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Lynchets in eastern Belgium – a geomorphic feature resulting from non-mechanised crop farming

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Abstract

This paper investigates soil stratigraphy of lynchets in sloping lands in eastern Belgium, and rates of their development by comparison to tillage translocation by non-mechanised agriculture. In Belgium, detailed topographical surveys and augerings were carried out at three sites that were under cropland till 1900-1950. Rates and diffusion constants of current non-mechanised tillage erosion were monitored in Ethiopia using tracers, and by precise surveys of tillage steps of known ages. The lynchets in Belgium consist of colluvium that was removed at the upper border of previously farmed plots. Repeated tillage with animal drawn implements results in soil translocation fluxes to the lower plot borders in the order of 11 to 91 kg m^{-1} $year^{-1}$ (for slope gradients between 0.03 and 0.35 m m^{-1}). The studied lynchets in eastern Belgium would have required cropping agriculture for a total of 217-585 years on steep, and 1037-1867 years on gentle slopes. The establishment of lynchets hence took place without any deliberate action of digging, but due to repeated tillage, even with simple implements, and water erosion. Calculated time spans of tillage indicate that some parts of the study area had already been under cultivation during the Gallo-Roman period, others since the Middle Ages.

Key words: Plough; Cultivation terrace; Ethiopia; Lynchet; Tillage erosion

1. Introduction

A controversial issue in the understanding of topographical features is the origin of lynchets or cultivation terraces (Figure 1) in (previously) cultivated sloping lands of NW Europe. A first theory links the lynchets to geological features, particularly bundles of faults and joints in the underlying geological formations (Bracq and Delay, 1997; Gosselet, 1906; Lasne, 1890; Pahaut and Tavernier, 1964; Vandycke, 1992). This theory has been rapidly rejected as it appeared that excavations show that the lynchets are composed of an accumulation of fine material, often bearing plough marks at the interface with the bedrock (Nyssen *et al.*, 2000a; Wood, 1961). Occurrence in relation to farm- and woodland boundaries that are located along the contour (Szabó, 2010) and to land cultivation has been established rapidly (Aufrère, 1927; Raistrick and Chapman, 1929). Whereas for most soil scientists and geomorphologists (Chartin *et al.*, 2011; Dabney *et al.*, 1999; Ozer, 1969; Patro et al., 2008) there is no doubt that lynchets have grown as a consequence of tillage and water erosion, speculations on deliberate digging of terraces regularly surface (Fénelon, 1956; Fénelon, 1963; Raistrick and Chapman, 1929; Van Westreenen, 2008).

Tillage erosion is caused by the mechanical action of the plough only that detaches soil particles and translocates them, resulting in a downslope movement of the topsoil (Govers *et al.*, 1994; Quine *et al.*, 1999; Veseth, 1986). Soil translocation as a consequence of tillage with modern implements in a number of study areas has been demonstrated to have a more important impact on soil profile truncation than erosion caused by water or wind (De Alba *et al.*, 2004; Poesen *et al.*, 1997; Van Oost *et al.*, 2005). Yet, would the development of lynchets not at least have been initiated through digging, as the etymology of some local words for lynchet may suggest? In NE Belgium, S Netherlands and W Germany, the word *graaf*, *graft* or *Graf* is commonly used for lynchet, and it is thought to be derived from *graven* or *graben* (to dig) (Van Westreenen, 2008). In contrast, etymologies of various local French names (Aufrère, 1927) such as *royon* (furrow) indicate the mere action of tillage. Could the use of simple ploughs in the Middle Ages lead to metres high lynchets? As such tillage operations cannot be observed anymore in NW Europe, we carried out detailed field studies in Ethiopia (Figure 2), where farmers use a simple ox-drawn ard (*mahrasha*), a single-tined plough which breaks the soil without turning it (Figure 3), with an average tillage depth of only 8.1 cm (Nyssen *et al.*, 2000b; Solomon Gebregziabher *et al.*, 2006).

* * * Figure 2 about here * * *

* * * Figure 3 about here * * *

This study addresses the geomorphology and genesis of lynchets in Europe and their relation to tillage with simple animal-drawn tools. Detailed topographical surveys and augerings were done, and land use changes analysed. The rate of soil translocation induced by non-mechanised tillage was studied in Ethiopia where tillage with oxen and the presence of unploughed grass strips between farmlands lead to the development of lynchets.

2. Materials and methods

2.1 Study areas in Belgium and secondary data

Field observations were carried out at 3 sites on Mesozoic chalk, close to the town of Visé[1] (50.737 °N, 5.696 °E) in East Belgium, and located in the geomorphological regions "Pays de Herve" and "River Meuse terraces". The overall geology of the area comprises a series of subhorizontal formations, with (from bottom to top): (i) Carboniferous bedrock, peneplanated after the Hercynian orogeny (Demoulin, 2006), that provides a structural control to the depth of valley incisions but that has not been incised itself (Barchy and Marion, 2000; Claes *et al.*, 2001); (ii) three Cretaceous formations, the 30-m thick Vaals formation (Boulvain, 2008; Claes *et al.*, 2001; Felder and Bosch, 2000) locally containing clay (disused terminology: Herve smectites (Moorkens and Herman, 2006)), the 70-m thick Gulpen formation composed of brittle chalk (Felder and Bosch, 2000; Robaszynski, 2006) that was quarried by local farmers for use as soil amendment (Barchy and Marion, 2000; Bats, 1992), and the Maastricht formation comprising coarser and yellowish chalk (Felder and Bosch, 2000; Robaszynski, 2006); (iii) Tertiary weathering and dissolution (Felder and Bosch, 2000; Gallois, 2009) of these formations resulted in an up to 10-m thick formation of clay-with-flint that is best preserved in the centre of the plateaus (Barchy and Marion, 2000; Loveday, 1962) while occurring mostly in a degraded form at its edges, as it tends to be mixed with remnants of overlying formations due to the occurrence of sinkholes and Pleistocene periglacial processes (Gallois, 2009) - the presence of this formation provides a protection that preserves the plateaus and, hence, leads to the occurrence of steep slopes in the topography (Hodgson *et al.*, 1974); (iv) Eocene marine sands, particularly belonging to the Tongeren group (Claes et al., 2001; Laga *et al.*, 2001), appearing towards the W as

[1] As the study area is located at the transition zone between French and Dutch languages, names of localities may appear differently in literature and on maps: Visé or Wezet, St. Martens-Voeren or Fouron St. Martin, Warsage or Weerst, Wonck or Wonk, R. Meuse or Maas.

thick deposits and to the E as preserved pockets in cryptokarstic depressions (Felder and Bosch, 2000); and (v) terrace deposits of Meuse R., either poorly preserved remnants of the late Tertiary “trainée mosane” or belonging to the mid-Pleistocene Wonck terrace (Juvigné and Renard, 1992). Whereas it is present on wider plateaus and in wind-sheltered depressions, no remnants of Pleistocene loess (Van den haute *et al.*, 2003; Vancampenhout *et al.*, 2013) exist on the slopes where the studied lynchets have developed.

Using archaeological and palynological information, Brounen (1989) concluded that in a region close to the study area slow but continuous deforestation took place from late Neolithic till Roman ages. Roman villas, large farms that produced grain for the towns and the military, were constructed as of the first century CE (Del Vaux, 1851; Renes, 1993). The decline in population density and in farmed area started at the end of the 3rd century and the forested area continued to increase until the 6th century, as shown by palynogical data (Bunnik, 1999; Janssen, 1960). Around 1000 CE a period of rapid deforestation started (Janssen, 1960) and by 1300 the larger part of the study area was under agriculture (Renes, 2010; Renes, 1988). Old land lease contracts and tribute accounts show that as of the 14th Century cropping agriculture took place in the study area, with permanent pastures around the villages and forests and shrub lands on plateaus and in humid places of the valley bottoms (Bats and Vanden Eede, 1982). Land use changes were analysed using historical maps (de Ferraris, 1771-1778a; de Ferraris, 1771-1778b; ICM, 1937; ICM, 1938; NGI, 2007; NGI, 2008). The 18th century maps, produced just before the industrial revolution, allow to have an understanding of the landscape that is expected not to have changed much since the Middle Ages (Bracke, 2009).

2.2 Topographical studies and augering line

Detailed topographical surveys, complemented with 2-m deep soil augerings, were done at 3 sites, all currently under permanent pastures.

1. On a WNW-exposed slope at Groensdael (50.746 °N, 5.786 °E), halfway between the villages of St. Martens-Voeren and Warsage, where observations could be made across a lynchet, through a series of parallel soil augering transects, each 40 m long, as well as in a temporary 3 m deep soil trench (dug for a gas pipeline) (Figure 4). The lynchet is located on Gulpen chalk, overlain by a thin layer of colluvium that comprises clay-with-flint and sand and pebbles, originating from Tertiary formations located several hundreds of metres upslope;

2. On a south-exposed slope at Martelberg (50.754 °N, 5.815 °E; Figure 5), at the northern side of the village of St. Martens-Voeren, a site where the lynchets have been studied, particularly their high density and the associated ecological corridors that they provide (Van den Balck and Durinck, 2012) and their landscape value (Bats and Vanden Eede, 1982). The augering line was 161 m long and crossed 6 lynchets, with a total vertical interval of 35 m. The Martelberg slope is mostly within the Gulpen formation. At its lower side the Vaals formation outcrops, leading to a perched water table, and the upper part of the slope affects the residual clay-with-flint that functions as a structural protection of the plateau on which remnants of Tertiary sands and early Meuse deposits are present. Colluvial deposits on this slope are in the order of one metre and comprise clay-with-flint *sensu lato* (Gallois, 2009), most probably mobilised as Pleistocene gelifluction material.

3. On a north-exposed slope at El Tawe (50.769 °N, 5.654 °E; Figure 1), to the E of the village of Wonck, another site with a dense network of well-preserved lynchets exists. The

augering line was 74 m long and crossed 4 lynchets, with a total vertical interval of 20 m. This steep (0.28 m m^{-1}) slope is located on the Maastricht formation, overlain by Tertiary Tongeren sands (Claes et al., 2001; Felder and Bosch, 2000) and the mid-Pleistocene Wonck terrace (Juvigné and Renard, 1992) that was however not remodelled by the lynchets. Both upper formations contribute to the colluvium that, on this slope, is only present in the lynchets. In outcrops and augerings, the clay-with-flint was absent at this site.

At all sites, topographical surveys were made using compass, GPS, clinometer and metre tape along downslope-oriented augering lines. Topographical measurements were plotted in the vertical plane using trigonometry. Two-metre deep augerings were done along these transects, in Martelberg and El Tawe at the top and the foot of the lynchets and on the median position between two lynchets. A distance of one metre from the structures was kept at Martelberg to avoid the dense tree roots. At Groensdael, a detailed survey was done, involving three parallel transect lines, and the average cross-section of the three transects was drawn (Figure 4).

Observed cross-sections allowed to qualitatively interpret the occurring stratigraphy, as well as to calculate volumes of colluvium in the lynchets, that could be compared to rates of non-mechanised tillage erosion, and hence to assess the number of years of tillage that were necessary to obtain lynchets of the observed sizes.

2.3 Field studies of effects of early tillage methods

2.3.1 Study area in Ethiopia

To assess the potential effects of simple tillage tools on the development of lynchets, field studies were done in Ethiopia where such tillage practices are still commonly used. The agricultural system in the north Ethiopian highlands is typically one with permanent cropping on parcels with fixed boundaries (Westphal, 1975). High elevations induce a temperate climate and major crops are wheat, barley and an endemic cereal, *Eragrostis tef*. After harvest, livestock is allowed to graze the stubble, a typical phenomenon in *openfield* landscapes. To prevent the free-roaming livestock from feeding on standing crops in neighbouring farmland, crop rotation is organised by blocks, whereby yearly the same crop is sown in blocks of 20-25 parcels and harvested at about the same moment, after which livestock is allowed on the farmland (Nyssen *et al.*, 2008a). There are many parallels with the mediaeval agricultural system of west and central Europe (Lebeau, 1991). Tillage is done with an ox-drawn ard plough, called *mahrasha* (Nyssen et al., 2000b), and lynchets develop at the very position of farmland boundaries (Nyssen et al., 2000a).

Qualitative field observations were done during visits in Tigray (north Ethiopia) between 1994 and 2013, whereas in situ measurements and monitoring of soil translocation by tillage pertain particularly to the region around Hechi and Hagere Selam (13.64 °N, 39.2 °E).

2.3.2 Tillage erosion rate measurements

To quantify erosion rates caused by the ard plough in Ethiopia, in a first approach, painted and numbered rock fragments, 3 - 5 cm in intermediate diameter, were used as tracers to monitor soil movement on 16 sites, each having a different slope gradient (0.03 – 0.35 m m^{-1}) (Nyssen et al., 2000b). Next, the tillage steps with a triangular cross-section representing the soil profile truncated by tillage at the upper side of farm plots (see Figure 6 at left), were analysed (Desta Gebremichael et al., 2005). The dimensions of these cross-sections with their respective slope gradients were measured at 202 sites and the volume of soil loss per unit contour length calculated as the product of the cross-sectional area, one metre length along the contour and dry bulk density of the soil. Rates of soil transport due tillage erosion were calculated from measurements of these tillage steps:

$$Qs = C_L \, Bd / T \qquad (1)$$

Where: Qs = unit soil transport rate by tillage erosion (kg m^{-1} yr^{-1});

C_L = cross-sectional area of the tillage step (m^2);

Bd = dry soil bulk density (1200 kg m^{-3});

T = age of the structure (yr).

2.3.3 Sheet and rill erosion measurements

Four experimental sites with 14 - 37-m long bounded runoff plots, representative for the present-day conditions of arable land, were established in farmers' fields (Nyssen *et al.*, 2009). The eroded sediment was trapped in collecting trenches lined by masonry and its volume was measured. The calculated mass of soil which entered into the collecting trenches by tillage translocation was deduced from the total mass of sediment deposited in the trenches, in order to obtain soil loss by sheet and rill erosion only. Soil flux Qs, the mass of sediment transported yearly through a unit length on the contour, was calculated by dividing total dry sediment mass by the bottom width of the plot.

2.3.4 Topographical surveys

Fieldwork included topographical surveys of lynchets by theodolite and the drawing of cross-sections through these lynchets. Farmers were interviewed regarding present-day and previous locations and dimensions during fieldwork. To assess the evolution of the soil conservation structures in the landscape, pairs of aerial photographs taken in 1974 and 1994 were interpreted by stereoscopy (Nyssen et al., 2000a).

3. Results

3.1 Historical land use changes on the Mesozoic chalk in East Belgium

Map interpretation (de Ferraris, 1771-1778a; de Ferraris, 1771-1778b) showed that the study area was largely cropped in the late 18th Century (Fig. 7a). At the end of the 19th-early 20th Century, a large-scale land-use conversion from croplands to permanent pastures took place in the study area in general and on the three study sites in particular, as crop production costs were high (small plots, steep slopes) and grain productivity low on these marginal less fertile slopes. Worldwide decreasing grain prices led then to the abandonment of such slopes for cropping and to a conversion of cropland into pastures (Beyaert *et al.*, 2006).

Sequential analysis of maps shows that this conversion from arable land to cropland was ongoing in the 1930s at El Tawe, and took place around 1935-1950 in Groensdael and around 1900-1940 at Martelberg (Figure 7). Older inhabitants of Sint-Martens-Voeren recall that in the 1920s, on several farmlands at Martelberg, which were not yet converted into pastures, sediment deposition on top of lynchets also took place after intense storms (pers. comm. E. Vandenabeele, Sint-Martens-Voeren). All study sites are currently under permanent pastures. However, the introduction of fodder maize around 1965, implemented with the use of heavy machinery, allowed converting pastures (on the clay-with-flint plateau and on humid lower slopes) into farmlands. Such is the case for the land above lynchet 1 at Martelberg, where it led to the rapid development of that lynchet. The process is also illustrated on Figure 5.

* * * Figure 7 about here * * *

3.2 Lynchet topography and erosion/accumulation areas

Based on an extensive survey of 304 lynchets (Van den Balck and Durinck, 2012), the lynchets were found to have an average height of 2.96 (±1.66) m, with outliers up to 15 m; an average slope gradient of the risers of 0.83 (± 0.17) m m^{-1}, ranging between 0.36 and 2.75 m m^{-1}; a reported shoulder width of 1 m or less in 81% of the cases, but 6 lynchets have a shoulder of 6-9 m wide. No precision was given regarding the exact criteria defining a shoulder in this inventory (Van den Balck and Durinck, 2012).

The lynchet at Groensdael (Fig. 4 and 8a) comprises a lower part with up to 2 m thick colluvium and an upper part where the chalk outcrops. At the steeper El Tawe (Fig. 8b) site, the two lower lynchets are similar to the Groensdael one, with (weathered) chalk outcropping and colluvium in the treads, i.e. the lands located between two subsequent lynchets or the inter-lynchet slope segments; the third lynchet has the same morphology but the parent material are Tertiary sands, whereas the fourth lynchet affects the R. Meuse terrace. Pebbles belonging to the latter were recovered in the colluvium of all lower lynchets. At Martelberg (Fig. 8c), complexity arises from the presence of clay-with-flint at the interface between chalk and colluvium at many augering locations. However, also here thick colluvium is present in the lynchet treads that thins out towards the upper side.

* * * Figure 8 about here * * *

For all slopes, the treads are on average 45% less steep than the overall slope gradient (0.13 m m^{-1} as compared to 0.23 m m^{-1}). The topography of the treads very often shows the shape mentioned by Aufrère (1929), i.e. a slope that is concave just above the lynchet, and that, when moving upslope towards the next lynchet, becomes convex. In many cases, the boundary between the upper part of the level land and the riser of the lynchet does not consist of a sharp break of slope, but shows a smooth transition in slope where colluvium is present (Figure 9). Only the upper tread at Martelberg is an exception, but it should be noted that the upper lynchet is affected by a recent reconversion (<20 y) of the upper plot (to the left of the section) from permanent pasture to cropland for maize production.

When comparing the cross-sectional areas of the tillage steps at the upper part of the inter-lynchet areas at El Tawe (average of 8.04 m^2) to the cross-sectional sediment accumulations in lynchets (7.66 m^2), the correspondence between both is striking (Fig. 8b), whereas those areas are difficult to establish for Martelberg, due to microtopography (Fig. 8c).

3.3 Soil stratigraphy of the lynchets

The cross-sections shown in Fig. 8 present idealised situations as the contacts between the different soil layers observed during augering are not sharp. All augerings show a topsoil of approx. 10 cm that is not further taken into account in this study. In the cross-sections, the contact between in-situ clay-with-flint and underlying chalk is schematically represented by a wavy line.

At El Tawe the lynchets directly affect the parent material (weathered chalk and Tertiary sands and river terrace deposit), with the only colluvium available being the one that is accumulated in the lynchets (Fig. 8b). The same holds for Groensdael, where the upper part of the inter-lynchet areas is composed of chalk (Fig. 8a). At Martelberg, at the upper part of the slope on clay-with-flint, the lynchets are composed of colluvium originating from the edges of the upper plateau (mix of clay-with-flint, Tertiary sands and rounded pebbles of the *trainée mosane*, and including charcoal and locally brick/pottery fragments); in-situ clay-with-flint outcrops in the upper part of the inter-lynchet areas (Fig. 8c). Further downslope, in many augerings a 13-66 cm thick layer of clay-with-flint s.l. was observed under the lynchet colluvium, which was thinner at the foot of the lynchet than at its top. Between lynchets 5 and 6 on the lower side of the Martelberg transect, a break in slope indicates most probably the location of a lynchet that has been destroyed.

3.4 Development of lynchets under non-mechanised farm conditions

3.4.1 Water erosion and sediment deposition in grass strips in Ethiopia

At the scale of small catchments in Ethiopia, soil loss due to water erosion is in the order of 6 t ha^{-1} $year^{-1}$ (Nyssen *et al.*, 2008b); it is partially controlled by the grass strips between the farmlands which result in the development of progressive terraces (Hudson, 1992). Sediment is deposited in the lynchets' vegetative barriers. They also perfectly buffer rill erosion. Where the slope of farmland becomes level, i.e. at the top of the lynchet, no rill erosion occurs but sediment deposition takes place.

3.4.2 Tillage translocation as a consequence of tillage with ox-drawn ard

Average measured net soil translocation and hence also sediment deposition rates at the plot border caused by tillage erosion in Ethiopia were between 11 and 91 kg m^{-1} $year^{-1}$, or the mass of sediment that is deposited yearly per metre of lynchet. This is the consequence of the mechanical process through which the plough layer is displaced down slope over an annual distance between 9 and 103 cm at slope gradients between 0.03 and 0.35 m m^{-1} (Nyssen et al., 2000b).

For diffusive geomorphological processes, such as splash and sheet erosion, soil creep or tillage erosion, the coefficient K (kg m^{-1} yr^{-1}), established based on experimental measurements, allows comparing intensities, while discounting the slope gradient (Kirkby, 1971):

$$K = Q_s/S \tag{2}$$

with

Q_s = unit sediment transportation rate (kg m^{-1} yr^{-1}), and

S = slope gradient (m m^{-1}).

Tillage-induced soil fluxes by animal-drawn implements shows K-values between 68 and 187 kg m^{-1} yr^{-1}, which is relatively high compared to other diffusive erosion processes (Table 1).

3.4.3 How do lynchets in north Ethiopia develop?

All level land in north Ethiopia has been cultivated for centuries; there is little agricultural intensification, hence increasing population density leads to land clearing on steeper slopes.

After clearing, crops are sown in the fertile Phaeozem forest soils. As these forest soils produce good crop yields, farmers do not feel the need to immediately establish soil conservation structures, leave alone to carry out larger levelling activities. Intentionally, however, they will leave a 2 m wide grass strip uncultivated at the parcel's lower side as physical evidence of the parcel's boundary as well as for sake of soil erosion control; within a few years, a lynchet will develop (Nyssen *et al.*, 2010). These structures are not only partial barriers for sediment transport by water, but also a total barrier for downslope soil transport created by tillage erosion (Govers *et al.*, 1999; Turkelboom *et al.*, 1999). Sediment accumulation occurs at the lower border of the farmed plots and soil profiles are truncated at the upper part, at the foot of the lynchet (Herweg and Ludi, 1999; Nyssen et al., 2000a; Nyssen et al., 2000b). Long-existing, well-developed lynchets often reach heights of 3 m and risers have slope gradients of 0.5 – 0.83 m m^{-1}. Beyond that gradient, slumping may occur, which is frequent when the farmer ploughs too close to the foot of the lynchet (Nyssen et al., 2000a).

Our field measurements further indicate that on average half of the sediment volume accumulated in lynchets was transported by runoff, and the other half through tillage translocation (Desta Gebremichael et al., 2005; Nyssen et al., 2000b).

3.5 Assessment of age of lynchets in eastern Belgium

The combination of cross-sectional area of sediment trapped in the studied lynchets (C_C) with rates of non-mechanised tillage erosion allows assessing the number of years of tilled agriculture that would have been necessary for the lynchets to reach their final dimensions. We assumed an average diffusion coefficient for tillage erosion K of 134 kg m^{-1} yr^{-1}, that represents the average of K coefficients obtained in various studies on non-mechanised tillage (Table 1), soil bulk density of unploughed soil Bd of 1500 kg m^{-3} (Mwendera, 1992), and a slope gradient of the tread that is the average between the original (natural) and final (current) gradient, and then calculated the unit sediment transportation rate Q_s (in kg m^{-1} yr^{-1}) by reorganising eq. (2). The number of years needed to reach the measured volumes (T) was then calculated using

$$T = C_C \times Bd \times F_{TE} \times 1\ m / Q_s \qquad (3)$$

The fraction of colluvium in the lynchet generated by tillage erosion (F_{TE}) was set at 0.5 (based on active process rates measured in Ethiopia, section 3.4) and at 0.9 (since measurements at El Tawe seem not to give much room for other processes besides tillage erosion, section 3.2).

Calculations (Table 2) show that the lynchets at both El Tawe and Martelberg needed some 200-600 years of tilled agriculture to develop, whereas the lynchet on the gentler slope at Groensdael, would have needed 1000-1900 years of tilled agriculture in addition to probable periods where no agriculture took place.

4. Discussion

4.1 Formation process of lynchets

Lynchet profiles and soil stratigraphy, as observed in the study area in E Belgium are fully in line with the didactic drawings by Wood (1961) and Curwen (1939), whereby topsoil is removed from the upper part of the inter-lynchet area, sometimes down to the parent material (fresh bedrock) and then redeposited in the lynchet, where it forms a triangular wedge with the thickest deposit of colluvium at the position of the lynchet's shoulder (Fig. 4).

Tillage and water erosion have led to such accumulations. As observed in Ethiopia, tillage erosion by simple tools, in addition to sediment transport due to water erosion, can lead to fast soil accumulation in the lynchets (Chartin et al., 2011; De Alba et al., 2004). As the rate of tillage erosion is independent from slope length, imposing lynchets can also develop on narrow parcels, established along the contour, as shown elsewhere (Patro et al., 2008).

Similar results regarding the geomorphic impact of non-mechanised tillage were found for soil tillage with oxen in southern Africa, the Philippines, China and the Andes (Dercon *et al.*, 2007; Quine *et al.*, 1999; Rymshaw *et al.*, 1998; Thapa *et al.*, 1999), with horses in Poland (Martini, 1955) or for soil tillage by hoe in Thailand, Rwanda and Tanzania (Kimaro et al., 2005; Poesen et al., 2000; Turkelboom et al., 1999). In case of mechanised ploughing, the soil translocation by tillage erosion will even be larger. Measurements in southern Africa show that the use of animal-drawn turning ploughs typically leads to very large tillage erosion rates, as the farmer turns the soil down slope at each tillage pass, in order to decrease the energy requirements (Quine et al., 1999), as was already hypothesised by Curwen (1939).

The numerous charcoal fragments in the colluvium of the lynchets, particularly at Martelberg, are not surprising, as hedgerows appear already on the 1770s map (Fig. 7a) as well as on a 1915 photograph of the study area. Trees growing on the risers of the lynchets were pollarded regularly in the traditional farming system and smaller branches burnt. Furthermore, part of the study area is used for a yearly community fire on St. Martin's day.

4.2 Age and microtopography of lynchets

Depending on the assumed contribution by tillage erosion (50% or 90%), the volumes of sediment accumulated in the lynchets would have required 325 (± 93) or 585 (± 167) years of tilled agriculture at Martelberg and 217 (± 35) or 391 (± 63) years at El Tawe (Table 2). All time spans found tend to indicate that agriculture started on these slopes in the Middle Ages.

Time spans at Groensdael of 1037 (± 269) or even 1867 (± 483) years, for respectively 50% or 90% contribution by tillage erosion to the volume of sediment accumulated in the lynchet, indicate that on this land with a gentler slope (0.11 m m^{-1}) a much longer time was needed for the development of the lynchet. Cropping from the mediaeval period till tractorisation only (1000-1950) would not have sufficed to obtain the lynchet. Hence, one may reasonably assume that, before the Early Middle Ages, the area had already been tilled during the Gallo-Roman period, particularly taking into account the existence of the Steenbosch *villa* (dated 14-275 CE, Del Vaux, 1851) 800 m to the NW, at the foot of the gentle Groensdael slope on which the lynchet is located.

The typical convex-concave profile of the treads, as observed at Martelberg (Fig. 9a), reveals a not yet fully developed lynchet, where water and tillage erosion processes did not yet lead to a complete slope levelling, because cropping was not done over a sufficient number of years. It is an intermittent situation between the natural slope and a full developed lynchet, as observed at El Tawe (Fig. 1) or in long-cultivated areas in Ethiopia (Fig. 2). Most probably the Martelberg slope was too marginal for longstanding intensive practice of cropping agriculture; not only the land itself is steep, but the harvest needed also to be transported through steep sunken lanes, on which -oral history says- four Brabant horses were needed to pull a cart with crop yield uphill.

The colluvium that blurs the contact between the foot of the lynchets and the tillage steps is attributed to badger (*Meles meles*) burrowing, gully and pipe erosion (Faulkner, 2006), and slumping in the lynchet. When moving more eastwards of the study areas, to regions where cropping has ended much earlier (for instance, in the Hombourg – Aubel sector, 50.68°N, 5.91°E) the shapes of the lynchets have been smoothened due to longer occurrence of the soil translocation processes described. A traditional practice of carrying fertile soil upslope towards the tillage step (as observed in southern France by Lowdermilk, 1939) has not been reported for the study area. Slumping of lynchets, on the other hand, is frequent on cropped land, whereby tillage often takes place too close to the foot of the lynchet. In the wider study area, 17 % of the lynchets show evidence of ongoing slumping; most of them are bordered on the lower side by farmland (Van den Balck and Durinck, 2012) and slumping is directly related to undercutting by soil tillage. Active bank gullies occur in 4.6% of the lynchets in the study area (n = 304) (Van den Balck and Durinck, 2012). Occupied and unoccupied badger setts were observed at various locations in the lynchets (Van den Balck and Durinck, 2012), as woody hedgerows and sloping ground are preferred locational conditions for badger burrows (Byrne *et al.*, 2012; Remonti *et al.*, 2006).

4.3 Soil creep or Roman vineyards?

The occurrence of lynchets on slopes that are currently under grassland may suggest creep-induced soil accumulations at the location of hedgerows. This hypothesis does not fit with the following field observations: (1) existence of lynchets on farmland where there are no hedgerows, (2) the rectilinear character of lynchets that does not fit with the lateral variability of creep rate on slopes, (3) the existence, both in Europe and in Ethiopia of sharp contacts between *in situ* material and colluvium in soil profiles (Figures 4 and 6), and (4) the fact that the K coefficient for diffusive processes, such as splash erosion or soil creep, is two orders of magnitude smaller than that for tillage erosion (Table 1).

Neither is the outcropping bedrock such as chalk (Van Westreenen, 2008; Wood, 1961) in the upper part of the terrace at the foot of lynchets in Europe evidence for intentionally dug out structures. It is rather a consequence of tillage erosion, as also evidenced by the presence of historical plough furrows in the upper part of the outcropping rock, both in Ethiopia (Nyssen et al., 2000a) and in Europe (Wood, 1961). The excavation of forest soil and periglacial colluvial deposits, leading to a deliberate exposure of chalk or other parent rock at the surface of croplands, would not fit with the economy of pre-industrial agricultural systems.

In the representative set of 304 lynchets, inventoried by (Van den Balck and Durinck, 2012), no preferential exposition could be found. The studied El Tawe site where lynchets are very well developed has a full north exposition (which, given the steep slope gradient and according to the current farmer, leads to a yearly crop-growing period that is one to two months shorter compared to south-facing slopes). This again contradicts the theory that lynchets could have been deliberately dug to establish very productive land or even vineyards (Joode and de Schütte, 1981; Van Westreenen, 2008).

4.4 Distribution of lynchets on slopes

Remarkably, the distance between lynchets corresponds to the average parcel length and to the very location of parcel boundaries that were in use in the 19th Century (Popp, 1842-1879). The current variability in local lynchet density that one can observe in NW Europe is related to lynchet destructions. Particularly as a consequence of land consolidation, a farmer could decide to increase the tilled area of his farmland by ploughing the lynchet. In the adjacent area of Zuid-Limburg (The Netherlands) about half of the lynchets have disappeared since 1910 and particularly since 1950 (Boardman *et al.*, 1994; Renes, 1993). Also in north Ethiopia, analysis of aerial photographs shows that 21 % of the lynchets disappeared between 1974 and 1994 (Nyssen et al., 2000a). A large number of these have been levelled to increase the cropping area and to spread the fertile sediment accumulation in the lynchets over the croplands. Famine and poverty pushed the farmers to increase the short-term agricultural productivity in this way.

5. Conclusions

The clearly demarcated colluvial deposits in the lynchets of East Belgium confirm their relation to tilled agriculture. At El Tawe and Groensdael the colluvium in the lynchets is fully discordant with the Mesozoic and Tertiary parent material. At Martelberg, the lynchets consist for a large part of reshaped clay-with-flint s.l. that covers the slope. The link to previous land use for cropping is well established. The typical topography of inter-lynchet areas in tilled land has been largely preserved. As landforms, lynchets in East Belgium are also remarkably linear, locally departing from topographical accidents, as they correspond to farm plot boundaries on traditionally tilled land.

Most lynchets studied in Ethiopia are very similar to those in NW Europe, where it has also been shown that they resulted from soil translocation by tillage and water erosion of temporarily bare soils (Bollinne, 1971; Gerlach, 1963; Ozer, 1969; Patro et al., 2008; Poesen et al., 1997; Van Oost and Govers, 1998). This study did not consider risers of non-agricultural origins such as brick earth excavations, river terraces, and road or river banks.

The worldwide field observations and measurements link the development of lynchets to the combined action of erosion by runoff, tillage and gravity, and sediment deposition at the lower plot border which takes place as soon as land is cultivated. This evidence strongly overrides hypotheses on intentional anthropogenic excavations that are based on etymology only. The observed tillage translocation rates with simple ploughs in Ethiopia and elsewhere reject statements (Fénelon, 1956; Raistrick and Chapman, 1929; Van Westreenen, 2008) that non-mechanised tillage could not lead to the accumulation of important soil volumes. We totally disagree with the hypothesis that mediaeval and earlier farmers would have wasted time and energy to dig out fertile forest soils on steep slopes with the risk of bringing chalk and other parent material to the surface.

Once a lynchet starts developing at a parcel border, it continues to grow, whereby the tread or inter-lynchet area first shows a convex-concave profile that continues to develop until the slope section becomes rectilinear. Given the volumes of colluvium in the lynchets and knowing rates of non-mechanised tillage translocation, cropped agriculture is assumed to have started in the Middle Ages at Martelberg and El Tawe, and in the Gallo-Roman period at Groensdael (allowing for an interruption during the Early Middle Ages). After tilled agriculture stopped in the early 20th century, pasture (sometimes forest) vegetation stabilised the topography that evidences the previous land use.

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Figure captions

Figure 1. Lynchets at El Tawe (Wonck, East Belgium). Conversion of farmland to permanent pastures occurred around 1930 and these topographical features were well preserved under the current pastures planted with poplar. Outcropping parent rock can be observed at the lower side of the lower lynchet (Photo K. Nyssen).

Figure 2. Landscape with lynchets near Ashenge (north Ethiopia). Lack of land forced the farmers to plough close to the foot of the lynchets, which provokes their collapse. Also the width of the grass strips on the shoulder has been extremely reduced.

Figure 3. Tillage with a pair of oxen and ard plough in north Ethiopia leads to a downslope displacement of the plough layer by gravity (Photo A. Roelofs).

Figure 4. An excavation shows the accumulation of colluvium in a lynchet at Groensdael (Belgium). The average stratigraphy recorded in soil augerings (indicated by arrows) along three transect lines A-C is represented in Fig. 8a.

Figure 5. The stepped farmlands that existed on the Martelberg in Sint-Martens-Voeren (Belgium) has been converted into pastures in the first decades of the twentieth century. The lynchets remain as a witness of the previous land use. At the foreground, a parcel was recently converted into cropland for maize production, leading to the emergence of a new lynchet within a dozen of years (Photo W. Clymans).

Figure 6. Section across a lynchet in Hechi, Tigray, Ethiopia. The red line represents the original soil surface at the moment of the establishment of the lynchet. A is the accumulation zone, B the erosion zone (Photo K. Vancampenhout).

Figure 7. Excerpts of historical maps showing land use changes at Martelberg: a 1771-1778 (de Ferraris); b 1937 (ICM); c 2007 (NGI). Homologous locations are indicated by dots. Red lines indicate location of transect lines represented in Figure 8c. Note the schematic representation of three hedgerows on the 18th Century map (southwest of the transect line).

Figure 8. Cross-sections along three transect lines, based on topographical surveys and augerings (no vertical exaggeration), for the sites of (a) Groensdael (average of 3 cross sections through one lynchet, for location, see Fig. 4), (b) El Tawe, and (c) Martelberg. “Negative lynchets” (sensu Wood, 1961) at El Tawe are indicated with dotted lines.

Figure 9. Typical microtopography of the tread or inter-lynchet area at Martelberg (Belgium, a) and at Hechi (Ethiopia, b). The steeper slope in the middle of the tread and leveling off at its upper and lower sides can be observed in both cases.

Figures

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

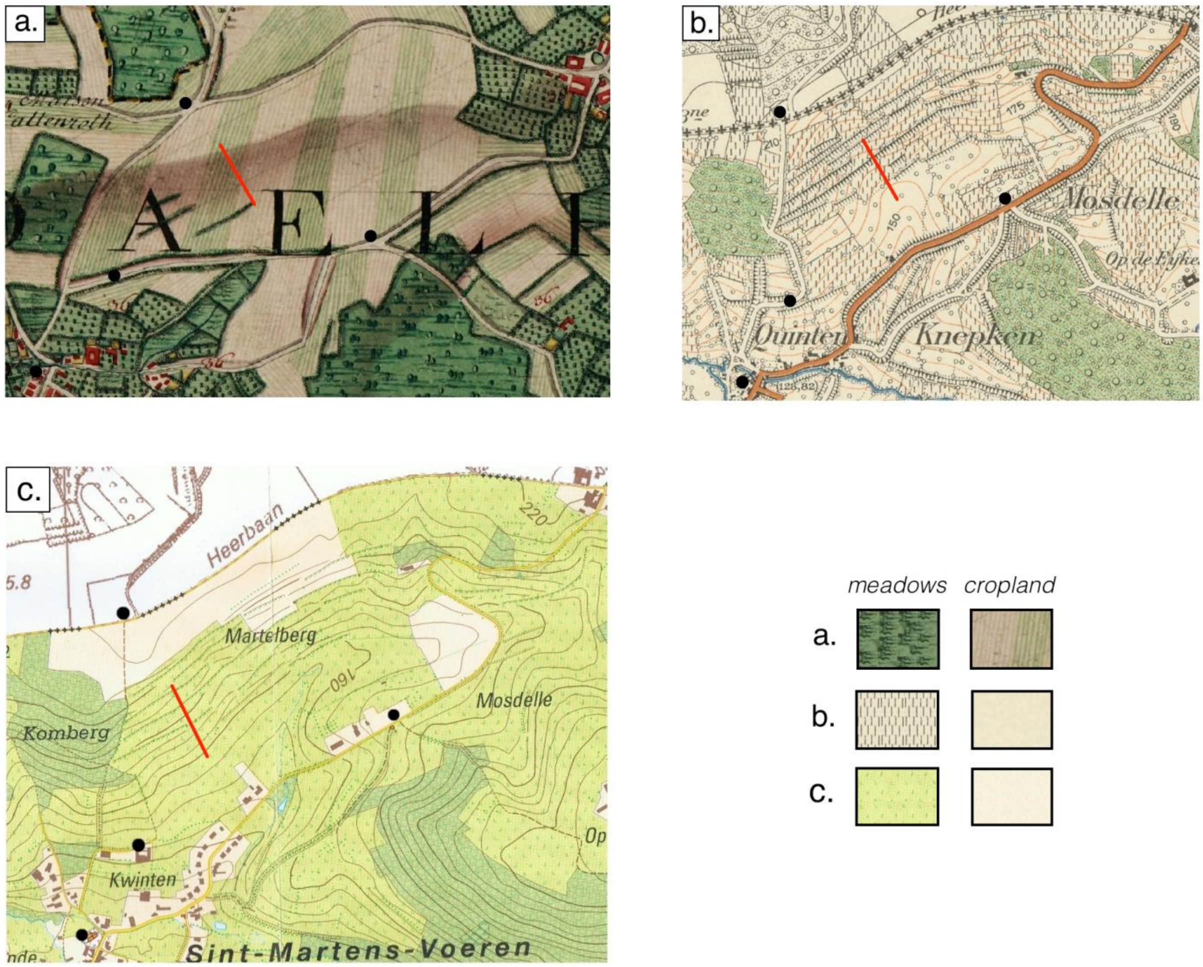
a.
b.
Mosdelle
Quinten
Knepken
175
150
c.
Heerbaan
Martelberg
Mosdelle
Komberg
Kwinten
Sint-Martens-Voeren
220
meadows
cropland
a.
b.
c.

Figure 8.

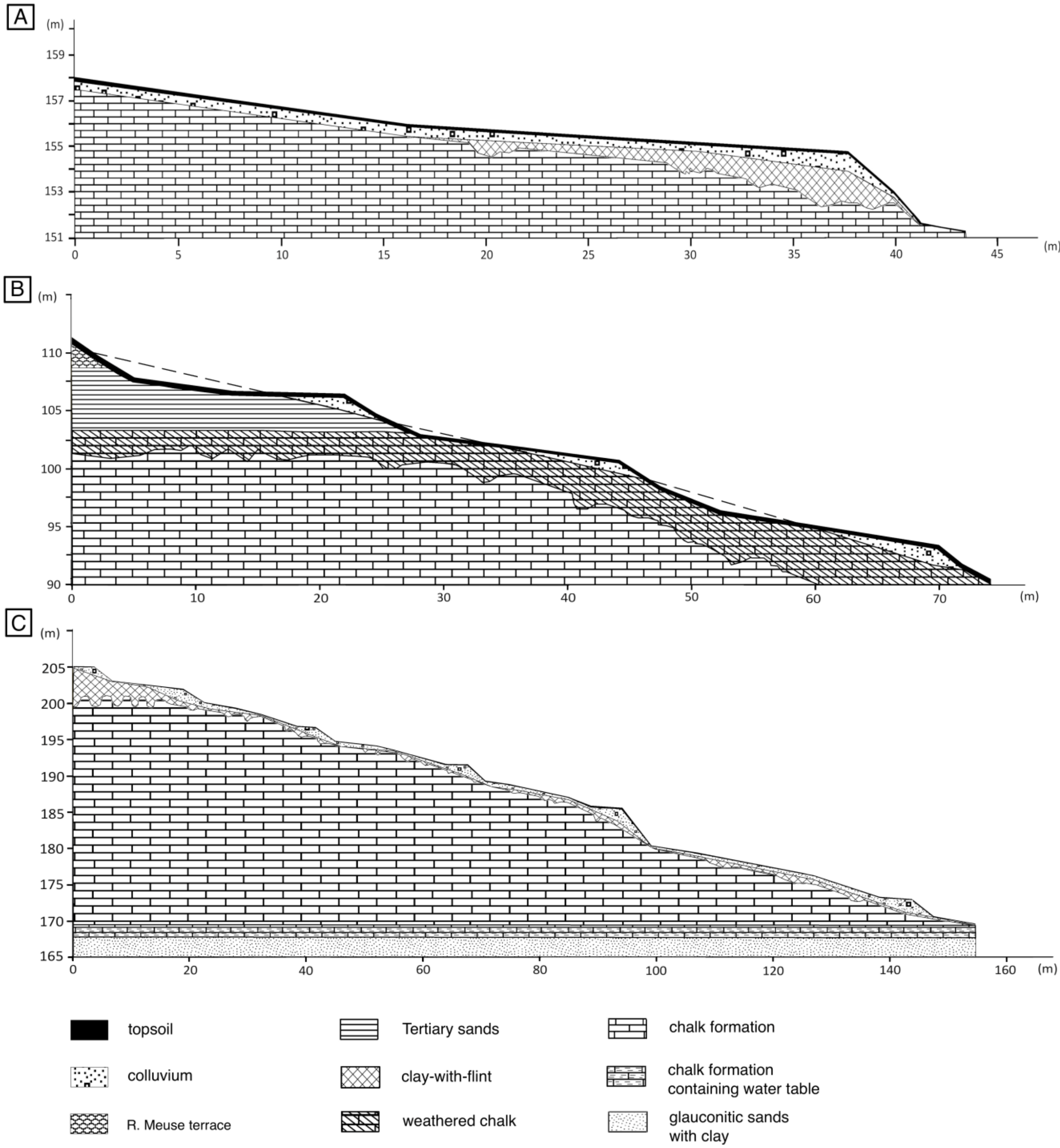
A
B
C
(m)
topsoil
colluvium
R. Meuse terrace
Tertiary sands
clay-with-flint
weathered chalk
chalk formation
chalk formation containing water table
glauconitic sands with clay

Figure 9.

a b

Tables

Table 1. Magnitude of the diffusion constant (K in eq. 1) for various diffusive erosion processes.

Process	Region	K (kg m^{-1} yr^{-1})	Source
Tillage erosion: ard	Ethiopia Andes	68 - 136 187	(Nyssen et al., 2000b) (Dercon et al., 2007)
Tillage erosion: hoe	Thailand Rwanda	107 173	(Turkelboom et al., 1999) (Poesen et al., 2000)
Tillage erosion: mechanised agriculture	Belgium Spain	350 - 550 800 - 1000	(Van Oost et al., 2005) (Poesen et al., 1997)
Water erosion on cultivated land	Ethiopia	173	(Nyssen et al., 2008b)
Splash erosion	Belgium	5 - 25	(Poesen, 1986)
Soil creep	USA Belgium	44 5 - 10	(McKean *et al.*, 1993) (Govers *et al.*, 1993)
Rock fragment movement on scree slopes (by livestock trampling)	Ethiopia Greece	4 - 69 3 - 121	(Nyssen *et al.*, 2006) (Oostwoud Wijdenes *et al.*, 2001)

Table 2. Average characteristics of lynchets per study site and assessment of number of years (T) needed for the development of their current dimensions.

Site	n	S [1] (m m^{-1})	Q_s [2] (kg m^{-1} yr^{-1})	C_C [3] (m^2)	In case of F_{TE} = 0.5 [4]		In case of F_{TE} = 0.9 [4]	
					Mass[5] (kg m^{-1})	T [6] (years)	Mass[5] (kg m^{-1})	T [6] (years)
El Tawe	3	0.20	26.2	7.66	5744	217 ± 35	10340	391 ± 63
Groensdael[7]	3	0.11	14.2	19.64	14729	1037 ± 269	26512	1867 ± 483
Martelberg[8]	5	0.19	25.1	10.99	8245	325 ± 93	14842	585 ± 167

[1] S = average slope gradient when the process was ongoing, calculated average of original (natural) slope, and current slope of the tread; [2] Q_s = unit sediment transportation rate by tillage erosion, based on eq. (2) with K = 134 kg m^{-1} yr^{-1} (average of measured K under current conditions of non-mechanised tillage worldwide); [3] C_C = cross-sectional area of sediment trapped in the studied lynchets; [4] F_{TE} =fraction of colluvium in the lynchet generated by tillage erosion, set at 0.5 (based on active process rates measured in Ethiopia) and at 0.9 (based on measurements of positive and negative lynchets at El Tawe); [5] mass of sediment in one m of lynchet, accumulated due to tillage erosion, taking into account C_C, soil bulk density Bd of 1500 kg m^{-3} (Mwendera, 1992), F_{TE}, and a width of 1 m along the contour; [6] T = number of years needed to reach the measured volumes of accumulation in the lynchets (eq. 3); [7] 3 parallel measurements on the same lynchet; [8] upper lynchet not taken into account because sub-recent (see section 3.2)