover, concentrated after fine particles removal by runoff (Favis-Mortlock *et al.*, 1991; Boardman, 2003; Navas *et al.*, 2005; Fig. 8b). *Stoniness* would be visible on stony hillslopes, at topographical locations affected by sheet erosion, preferentially on steep slopes.

Figure 8. Illustration of the pedological SEDI "Rock fragment cover" in a tilled field.

Soil erosion-deposition processes in agricultural landscapes involve predominantly the translocation of particles located in upper soil horizons, i.e. organo-mineral horizons. The depletion or accumulation of this rich part of soil has consequences on soil quality and properties. Among these several consequences, some confers SEDI such as ever evoqued *stoniness*, *rock fragment cover* or *horizons morphology*. *Soil colour/reflectance* and the biological SEDI *crop yield* are directly linked to the quality and constitution of upper soil horizons. *Soil colour* or *reflectance* of shallow eroded soils are close from those of the bedrock, whereas they appear more organic (browny) on areas where deposition occured (De Jong, 1992; Mathieu *et al.*, 1998; Hill and Schütt, 2000; Stavi and Lal, 2011). Figure 9 presents an aerial view of a cultivated area where water erosion-deposition processes dominate. The lightened areas which correspond to eroded shallow soils present different characteristics of spatial variability inherited from the processes involved. *Crop yield* depends on soil quality, fertility. Its spatial variability can give information about the locations of areas mainly subject to erosion, and areas mainly subject to deposition (Jones *et al.*, 1989; Mokma and Sietz, 1992; Pierce et Lal., 1994; Papiernik *et al.*, 2009). In areas where *crop yield* is weak, with small plants and slight vegetal cover, erosion dominates. Conversely, in areas where *crop yield* is more important, with tall plants and high vegetal cover, deposition dominates.

Figure 9. Illustration of the pedological SEDI “Soil colour / Reflectance” in a context where soil erosion-deposition is mainly controlled by water translocation. (Source: Google Earth)

To finish, among the SEDIs witness of both tillage-induced and water erosion processes, some present the advantage to track sediment translocation: *magnetic susceptibility* (Pedological physical SEDI), *stable elements* and *radionuclides* (Pedological chemical SEDI), and *artefact cover* (Archaeological SEDI; Table 5). As the topographical SEDI used at landscape-scale, they can be used to assess soil material eroded or deposited. These different tracers are discussed in the following part (*cf.* *§* 3.3.3).

3.3.3. Tracers of soil erosion-deposition at landscape-scale

The SEDIs *magnetic susceptibility, stable elements, radionuclides,* and *artefacts cover* have potential for tracking sediment throughout cultivated hillslopes. Each of these SEDIs presents a punctual source or homogeneous input of their related tracers. So, the study of their spatial variability gives information about soil erosion and deposition in a landscape.

The SEDI *stable elements* refers to different stable chemical components of soil which spatial variability of concentration gives information about soil translocation. These chemical tracers can be natural major or trace elements (McGrath and Lane, 1999; Salvador-Blanes *et al.*, 2006; De Gryze *et al.*, 2008), or human-induced elements such as Cu and N (Sibbesen *et al.*, 2000; Van der Perk *et al.*, 2004; Fernández-Calviño et al, 200; Rusjan *et al.*, 2007). Among these different *stable elements,* natural major or trace elements come from bedrocks. If limits between bedrocks of different lithology (and then different chemical composition) are known through a study area, the sources of the different potential natural tracers are known. Their distribution in space relatively to their respective source is then an important information about the intensity of soil translocation in the area. In an area where bedrock lithology is more or less identical, the spatial variability of their concentration at a given depth of soil is a way to study erosion-deposition patterns. Concerning the human-induced *stable elements,* they are spread more or less uniformly on soil surface, and then can be easily removed by runoff or mixed through the displaced tilled layer. The relative variability of their concentration in soil can provide informations about erosion and deposition.

The use of *magnetic susceptibility* (Pedological physical SEDI) as soil translocation tracer works similarly to *stable elements.* The measurement of *magnetic susceptibility* provides informations about the quantity of magnetic components in soils which come from a delimitated source of bedrock in a study area (Thompson and Olfield, 1986; Dearing, 1994; Royall, 2001).

Archaeological SEDIs open soil erosion discipline to archaeometry. At landscape-scale, the study of the *artefact cover* can provide efficient tracks of soil translocation and a way to assess erosion-deposition rates by the way of dating. The use of *artefact cover* as a tracer appears possible only if a specific source of artefacts is discovered and delimited in an agricultural area; then, spatial distribution of related artefacts around this archaeological site provides information on erosion intensity since the site implantation (Roper, 1976; Quine and Walling, 1992; Brown *et al.*, 2003).

To finish, the homogeneously spread *radionuclides* detailed in the previous part 3.2.2 can be used also as sediment tracers at the landscape scale. The multiplication of punctual measurements and the calculation and mapping of differences between “reference” and inventories all over a study area, bring an efficient way to define total erosion-deposition patterning (Walling and Quine, 1992; Blake *et al.*, 1999; Walling et He, 1999; Schimmack *et al.*, 2002; Van Oost *et al.*, 2005; Mabit *et al.*, 2009). Some conversion models of radionuclides inventories into erosion rates have been developped to include spatial variation of measured inventories, especially for ^{137}Cs inventory conversion (Walling and He, 2001, Van Oost *et al.*, 2003). The various advantages related to the use of *Radionulides* (rapidity, accuracy, assessment of erosion rates...) made them practical tools to validate parametrisation of soil erosion models.

4. Conclusion

Water and tillage-induced processes of soil redistribution have consequences on physical and chemical characteristics of soil in agricultural context, or on features linked to soil state (e.g., topography, crop yields). These consequences constitute Soil Erosion-Deposition Indicators that give informations about soil redistribution and the processes involved at different spatial and temporal scales.

Litterature shows that numerous SEDIs have been defined and used, often independantly, for the study of soil erosion and deposition in cultivated hillslopes. Amongst the identified SEDIs, some are direct proofs of soil translocation (natural SEDIs), whereas others have been indirectly induced by human activities or landscape fragmentation (human-induced SEDIs). SEDIs related to water processes are predominantly induced by one specific process (splash, sheet, rill or gully erosion). Tillage erosion appears quite difficult to assess independantly of other processes, because SEDIs related to tillage-induced translocation are also related to the whole processes of soil translocation involved. Indeed, tillage practices induce the mixing of the soil surficial layer, and soil redistribution by tillage tends to overlay itself to previous soil redistribution induced by water processes. Tillage practices erase regularly SEDIs induced by specific water processes, except this related to gully erosion.

We presneted SEDIs identified in the literature through two different space-scales: local and landscape-scale. This spatial distinction highlighted relations between spatial-scale at which SEDIs are “readable” and temporal-scale during which the SEDIs have been developped enough to be “readable”. The SEDIs studied at local-scale are mainly related to non-concentrated water erosion processes. Their forms and layouts evolve at each rainfall event accordingly to rainfall intensity and soil conditions (roughness, porosity, vegetal cover). Consequently, the readibility of associated SEDIs also evolves at each rainfall event. The SEDIs readable at the landscape scale highlight mainly soil redistribution occuring during several decades to centuries. Hence, soil redistribution by tillage is mostly associated to SEDIs readable at the landscape scale. SEDIs used at landscape-scale can be affected by more or less perennial landscape fragmentation and landuses. Moreover, spatial fragmentation and landuses can induce SEDIs. Then SEDIs readable at the landscape scale could be pratical tools to highlight the effects of evolutive spatial fragmentation on soil redistribution.

The assessement of soil erosion and deposition through the study of such indicators presents some additional advantages. The study of one or few SEDIs could rapidly characterise soil redistribution processes locally or over cultivated hillslopes at various temporal scales. Although few SEDIs allow a direct quantification of soil redistributions, the use of complementary datation techniques could be then greatly beneficial. The combination of different SEDIs, readable at local and landscape-scales, could bring an interessing comparison between present and past soil redistributions. To finish, the study of SEDIs does not need any in-field monitoring when datas related to middle and long-term erosion are sparse, and nowadays research projects last few years only.