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Sunken lanes - development and functions in landscapes

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Abstract. Sunken lanes are roads or tracks, 2 m or more wide, that are incised at least 0.5 m, but often by several meters, below the general level of the surrounding land surface. They are formed by the passage of people, animals, vehicles and erosion by water and gravity. Although these anthropogenic landforms are quite common worldwide they received limited interest by the international scientific community. This comprehensive review analyzed all available information on their characteristics, development and functions in landscapes. Most research on sunken lanes has been conducted in Europe, whereas sunken lanes have been occasionally reported in other continents as well. Major topics addressed are spatial distribution, origin and development, morphology, erosion rates, hydrology, ecology, management, geotourism and research needs.

Mean dimensions of sunken lanes reported for various regions vary widely: i.e. 30 – 2300 m for their length; 0.6 – 12.5 m for their depth and 2 – 36 m for their top width. Typical sunken lane densities in European regions (10 to 100 km^2 large) characterized by such landforms range between 0.2 and 0.5 km km^{-2} but for smaller areas (< 10 km^2) densities may reach 1-2 km km^{-2}. In Europe and the Middle East sunken lanes already started to form during prehistoric times. During later periods, with increasing population, settlement density, cropland area and traffic, sunken lanes further deepened and widened and new ones were formed. Some of these evolved towards large permanent gullies whereas others became footpaths or were completely abandoned and can still be observed today as dormant sunken lanes in old forests.

Sunken lane formation results from interactions between natural factors (i.e. lithology and soils, topography, climate, vegetation) and anthropogenic factors (i.e. traffic, land use and management). Rock type, weathering status and soil types control the erodibility of hillslope materials and hence the development and preservation of sunken lanes. Sunken lanes have been reported in several lithologies but most have been studied in loess regions. Sunken lanes, can be initiated at topographic landscape positions with a much lower slope gradient and corresponding contributing area than those needed to initiate classical gullies, due to the combined action of natural (i.e. concentrated flow erosion and mass movements) and anthropogenic processes (i.e. erosion by animal and human trampling, wheel traffic and digging). Once formed, medium to long-term average incision rates of unpaved bare sunken lanes are 1 to 5 cm year^{-1} often exceeding erosion rates on nearby cropland by at least one order of magnitude.

Sunken lanes perform many functions in landscapes i.e. microclimatological, hydrological, geomorphological, ecological, transport, aesthetic, geotouristic, educational, scientific, strategic, and historical functions. Sunken lanes represent long-standing heritage of past agricultural landscapes and, taking into account their natural and cultural assets, justifies their protection. Unfortunately in several regions, sunken lanes are threatened by urban sprawl, agricultural intensification or land consolidation programs. It remains a challenge for environmental planners to conserve this characteristic geomorphosite for the Anthropocene and to reconcile its competing functions.

Keywords: sunken road, hollow road, hollow way, Anthropocene, anthropogeomorphology, geoheritage, ecosystem services.

1. Introduction

The Anthropocene offers unique opportunities to study particular landforms whose development are driven by a combination of biophysical and socio-economic forces. Research in anthropogeomorphology focuses on geomorphologically based interactions between humans and landscape resulting in particular landforms (Goudie and Viles, 2010; 2016, Szabó et al., 2010; Huggett, 2017, Tarolli et al., 2019). One of such anthropogenic landforms induced by traffic in rural landscapes are sunken lanes or hollow roads (White, 1788; Lach, 1984; Lóczy and Süto, 2011; Latocha, 2009). Unpaved roads may be rapidly transformed into permanent landforms as a result of human and animal trampling, vehicle traffic, water erosion and mass movements. The term sunken lane (road gully) is understood as a road deepened, compared to the adjacent land surface, by at least 0.5-1.0 m (Allemeersch, 1987a, b; Nowocien and Podolski, 2008; Zgłobicki, 1998b). This corresponds to the height difference between the road and the neighbouring land surface too large for an agricultural vehicle to cross. Sunken lanes are generally ascribed to the downcutting action of wheeled traffic on the formerly unmade road, augmenting and accelerating the natural process of weathering and erosion (Barton 1987). Boardman (2013) defines sunken lanes as "*road or tracks that are incised below the general level of the surrounding country, often by several meters. They are formed by the passage of people, animals, vehicles and the action of water and gravity (mass movements)*.

Sunken lanes are denoted by various terms in different languages (see Table 1). Figure 1 illustrates some typical sunken lanes observed in various European countries.

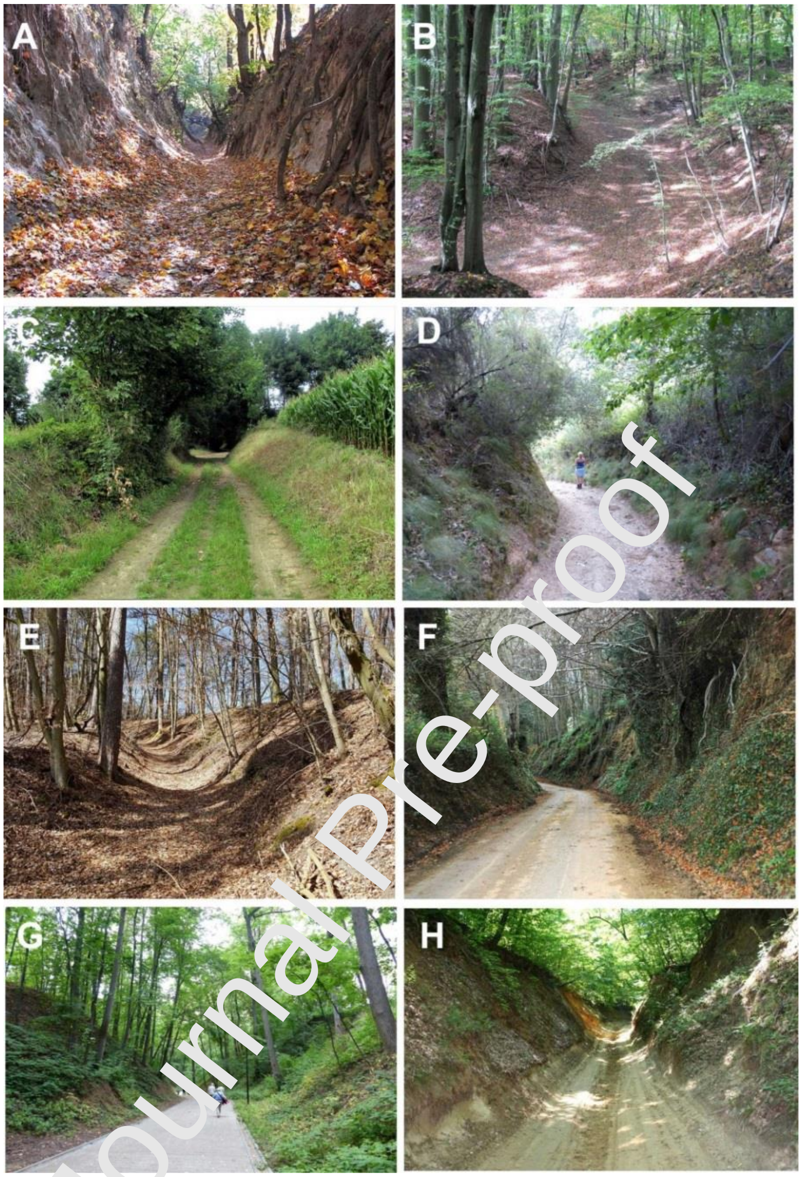

Figure 1. Illustration of typical sunken lanes in Europe. A) Queen Jadwiga Gully, Sandomierz, central Poland (loess), photo: W. Zgłobicki, B) Myjava Hill Land, Slovakia (colluvium on flysch), photo: M. Stankoviansky, C) Central Belgium (loess), photo: J. Poesenn, D) Carucedo, Spain (sandy gravel deposits), photo: J. Poesen, E) Taunus uplands, Germany (loess and debris containing periglacial cover beds over weathered Devonian slates), photo: Ch. Stolz, F) Shepton Beauchamp, Somerset, UK (Jurassic, Bridport Sands), photo: J. Boardman, G) Kazan, Russia

(loamy to sandy deposits), photo: J. Poesen, H) Calea Neagra (Black Lane), Central Moldavian Plateau, Romania (sands), photo: I. Ionita.

Table 1. Terms denoting sunken lanes in several languages

Language	**Terms**
English	Sunken lane, sunken road, hollow road, holloway
Dutch	Holle weg
French	Chemin creux, chemin de service
German	Hohlweg, Hohle, Hohlwegbündel denotes "a bundle of sunken lanes".
Italian	Sentiero/via/strada incavata
Polish	Wąwóz drogowy, głębocznica, wądroże
Slovak	Úvoz, úvozová cesta
Spanish	Camino excavado, camino hueco, camino hundido
Romanian	Drumuri de coasta
Russian	Dorozhny ovrag

The formation of sunken lanes is part of the anthropogenic landscape transformation (Szabó et al., 2010). These landforms are quite common in sloping rural areas of many countries. The formation of sunken lanes in agricultural land, along with the development of gullies and cultivation terraces, can be considered significant features of the anthropogenic phase of the Holocene morphogenesis (Lach, 1984). Due to their relatively small dimensions, sunken lanes do not change the main topographic features of a landscape significantly, but modify the surface of older and larger landforms. Sunken lanes played and still play important roles for humans. All of them functioned or still function as access roads used for transport of animals, goods and persons in rural landscapes (e.g. Westerdahl, 2006; Dotterweich et al., 2012; Superson et al., 2014; Nir et al., 2021). Analysis of the spatial patterns of sunken lanes allows a better understanding of past human movement and historical route networks on both an inter-site and inter-regional level. It can offer a better understanding of human-landscape interactions and settlement patterns, as routes both reflect and influence large-scale cultural and landscape processes, and play a crucial role in the exchange of resources, knowledge, and ideas. Sunken lanes are valuable landscape elements that contribute to the understanding of the (economic) history of a region (Dyer, 2006). Detailed inventories of sunken lanes therefore allow us to supplement and expand the knowledge gained from historical written sources and cartographic data (e.g. Westerdahl, 2006; Volkmann, 2017; De Gruchy and Cunliffe, 2020; Iriarte et al., 2020; Stone, 2020; Verschoof-van der Vaart and Landauer, 2021). In addition, descriptions of sunken lanes as strategic landscape spots, e.g. for hiding troops on the battlefield or for creating obstacles hindering the movement of troops (e.g. cavalry) appear on the occasion of significant military events in European and North American history (e.g. Ehlen and Whisonant 2008; Hippensteel 2019).

Sunken lanes influence the functioning of geomorphological systems and related processes, hydrology and biodiversity. In the past, sunken lanes played an important role in the development of large gullies (e.g. Dotterweich et al., 2012, Superson et al., 2014, 2016; Nir et al., 2021). Today they belong to landforms with a very high intensity of geomorphic processes (Nowocień, 1996; Nowocień and Podolski, 2008; Zgłobicki, 1998b). Sunken lanes increase hydrological and geomorphological connectivity in the landscape by acting as periodic runoff channels during heavy rainfalls, which facilitate and accelerate sediment transfer and increase sediment delivery to rivers (e.g. Słupik, 1984; Froehlich and Słupik, 1986; Froehlich and Walling, 1997; Verstraeten and Poesen, 1999; Kroczak, 2010; Boardman, 2013; Latocha, 2014). When deeply cut into the hillslopes, they drain adjacent areas, which reduces the water content in the nearby soil. Sunken lanes can be hotspots of soil erosion, producing locally large volumes of sediments causing downstream siltation on cropland, in drainage ditches as well as in rivers and reservoirs (Józefaciuk and Józefaciuk 1992; Boardman et al. 2019). According to Nir et al. (2021) human movement creates pathways and roads, which decrease the water infiltration potential and hence results in significant runoff generation and possibly gully erosion. Sunken lanes complicate farming of the land and the performance of farming practices, including soil conservation measures and land consolidation (Nowocień and Podolski, 2008). At the same time, sunken lanes constitute a specific habitat for plants and animals, thus increasing the biodiversity of many agricultural areas (e.g. Stevens, 1987, 1997; Herault et al., 2003; Martens, 2013; Heneberg and Bogusch, 2020). Finally, they arouse the interest of tourists and geotourists as attractive and convenient places for hiking and education (Zgłobicki et al., 2015; Warowna et al., 2016). A better understanding of this geomorphic feature is therefore important for landscape management, but also for bio and geodiversity studies (Pauwels and Gulinck, 2000; Schrodt et al., 2019).

Although sunken lanes are a common geomorphological feature in many regions around the globe, resulting from human-environment interactions and playing an important role in the functioning of rural landscapes, a global review (state of the art) of the different aspects of this landform is currently lacking. Reported specific information on sunken lanes is also often dispersed over several disciplines (e.g. geomorphology, biology, ecology, archaeology, hydrology). Most scientific literature on sunken lanes comes from Europe (see tables 2, 3 and 4 for references)). For many regions, no studies on sunken lanes have been published so far. Even in countries where the number of publications is relatively high, several aspects of sunken lanes have not been addressed, and most publications deal with only one particular sunken lane. There is a lack of area-wide mapping, characterization, dating and understanding of the various functions of sunken lanes in rural landscapes around the globe.

The objective of this paper is therefore to review relevant literature reporting on various aspects of sunken lanes in a selection of European countries where sunken lanes are abundant. These aspects include the conditions for their formation (controlling factors), their spatial distribution, geomorphological processes shaping them, contemporary changes, and the role of appropriate management. Relevant literature reporting on all aspects of sunken lanes was searched and collected in 2020 and 2021 using Web of Science (all databases), Google Scholar and ResearchGate by selecting key words denoting sunken lanes in several languages (i.e. English, Dutch, French, German, Italian, Polish and Spanish; see Table 1). All authors also retrieved "grey literature" (e.g. books, theses, reports, geotouristic brochures) on sunken lanes published in their country and complemented this with their field observations made over the last 50 years.

2.Where do sunken lanes occur in Europe?

Reports and field observations reveal that all European countries have sunken lanes, though their number and density may vary a lot. Apart from individual studies, however, there is no systematic research for larger areas on the influence of lithology on the development of sunken lanes. Reported case studies of these forms in European countries published in international and national research papers is presented below (see also Tables 2, 3 and 4). A recent review by De Geeter et al. (2020) indicates that most sunken lane studies conducted in Europe have focused on hilly loess areas. This may indicate that the density of sunken lanes in these areas is highest. On the other hand metrics such as density of SLs are strongly linked to the density of investigation.

In **Belgium**, sunken lanes are common geomorphic features in sloping rural areas of the silt loam and sandy loam belt (central Belgium) (De Geeter et al., 2020). These have attracted the attention of local and regional organizations as well as scientists investigating various aspects (see Table 2). In **Czech Republic** Demek et al. (2012) reported a dense network of old sunken lanes, formed especially in loess deposits of the Moravian-Silesian Carpathians. Over time, many of these transformed into gullies. In **Denmark and Sweden** ancient sunken lanes connecting settlements and fortresses have been studied by archaeologists because roads contain the collective memory of human travel from prehistory to the present (e.g. Stensager, 2002; Westerdahl, 2006; Ulriksen et al., 2020). In **Germany**, most investigated sunken lanes are located within the central German uplands (Dotterweich, 2008). Sunken lanes contribute to the character of the landscape especially in loess regions and in areas with viticulture (e.g. Rheinhessen, Kaiserstuhl) and along important historic road systems in the uplands (Table 2). The investigation of sunken lanes and former road networks has a long tradition in Germany but so far no systematic analysis of their spatial distribution has been made. In **Great Britain**, sunken lanes are mainly described in the southern part of the country. They occur on the Bridport sands in Somerset and Dorset, on the Lower Greensand in West Sussex and Surrey and on the Chalk of the North and South Downs (Table 2). They also occur on sandstones in the Midlands and in the south west (Boardman 2013). In **Hungary**, sunken lanes are a common landscape feature, particularly in areas with thick loess-mantled hills such as in the Somogy hills or the Tokay hills (Jakab and Szalai 2015; Kerényi, 2015) or on slopes along the Danube river (David et al. 2011). In **Poland**, Józefaciuk and Nowocień (1991) report that the total length of sunken lanes is ca. 19 000 km, which is ca. 50% of the total gully network length (Józefaciuk and Józefaciuk, 1992). Within agricultural uplands they are particularly common in loess areas. For example the total length of sunken lanes within the Lublin Upland and Roztocze (E Poland) amounts to 1451 km, which compared to 3880 km of permanent gullies is a considerable length (Kołodyńska-Gawrysiak et al., 2011; Harasimiuk and Gawrysiak, 2012). Sunken lanes are also found in the highlands, in the Carpathians and the Sudetes (Froehlich and Słupik, 1980; Froehlich and Walling, 1997; Kroczak, 2010; Latocha, 2014; Migoń and Latocha, 2018) (Figure 2). Occasionally they occur in the Lakelands, especially in Pomerania, on the edges of glacial plateaus (Jaworski, 2018) and exceptionally in the lowland belt on the side slopes of large valleys (Rodzik et al., 2015). In **Romania**, sunken lanes are found on the plateaus i.e. Moldavian Plateau, Getic Plateau and Transylvanian Plateau of the Sub-Carpathians (Radoane et al. 1995; 2017). The Barlad Plateau, i.e. the major subunit of the Moldavian Plateau (east Romania), is by far the most representative area where sunken lanes developed. Nykamp et al. (2015) reported the presence of ancient sunken lanes in West Romania that evolved towards gully channels. Sunken lanes are also common in other Romanian hilly areas but they received little or no research attention

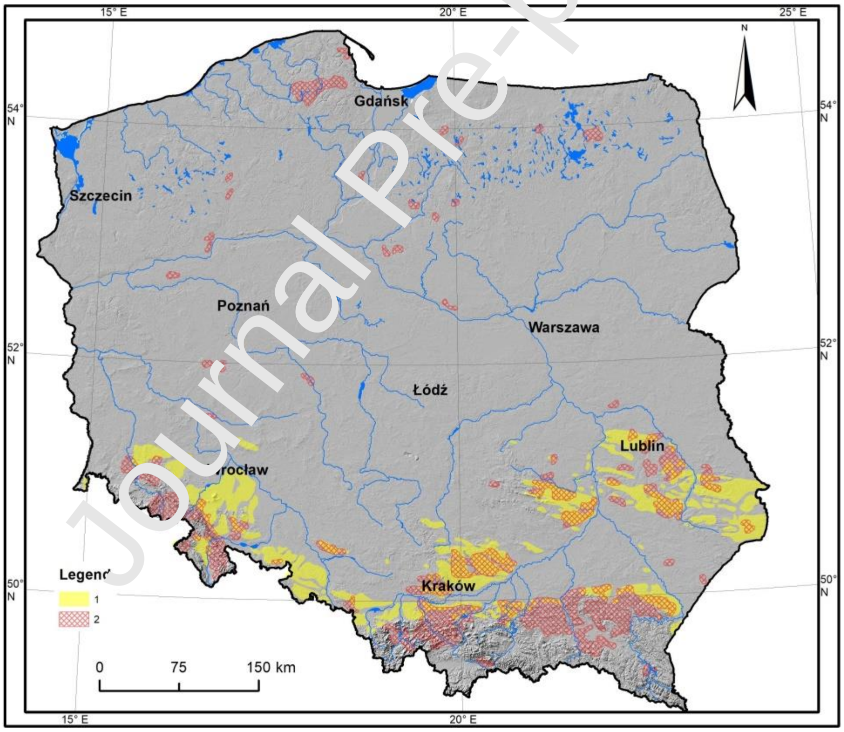

Figure 2. Loess covered areas (1) and regions in Poland with high densities of sunken lanes (> 0.5 km km^{-2}) (2) (based on Józefaciuk and Nowocień, 1991). Loess covers according to Maruszczak 1961, 1987; Hasse et al. 2007.

Sunken lane density is very low in the European Part of **Russia** (EPR). They are relatively uniformly distributed within the southern half of the EPR, where most agricultural lands are located. Most sunken lanes are formed on the relatively steep banks of the different slope sections of the fluvial network (river valley and dry valley, so called balka) as part of unpaved roads connecting different settlements (Dokuchayev, 1936; Sobolev, 1948). In addition, sunken lanes are a very typical element within old Russian cities, located on steep river-banks. They are very often part of old trade roads, which were used for transportation of agricultural products to the local trade fair (Massalsky, 1897; Dokuchayev, 1936; Rysin, 1998). In agricultural areas the density of sunken lines is somewhat greater within the uplands (Srednerusskya, Privolzskaya, Smolensko-Moskovskaya etc.) due to the larger valley densities and the more contrasted relief compared to the lowlands (Sobolev, 1948). In the Carpathian part of Slovakia sunken lanes are linked to the topography of uplands and mountains on one side and downfaulted intra-mountain basins and structurally-lithologically conditioned depressions on the other (Bučko and Mazúrová 1958). In lowlands of the Pannonian Basin the formation of sunken lanes affected mostly the higher parts of hill lands, especially in the contact zones with mountains.

3. Main research topics

An analysis of the literature indicates that various topics of sunken lanes have been addressed by geographers, biologists, archeologists and historians (Table 2). Geomorphologically-oriented studies mainly dealt with processes and intensity of sunken lane development, factors controlling their formation and spatial distribution. In Great Britain and in the papers on the Polish Carpathians, attention was paid to the role of relief forms related to unpaved roads, and sunken roads in connecting hillslope and fluvial geomorphological systems. The important ecological role of sunken lanes was discussed in publications from Belgium and Germany. On the other hand, studies on sunken lanes as tourist and geotouristic attractions were undertaken in Poland. In Belgium, several publications provide guidelines for the multifunctional management of sunken lanes. This literature review suggests that sunken lanes are a typical phenomenon for rural areas in Europe. Field observations outside Europe, however, reveal that sunken lanes are also a common landscape feature in rural areas of other continents (Figure 3).

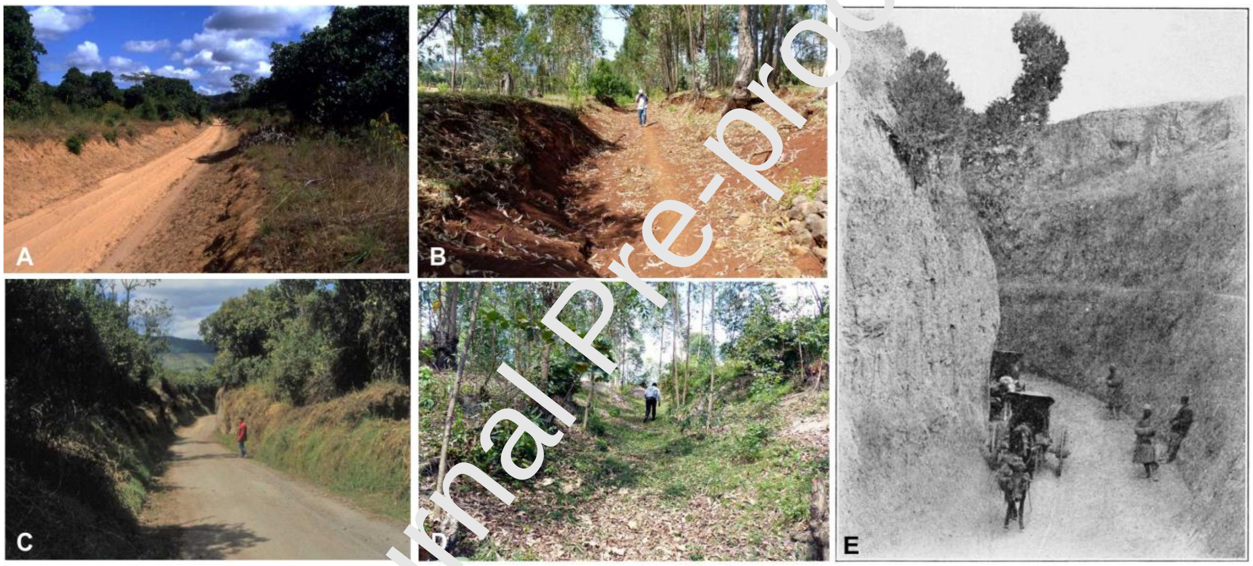

Figure 3. Illustration of sunken lanes observed in Africa, South America and Asia. A - Rondo Plateau, Tanzania (loamy sands in fluvial deposits), B - Arb Gebeya, Ethiopia (loamy clay soils on strongly weathered volcanic rocks (basalts and ignimbrite), C - Quito region, Ecuador (weathered volcanic ash deposits), D - Kaninga, West Uganda (sandy- clayey lacustrine deposits), - - (Photo A-D: J. Poesen), E – loess area, beginning of 20th century, China, (unknown area and author, https://en.wikisource.org/wiki/File:PSM_V82_D117_Roadway_sunken_into_the_loess_by_centuries_of_travel.png).

Table 2. Main research topics of sunken lane studies in some European countries.

Topic	Belgium	Germany	Poland	Slovakia	UK
Distribution	Stevens, 1987; Vanwalleghem et al., 2003; De Geeter et al., 2020	Eichhorn, 1965, Straßmann, 2004; Burse, 2017; Herzog, 2017; Volkmann, 2017 Kirchner et al., 2020;	Kroczak, 2010; Kołodyńska-Gawrysiak et al., 2011; Krzemień and Wałdykowski, 2013; Latocha, 2014	Bučko and Mazúrová, 1958 Stankoviansky, 2003a,b	-
Origin and development	Stevens, 1987; Poesen, 1989, 1993; Poesen, 2018; Poesen et al., 2018. De Geeter et al., 2020	Denecke, 1969; Baier and Wolff, 1993; Ambos and Kandler, 1999; Sandner et al., 2014	Rodzik, 2006; Dotterweich, et al. 2012; Krzemień and Wałdykowski, 2013; Latocha 2009, 2014; Superson et al., 2014, 2016	Stankoviansky, 2003a, b	White, 1788, Boardman, 2013, 2014
Morphology	Allemeersch, 1987a; Vanwalleghem et al., 2003; De Geeter et al., 2020	Hempel, 1957; Denecke, 1969; Kirchner, et al. 2020; Moldenhauer, et al. 2010; Ambos and Kandler, 1999;	Zgłobicki, 1988; Gardziel and Rodzik, 2001; Wałdykowski and Krzemień, 2013; Rodzik, et al. 2015; Migoń and Latocha, 2018	Sperling and Žigrai, 1970; Lukniš, 1977 Stankoviansky, 2003a, b	-
Erosion rates	Poesen, 1989, 1993; Poesen, et al. 1996; Verstraeten and Poesen, 1999	Moldenhauer et al., 2010; Stolz, 2011; Förster, 2012; Dannemann and Hermann, 2014; Kirchner et al., 2020	Ziemnicki, et al. 1975; Nowocień, 1996; Rodzik et al., 2015	-	Boardman et al., 2019
Hydrology	Verstraeten and Poesen, 1999	Bauer, 1993	Słupik, 1984; Froehlich and Słupik, 1986; Froehlich and Walling, 1997; Kroczak et al., 2016	-	Farres et al., 1993; Boardman, 2013, 2014b
Ecology	Deckers et al., 2005; Stevens, 1987, 1997	Baier and Wolff, 1993; Ambos and Kandler, 1999; Müller, 2005; Dannapfel, 2007	-	Kaňuščák, 1988	Way, 1977
Management	Stevens, 1987; Pauwels and Gulinck, 2000; RLD, 2004; RLHV, 2006; Verdurmen, 2018	Dannapfel, 2007	Józefaciuk and Józeaciuk, 1996; Mazur, 1999; Mazur et al., 2015, 2016	-	Barton, 1987

Tourism	-	Ambos and Kandler, 1999	Zgłobicki et al., 2015, 2019; Warowna et al., 2016	Papčo, 2014	-

4. Characteristics of sunken lanes

Different researchers use the terms sunken road or holloway (Table 1) to denote different geomorphological features. The term sunken lane is sometimes used for all unpaved roads whose bottom is below the soil surface. In other studies, these are only forms with a depth of several meters and vertical walls. For example in Poland, the term sunken lane is reserved only for landforms with an unpaved road surface and that are at least 1.5-2.0 m wide and at least 1-2 m deep. More attention has been paid to the morphology and role of unpaved roads (e.g. Wałdykowski and Krzemień, 2013) but not every unpaved road is a sunken lane. Detailed research conducted in the hilly landscape of Roztocze Szczebrzeszyńskie (**Poland**) indicated that the share of landforms connected to incised unpaved roads is as follows: i) shallow incisions (up to 0.3 m deep) - 72% of the landforms, ii) deep incisions (0.3-2.5 m) - 23%, iii) typical sunken lanes (> 2.5 m) - 5% (Zgłobicki, 1998a). For small catchments of Stołowe Mts (SW Poland), Latocha (2014) indicated that on average sunken lanes (road gullies) developed within 6% of the unpaved roads. Therefore, it is not always possible to compare the morphological characteristics of sunken lanes observed in different regions due to the absence of universal definition.

Sunken lanes are most often single, straight-line incisions that run perpendicular or oblique to the contour. A characteristic feature of sunken lanes is that they often have a very small catchment area (Zgłobicki 1998b; De Geeter et al. 2020). An important difference between sunken lanes and permanent gullies is the often oblique trajectory with respect to the contour of sunken lanes on steeper slopes. In contrast, gullies on steep slopes typically cut the contour lines perpendicularly. It should also be noted that when compared to permanent gullies, sunken lanes have no clear vertical headcut. In contrast to gullies not related to a road network cutting the bottom of dry valleys, sunken lanes often develop within convex hillslopes (Figure 4). In some regions a group of nearly parallel sunken lanes have been reported (e.g. Gardziel and Rodzik, 2001; Vanwalleghem et al., 2003; Westerdahl 2006; Demek et al 2012; Martinek and Bíl 2017). Denecke (1969) distinguishes between active sunken lanes (with wheel-tracks and trapezoidal cross section) and abandoned (dormant) ones (characterized by a U-shaped cross-sectional profile) that have become in some cases footpaths.

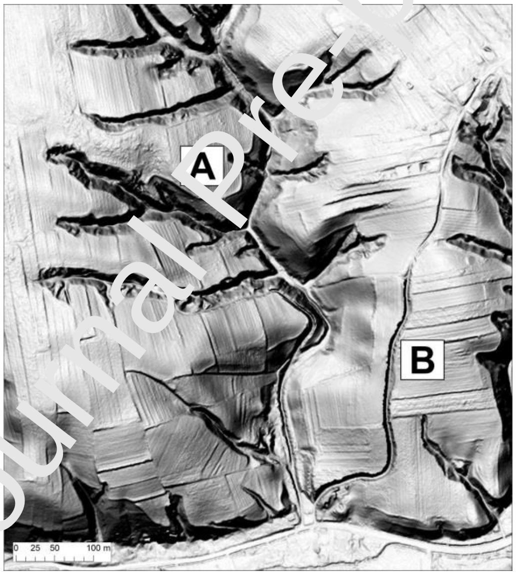

Figure 4. Illustration of a permanent gully (A) and a sunken lane (B) (Nałęczów Plateau, E Poland; source: LiDaR data; http://geoportal.gov.pl).

As to the minimum (bottom and top) width of a sunken lane, no threshold values have been proposed in the literature. Many sunken lanes originated as footpaths which over time became deeper but also wider, particularly when being used by carts. The distinction between an incised footpath and a sunken lane is not clear cut, which is similar to the distinction between a rill and a gully channel. In order to classify rills and gullies quantitatively, a critical channel cross section of 929 cm² (square foot criterion) has been proposed (Poesen et al., 2003). Along the same lines, a minimum bottom width of 2.0 m over most of its trajectory is therefore proposed to distinguish between a sunken footpath and a sunken lane. The transition from an incised footpath to a sunken lane represents a continuum, and any classification of these anthropogenic landforms is, to some extent, subjective. However, after abandonment the bottom width of sunken lanes may decrease to less than 2 m due to deposition of sediments (colluviation) originating from the lane banks (Figure 5).

Figure 5. Abandoned sunken lanes: A - Hungers lane, West Sussex, UK, photo: J. Boardman), B – Carpathian Forelands, S Poland; photo: W. Zgłobicki)

Typical dimensions of sunken lanes in several European countries are shown in Table 3. Most often sunken lanes are rather shallow (i.e. less than 2 m deep), but under favourable conditions they may reach considerable sizes: i.e. several hundred meters long, and even over 1 km and up to 12-15 m depth in Belgium, Poland and Hungary (Allemeersch, 1987a; David et al., 2011; Kołodyńska-Gawrysiak at al., 2011). Boardman (2013, Table 3) lists sunken lanes up to 2.3 km in length in the Midhurst area of West Sussex, UK, with gradients between 0.03 and 0.06 m.m^{-1}. In China, sunken lanes up to 40 m deep have been recorded (David et al., 2011). The banks at both sides of the road are often interrupted by passageways (side-roads) to access agricultural plots or due to a crossing with another sunken lane (Boardman, 2013).

Figure 6. Cross-sections of a sunken lane (A) and a typical permanent gully (B) (loess area, E Poland) (Photo: W. Zgłobicki)

The cross-section of sunken lanes is either trapezoidal or U-shaped (Figure 1 and 6). In cohesive silty sediments, such as loess, or sandy sediments with intercalated sandstone layers, the walls of these forms can be very steep, sometimes vertical. This applies in particular to currently used roads and clearly distinguishes these forms from permanent old gullies, which have most often a V-shaped or trapezoidal cross-section. U-shaped cross-sections often result from mass movement processes on the sidewalls. Sunken lanes that are currently in use typically have a flat 3-4 m wide bottom that is usually devoid of vegetation. If the road is intensively used and the bottom levelled regularly, the cross section is close to a rectangle. The depth of sunken lanes typically increases when travelling from hilltop downslope, reaching several meters in the case of roads used for several centuries (Figure 7). The maximum depth typically occurs at convex hillslope sections.

Table 3. Reported dimensions (mean, range, maximum) of sunken lanes in European countries.

Country	Region	Length [m]	Width (floor) [m]	Width (top) [m]	Depth [m]	Reference
Belgium	Central Belgium, Meerdaal Forest	65	1.1	4.6	0.6	Vanwalleghem et al. (2003)
Belgium	Central Belgium (6 villages, cropland)	285 (12-913)	2.3 (0.8-11.0)	10 (5-28)	2.5 (0.5-10)	De Geeter et al. (2020)
Germany	Lower Saxony	100 - 1200		< 10	< 2 - 8	Kirchner et al. (2020)
Germany	Taunus uplands	1100	1.5-3	< 10	< 5	Stolz (2011)
Germany	Rheinhessen loess area	83-320	2.5	-	< 6	Ambos and Kandler (1999)
Poland	Lublin Upland, Roztocze Region	310-1300	2-7	6-36	1.5-12.5	Gawrysiak, (unpublished data)
Poland	Nałęczów Plateau	100-600	3-5	-	up to 6-8	Zgłobicki (1998b)
Poland	Carpathian Mts.	-	2	5-16	0.5-5.0	Sajdak (1987)
Poland	Sudetes	20-720	-	-	0.4-4.0	Latocha 2014
Poland	Sudetes	Up to 1000	-	-	4-10	Jary et al. 2010
Romania	Moldavian Plateu	<600	3-5	10-15	< 4	Ionita (unpublished data)
Russia	Agricultural areas of the Russian Plain	30-60	3-5	4-7	1-5	Golosov (unpublished data)
Slovakia	Low Tatras	-	< 3.1	< 13.5	< 8	Sperling and Žigrai (1970)
Slovakia	Little Carpathians	<1200	-	-	< 4	Bučko 1963 Lukniš (1977)
Slovakia	Považský Inovec Mts	700	-	15	< 8	Liščák et al., (2012)
Slovakia	Myjava Hill Land	100 - 800	-	-	2 - 10	Stanoviansky (2003a,b; unpublished data)
UK	Midhurst	900-2300	1-4	1-5	< 10	Boardman (2013)

Figure 7. Active sunken lanes. Illustration of successive downcutting stages of unpaved roads by traffic and water erosion in the western part of Nałęczów Plateau (E Poland) (Photo: W. Zgłobicki).

There are only few measurements of sunken lane densities in various European regions. For some regions (10 to 100 km^2 large) characterized by sunken lanes in Belgium, Poland and the UK, reported densities are typically 0.2-0.5 km km^{-2} (Allemeersch, 1987a; Verstraeten et al., 2009; Kołodyńska-Gawrysiak et al., 2011; Boardman, 2013). Józefaciuk and Nowocień (1991) reported densities above 0.5 km km^{-2} for vast regions in Poland (Figure 2). For areas smaller than 10 km^2, densities may reach 1-2 km km^{-2} (Zgłobicki, 1998a; Latocha, 2014; De Geeter et al., 2020).

5. Age of sunken lanes

Research on determining the age of sunken lanes is very limited. According to Boardman (2013), determining the time of first incision of a sunken lane is not straightforward. The initial incision can be very old, but the slopes of the sunken lane banks can be very recent due to more recent erosion processes or mechanical widening by humans. Most data available on this subject are primarily estimates and are not based on detailed dating results. In this case, assessments of the age of the initial sunken lane incision is based on the assumption that the emergence of new rural roads is related to major socio-economic changes, the establishment of new settlements, or changes in the structure of agriculture. The association between ancient settlements (towns), tumuli, castles, fortresses, ports, mines, quarries and important roads with the presence of nearby sunken lanes (hollow roads) connecting sites of past human interventions is a strong indication that the initiation of these sunken lanes dates back to their age (see e.g. Shore, 1898; Stensager, 2002; Westerdahl, 2006; Wilkinson et al., 2010; Slamova et al., 2014; Nouwen, 2020; Ulriksen et al., 2020; Table 4.). This approach is associated with difficulties in estimating the age of these landforms and their continuous transformations by natural and anthropogenic erosion processes causing the blurring of the original morphology. For this reason, we only have more precise dates for the recent (i.e. less than 200 years old) sunken lanes. Determining their age is mostly based on the analysis of historical maps which allows one to reveal more precisely the period during which a road was constructed that developed into a sunken lane.

Table 4 summarizes the findings from case study areas and regions reporting periods during which sunken lanes most probably were initiated and in some cases evolved towards larger permanent gullies. From this overview, one can conclude that as soon as permanent settlements, tumuli, castles, fortresses, ports, mines and quarries were established sunken lanes in footpaths or unpaved roads could develop. This literature review indicates that in Europe and the Middle East sunken lanes already developed in prehistoric times: e.g. in Belgium, Czech Republic, Denmark, Germany, Romania, UK, Syria and Iraq. During subsequent periods with increasing population, settlement density, cropland area and traffic, sunken lanes further developed e.g. in the Roman Period (Belgium, Hungary), Middle Ages (e.g. Belgium, Czech Republic, Denmark, Germany, Hungary, Poland, Slovakia, and Romania) and early to late Modern times (e.g. Belgium, Poland, Romania, Russia, Slovakia). Over time, most sunken lanes further deepened and widened, some of them evolved towards large permanent gullies whereas some of these became footpaths or were completely abandoned and can still be observed today as dormant sunken lanes in old protected forests.

Table 4. Reported periods during which sunken lanes were most likely initiated in various countries.

Country	**Region**	**Age**	**Method**	**Reference**
Belgium	Meerdaal Forest	Prehistoric	Archaeological evidence	Vanwalleghem et al. (2003)
Belgium	Meerdaal Forest	Roman	Archaeological evidence	De Bie and Adriaenssens (2009)
Belgium	Tongeren	Roman	Archaeological evidence	Nouwen 2020
Belgium	Limburg	Late Medieval 18th century	Historical documents and maps	Allemeersch (1987b)
Czech Republic	Bohemia, Moravia	Prehistoric - Medieval	Archaeological evidence	Martínek and Bíl (2017)
Denmark	Broskov, Zealand	Stone Migration Age (AD 400-550)	Archaeological evidence	Westerdahl (2006)
Denmark	Borgring	Viking Age (10th century AD)	Archaeological evidence	Ulriksen et al. (2020)
Denmark	Jutland	Medieval	Archaeological evidence	Stensager (2002)
Germany	Lower Saxony	Prehistoric	Archaeological evidence	Asmus (1958), Hinz (1951/52)
Germany	Main River Region	Iron Age to High Medieval Period	Archaeological evidence	Volkmann (2017)
Germany	Taunus Mts.	Medieval	Historical documents	Stolz (2011); Eichhorn (1965)
Germany/France	Upper Rhine valley	Iron Age	Archaeological evidence	Faupel (2017)
Germany	Lower Saxony	Medieval	Historical documents	Kirchner et al. (2020)
Hungary	Hungary	Roman and Medieval	Archaeological evidence	David et al. (2011)
Poland	Nałęczów Plateau	Medieval	Historical documents	Hoczyk-Siwkowa (1999)
Poland	Nałęczów Plateau	16th -17th centuries	Dating of colluvial sediments	Dotterweich et al. (2012); Superson et al.

				(2014)
Romania	West Romania	Late Bronze Age	Archaeological evidence	Nykamp et al. (2015)
Romania	East Romania	Late Medieval 18th century	Historical documents	Ionita (pers. Comm.)
Russia	European part	17th and 18th centuries	Historical documents	Pallas, 1876; Sobolev, 1948
Slovakia	Zvolen – Pustý hrad	Medieval	Archaeological evidence	Slamova et al. (2014)
Slovakia	Myjava Hill Land	1550 - 1840	Historical maps and documents	Stankoviansky (2003a, b)
Syria	Mesopotamia	Early Bronze Age	Archaeological evidence	Ur (2003)
Syria	Tell Brak (northern Syria)	Bronze Age	Archaeological dating	Wilkinson et al. (2010)
Syria and Iraq	Southern Mesopotania	Bronze Age	Archaeological evidence	De Gruchy and Cunliffe (2020), Stone (2020)
UK	Hampshire	Anglo-Saxon (5th - 11th century)	Archaeological evidence	Shore (1889)
UK	Southern England	Iron Age	Archaeological evidence	Boardman (2013); Bell (2020)

Detailed geomorphological and archaeological investigations of an old forest in central **Belgium** (Meerdaal) suggest that the presence of old and abandoned sunken lanes may date back to prehistoric (Neolithic; Vanwalleghem et al., 2003; Poesen et al. 2018) and Roman times (De Bie and Adriaenssens 2009). In Limburg (East Belgium) few indications point to the presence of sunken lanes before Medieval times (Allemeersch, 1987b). During the late Medieval period, the road network in rural areas was fully established indicating that sunken lanes could have developed from these times onwards. Study of historical maps indicate that at the end of the 18th century most rural roads had already sunken lane sections (Allemeersch, 1987b).

Due to a strong population increase since Medieval times, the cropland area expanded and transportation intensity increased (Stevens, 1987, 1997). Moreover, most roads at that time were not paved which favoured the (further) incision of the sunken lanes. A second wave of road incision occurred in the loess belt in the late 19th and in the beginning of the 20th century (Allemeersch, 1987b). Again, an increase in transportation intensity occurred due to developments in agricultural techniques. Halfway through the 20th century the number of sunken lanes appeared to be reduced when comparing topographical maps with the current situation (Allemeersch, 1987b). Since the 1960s many sunken lanes disappeared during land consolidation activities (through infilling of sunken roads). Other sunken lanes were abandoned or filled up since they were no longer useful in the road network. At the outskirts of villages, sunken lanes disappeared due to urban sprawl and the remaining sunken lanes were often paved, preventing their further incision (Stevens 1987, 1997; Boardman, 2013). Also new sunken lanes originated during the construction of new roads, adjusted to the dimensions of modern agricultural vehicles and transportation needs (Stevens, 1987, 1997).

Several studies in **Germany** describe prehistoric sunken lanes and wagon tracks (Asmus 1958) and paths near prehistoric burial mounts in Schleswig,North Germany (Hinz ,1951/52). In Lower Saxony, Kirchner et al. (2020) investigated sunken lanes that were most probably formed in Medieval times. This is concluded from the ages of the nearby settlements and the analysis of soil profiles exposed in sunken lanes. A Late Medieval system of sunken lanes in the Taunus Mts. (Western Germany), in connection with a deserted settlement, was reported by Stolz (2011). However, at that time these roads were mostly not deeply incised. By combining studies on the social-economical history of rural areas with recent dating of sediments, researchers concluded that the development of the majority of the road gullies in Western Europe started during the late High Middle Ages. Stolz (2011) dated colluvial sediments from field terraces, which were partly cut by sunken lanes (and are therefore younger). Additionally, historical documents describing road trajectories have been analyzed.

In **Poland** the development of most sunken lanes was undoubtedly associated with the development of agriculture and trade in the Middle Ages, at the beginning of Polish statehood, and locally perhaps even earlier, in connection with the establishment of villages in river valleys and cropland plots on the plateaus (Hoczyk-Siwkowa, 1999). The rapid development of gullies, including sunken lanes, occurred since the end of the fourteenth century and was associated with the widespread establishment of villages and farms as well as the stabilization of land use and the intensification of cultivation, including the introduction of the three-field system (Maruszczak, 1988). After great geographical discoveries, the demand in Western Europe for forest and agricultural products: wood, tar, grain, ropes, canvas (Gierszewski, 1982) played an important role. Access roads to the river ports were intensively used then, including the town of Kazimierz on the Vistula. Kazimierz's "golden age" as a grain export centre falls at the turn of the 16th and 17th centuries. The intensive use of roads was accentuated by the extreme climatic phenomena of the Little Ice Age, resulting in the rapid development of gullies (Dotterweich et al., 2012; Superson et al., 2014). However, a large part of the sunken lane network is younger and was formed during the last 100-200 years.

Nykamp et al. (2015) describe sunken lane and gully channel patterns which were formed in association with Late Bronze Age pathways at the fortification enclosure of Iarcuri in Western **Romania**. The fact that certain channels can be associated with the verified gates or the settlements within the Late Bronze Age fortification suggests that they formed during the same period as hollow ways. These patterns are very similar to ancient hollow ways observed in Mesopotamia, Syria, south-eastern Turkey, and northern Iraq (Wilkinson, 1993; Wilkinson et al., 2010) or in the Northern Negev, Israel (Tsoar and Yekutieli, 1992). However, based on an analysis of permanent gully growth rate and the deforestation history of the area (Radoane et al. 1995, 2017; Ionita et al., 2015a) it can be concluded that most present-day sunken lanes on the Moldavian Plateau (east Romania) are not more than 300 years old.

The age of sunken lanes in the European Part of **Russia** is directly linked to the history of the country and the increasing population. During the Middle Ages, the main transport arteries in Russia were rivers. Permanent roads that connect major cities only appear from the beginning of the 17th century. From then onwards, sunken lanes developed on sections of these main roads (Tereschenko, 2007). Moreover, in each ancient city of Russia, whose age is approximately 900-950 years and younger, sunken lane formed from the moment of their foundation, since the cities were located on high river banks (Pallas, 1876; Sobolev, 1948). With the growth of the population, starting from the 18th century, the number of secondary roads between individual settlements began to grow along the shortest trajectory between settlements, in contrast to the main roads, which were mainly located along the relatively flat watersheds. The network of unpaved roads between settlements reached its highest density in the late 19th and early 20th centuries, i.e. at a time corresponding to the highest peasant population density in Central Russia (Ioffe et al., 2006). It is most likely that the majority of sunken roads, that are mainly located in rural areas in the southern half of the East-European Plain, originated in that period (Gelfer, 1901; Sobolev, 1948).

Analysis of written historical sources and old maps in the Myjava Hill Land in **Slovakia** suggests that sunken lanes in most of this territory originated in the 16th century until the 1840s (Stankoviansky, 2003a, b). Their development in this period results from the cumulative effect of both important land use and climatic changes. In this area there is ample evidence of the important role of roads in the development of gullies and sunken lanes. In a first phase sunken lanes formed in rural road tracks and paths. Later permanent gullies developed by erosional deepening of them. Gullies and sunken lanes that formed in parts of the Myjava Hill Land that were settled earlier, can be older (Stankoviansky, 2003a, b). At the Pustý hrad site near the town of Zvolen, it was confirmed that sunken lanes date from the Medieval period (Slámová et al. 2014).

Based on historical maps and archaeological data, it was found that some road patterns currently observed in southern England (**UK**) date from prehistoric and Roman times (Boardman, 2013). In the Midhurst area many sunken lanes link Saxon age villages (5th century AD), at river crossing points, to forest, heathland and grazing on uplands to the north and south (Boardman, 2013). They are likely to have been part of a system of transhumance, of seasonal movement of animals to upland pastures. Barton (1987) stated that "*while in most cases downcutting is of considerable antiquity the existing cutting slopes may be of much more recent age*". Many sunken lanes are now paved and downcutting has ceased. Hungers Lane (West Sussex, UK) was abandoned in 1800 as a major routeway linking the towns of Chichester and London (Figure 5; Vine, 1985). It is 1.3 km long and used today as a footpath.

6. Factors controlling the genesis and development of sunken lanes

The most important biophysical factors controlling sunken lane formation include slope gradient, type of soil and bedrock, climate as well as vegetation type and cover (Denecke, 1969). At the continental scale one may state that the development of sunken lanes basically requires the presence of two major natural factors: a lithology and soil type characterized by a low erosion resistance and a hilly topography (Kołodyńska-Gawrysiak et al., 2011; De Geeter et al., 2020).

Formation of these landforms is a type of gully erosion and hence slope gradient and catchment area control flow shear stresses and hence flow erosivity. To create a sunken lane an unpaved footpath or road needs to be first established on an inclined surface in an area with erodible soils that have some cohesion to maintain subvertical road banks. Next, various anthropogenic factors control its further development and evolution. These factors are discussed below. Literature presenting quantitative information on factors controlling sunken lane development is, however, scarce.

6.1. Lithology and soils

Rock type, weathering status and soils control the erodibility of the material in which sunken lanes develop, and hence their initiation, development and preservation. An inventory of sites and regions in Europe where sunken lanes have been studied reveals that most study areas are located on silty soils (De Geeter et al., 2020). In fact, most sunken lanes in Europe have been reported in loess landscapes with Luvisols and Cambisols (e.g. in Belgium, Germany, Hungary, Czech Republic, Poland, Russia). The incision of wheel-tracks by concentrated runoff can be extremely rapid in loamy, sandy loam and loamy sands as these textures rank amongst the most susceptible soil materials to soil erosion by water (Poesen, 1993; Knapen et al., 2007). However, so far, no systematic spatial analysis of the relationship between the occurrence of sunken lanes and lithology has been conducted, except one study in **Poland**. Research of the spatial distribution of sunken lanes in the Lublin region, E Poland (12,000 km^2) and their link with lithology indicates that more than half of them developed in loess deposits. Loess occupies about 27% of the study region, but 56% of all observed sunken lanes are located there (with a total length of 810 km). Loess areas have also the highest sunken lane densities, up to 9.5 km km^2 (Kołodyńska-Gawrysiak et al., 2011). Sunken lanes have been observed in Sudetes (SW Poland) in periglacial deposits (Migoń and Latocha, 2018) and occasionally in sands (Rodzik et al., 2015). In **Belgium** sunken lanes also formed in the sandy and the sandy loam belt as well as in areas where soft rocks (chalk, calcarenite or weathered shales) are present at shallow depth, provided there are sufficiently steep hillslopes. In the low mountain ridges in **Germany**, sunken lanes developed in profiles with thick periglacial deposits, and more rarely in saprolithic bedrock. The prevailing lithology for a long-term preservation of sunken lanes in **Romania** are sandy-loamy deposits, while a clayey substratum/soil or seams of clay and sand favour mass movements soon after their incision (Ionita et al., 2015a).

In mountainous parts of **Slovakia** the highest gully and sunken lane density occurs in areas with less resistant flysch and volcanic rocks. In the lowlands the densest network of these features is associated with Neogene sediments and especially with loess (cf. Bučko and Mazúrová, 1958). In the **UK** the materials of the sunken lane banks can range from loose sand of the weathered mantle, weakly locked or locked sands and harder, cemented rock bands or masses and their stability cannot be quantified by traditional soil or rock mechanics methods (Barton, 1987).

6.2. Topography

Sunken lanes typically develop as a result of erosion by surface runoff over a bare footpath or road surface with low permeability. Therefore, sloping surfaces are needed for this runoff to incise. The slope gradient does not have to be large to allow for the initiation of a sunken lane: i.e. 0.02 to 0.04 m m^{-1} (Stevens, 1997). In such cases, however, they form shallow road incisions (Zgłobicki, 1998a). Deeper sunken lanes develop on steeper slopes where the erosion rates increase rapidly above a longitudinal road slope gradient of 0.08–0.10 m m^{-1} (Nowocień, 1996). Only two studies discuss the relationships between topography and the occurrence of sunken lanes. A detailed analysis of the topographic characteristics of 132 representative sunken lane initiation sites in the Belgian loess belt revealed no clear trend between soil surface slopes of the surrounding land (S, ranging between 0.02 and 0.23 m m^{-1}) and the corresponding runoff contributing areas (A, ranging between 93 m² and 114 ha; De Geeter et al., 2020). The absence of a clear relation between S and A values for sunken lane initiation points contrasts with a clear negative trend in such topographic data for classical gully heads (Torri and Poesen, 2014; Torri et al., 2018). These observations clearly point to the importance of other than natural processes (i.e. concentrated runoff erosion) controlling the formation of sunken lanes, i.e. anthropogenic processes (erosion by animal and human trampling, wheel traffic and digging). This study also revealed that sunken lanes can be initiated at landscape positions with a much lower slope gradient and corresponding contributing area than those needed to initiate classical gullies, even under very erosion-prone land use types (De Geeter et al., 2020). Since sunken lanes may even incise gently sloping plateaus (e.g. in Poland and Belgium), the slope gradient threshold may be very small (i.e. 0.01 – 0.02 m m^{-1}).

According to Nowocień and Podolski (2008) the deepest sunken lanes in loess regions of E Poland formed on slopes with a gradient of 0.08 to 0.12 m m^{-1}, and the shallowest ones in areas with a slope less than 0.08 m m^{-1} and above 0.14 m m^{-1}. In areas with diversified relief, the basic network of agricultural unpaved roads (at least 25% of the total road length) is located on slopes with a gradient of 0.06 to 0.12 m m^{-1}. Intensive transport on these roads causes rapid destruction of the road surface, which in turn contributes to the development of permanent gullies. Roads with a gradient exceeding 0.14 m m^{-1} typically have less traffic. An analysis of the impact of topographic height differences within polygons of 10 km^2 on the occurrence of sunken lanes in an area of 12,000 km^2 (i.e. 1200 polygons) of SE Poland was made by Kołodyńska-Gawrysiak et al. (2011). The results indicated that these forms sporadically develop at relative topographic height differences of less than 20 m. Occurrence of height differences in the range of 20-40 m causes a slight increase in the average density of sunken lanes to 0.02 km km^{-2}. The average density further increases significantly with relative heights in the range of 40-60 m to 0.1 km km^{-2}. It further increases to 0.18 km km^{-2} when the height differences reaches 60-80 m, and the highest values (0.25 km km^{-2}) are reached when the height differences exceed 80 m.

Calculations made on the basis of precise LiDAR data for 24 representative sunken lanes located in the loess areas of Lublin region indicated a mean slope of the lane surface of 0.07 m m^{-1} (range 0.02-0.135 m m^{-1}). The average catchment area (upstream of the SL initiation point) was 2.2 ha (range 0.2 to 9.0 ha), while the average slope of the catchment area was 16.7%. (Gawrysiak, unpublished data).

6.3. Land use

Land use type plays an important role, as sunken lanes mostly occur in farmland and less in pastureland or woodland. Important for their rapid development is the frequency of traffic, which is influenced by the organization and size of the cropland parcels and pastures. Traffic on the rural roads is also related to the area served by the road and economic activities (Nowocień, 1996). The best land use conditions for the development of a network of sunken lanes are found in regions with important communication routes and access roads between villages located in valleys and arable fields and pastures located at higher elevations (Zgłobicki, 1998a; Gardziel, Rodzik, 1998, 2000, 2001; Dotterweich et al., 2012; Superson et al., 2014).

The lack of vegetation in the sunken lane bottom, contributes to an accelerated deepening of the road surface as well as to rill and gully erosion following abandonment. Topsoil degradation (i.e. by compaction and erosion) caused by animal trampling and vehicle driving, hinders the growth of herbs, shrubs or trees on the lane surface and strongly contributes to its deepening. In contrast, the development of a grass, shrub and tree cover in the sunken lane bottom and banks contributes to the conservation of its cross-sectional and longitudinal profiles and the identification of ancient sunken roads (Denecke, 1969). Similar to the other factors, no detailed spatial analyses were conducted to explore the relation between the occurrence of sunken lanes and land use type. The spatial pattern of sunken lanes in relation to land use in the Lublin region (**Poland**) shows that 77% of these forms developed within arable land. The land use mosaic (many small elongated plots), characteristic for E Poland, favours the development of a dense rural road network, which facilitates the formation of sunken lanes (Zgłobicki and Baran-Zgłobicka 2012).

In **Germany** most sunken lanes developed in connection with historical road systems of regional or trans-regional character. This also applies to other regions e.g. Westerdahl (2007); Volkmann (2017); De Gruchy and Cunliffe (2020); Iriarte et al. (2020); Stone (2020); Verschoof-van der Vaart and Landauer (2021). Mapping sunken lanes is a common method for the detection and reconstruction of ancient road systems (Eichhorn, 1965). Furthermore, sunken lanes functioned as access routes to particular sites such as castles, deserted settlements, historic ferry terminals, charcoal kiln sites or glass and ironworks. In Slovakia a relatively high density of sunken lanes is also found in regions with vineyards where they are linked with a dense network of access roads (Bučko, 1963; Lukniš, 1977).

7. Processes shaping sunken lanes

Because of the large range in slope gradients, microclimate and vegetation (cover and type) within sunken lanes, sunken lanes are also affected by several soil erosion processes: i.e. various water erosion processes (i.e. splash, sheet, rill, gully erosion, piping, tunneling) as well as mass movement processes (i.e. creep, soil fall, soil topples and shallow landsliding), soil transport by tree uprooting and digging animals on the steep sunken lane banks and anthropogenic erosion processes (detachment by animal and human trampling and vehicle traffic, soil digging and lane reshaping) (Denecke 1969; Lach, 1983; Poesen 1989, 1993; Kołodyńska-Gawrysiak, et al. 2011, Boardman 2013; Figure 8).

In a first stage, as a result of the mechanical impact of trampling (by humans and animals) and vehicle wheels, the vegetation is destroyed, the topsoil is compacted and small linear depressions, paths or furrows, are formed. These processes have been described in the development sunken lanes in hollow roads in Hungary (Veress et al., 2012), and in the vehicle wheel tracks leading to gully formation in the Karoo, South Africa (Boardman, 2014b). The topsoil compaction hampers vegetation growth and biomass production, both above and below ground. As vegetation cover decreases and root development is severely limited, these bare tracks (with reduced root cohesion) have a very low erosion resistance. Despite their compacted topsoil bare loamy topsoils become very vulnerable to various erosion processes due to soil detachment by trampling, vehicle traffic and during rainfall by slaking effects when initially dry (Le Bissonnais, 2016). The bare topsoil of these depressions is also characterized by a low infiltration rate and permeability, and therefore during rainfall significant overland flow is produced. Simulated rainfall experiments (with an intensity of ca. 105 mm h^{-1} and lasting 45 min) revealed event runoff coefficients of 80 % on unpaved roads, compared to only 0-20 % for agricultural fields (Ziegler et al. 2000). Because of their microtopography, the compacted area (with a low infiltration capacity) will concentrate runoff generated on the nearby areas. During rainfall the concentrated runoff exerts a large flow shear stress on this soil surface (having a low erosion resistance) resulting in soil detachment and transport, rill and ultimately gully erosion (Figs. 9 and 10). Soil detachment by trampling and vehicle passages (i.e. soil material being detached by vehicle wheels) prepares for the rapid evacuation of sediments during overland flow events and leads to a gradual lowering of the footpath, cattle track or road surface. Deepening of the rill channels progresses gradually and often the rills expand laterally, as passing wheeled vehicles break their edges. The development process of sunken lanes can be a gradual process but according to Stevens (1997) several documents report that during and immediately after a heavy rainfall event sunken lanes were washed out by several decimetres up to 1m. Thus, individual high-magnitude rainfall events may play an important role as well. Another process that operates simultaneously, is the collapsing of the sub-vertical slopes of the sunken lane (mass movements) and this is called bank erosion. When the road surface deepens, the side slopes are undercut and destabilised after which they evolve by mass movement processes to a new equilibrium (Figure 8E). Piping erosion processes on the sunken lane banks is also common. Soil removal by tree fall and animal burrowing (by e.g. rodents, rabbits, badgers) contributes to the further retreat of the sunken lane banks. If the erosion rate on the sunken lane bottom and banks is very high, also trees and shrubs growing in the sunken lane may be eroded as well (Stevens, 1997). Sunken lane surface lowering by large concentrated flow erosion events can be very intense (see table 5) compared to erosion rates in the surrounding areas. Deeply incised sunken lanes induce strong hydraulic gradients in their banks which may trigger soil piping and tunneling as well as various mass movement processes.

Piping erosion results from soil detachment and entrainment by subsurface (concentrated) flowing water often in macropores of various origin (i.e. soil cracks, biopores). This leads to the formation of linear voids which then may result in the collapse of the pipe roof and the formation of bank gullies in the sunken lane (Poesen, 1989, 2018). The probability of piping is very large in sunken lane banks that cut into thick loess covers. Particularly outcrops of undifferentiated (calcareous) loess (parent material) in sunken lane banks are very susceptible to piping and soil collapse (Nadal-Romero et al., 2011).

Figure 8. Common soil degradation processes in sunken lanes formed in loess. A – wheel compaction and soil detachment during traffic, B – rill erosion on the lane bottom, C – tree fall on the bank, D – piping and pipe roof collapse on a lane bank resulting in a bank gully, E – soil slumping on sunken lane bank (Lublin Upland, Sandomierz Upland, E Poland). (Photo: W. Zgłobicki, J. Rodzik).

Another process of sunken lane formation results from direct digging of the sunken lane by humans, for instance in the case of quarries where access routes have been dug. Recently, sunken lanes are mostly broadened by heavy machinery, scraping the sunken lane banks to allow large transport vehicles to pass (Stevens, 1997). This leads to significant erosion of the banks and levelling of the lane bottom.

The vast majority of sunken lanes originated in footpaths, cattle tracks or unpaved rural roads used by vehicles and then developed into sunken lanes as described above. However, some authors report that in a limited number of cases, the formation of gullies preceded the development of the sunken lane (e.g. Stevens 1987, 1997; Hassen and Bantider, 2020). In the latter case, once a gully channel formed it was subsequently used as an access road by humans and cattle (Poesen, field observations in East Africa).

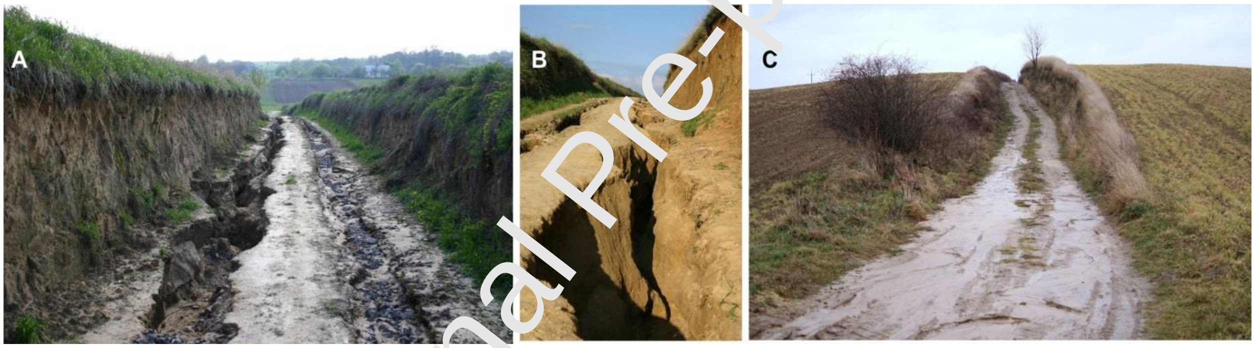

Figure 9. Gully erosion on the bottom of a sunken lane (A, B) and sediment deposition at the outlet (C) (Nałęczów Plateau, E Poland, loess) (Photo: J. Rodzik).

Table 5. Reported current (mean, range, maximum) erosion rates in bare, unpaved sunken lanes.

Country / Region	Rate of incision mean*, range**, maximum*** (cm $year^{-1}$)	Period (years)	Source
Belgium / Limburg	1-2**	500	Based on field data and historical sources Allemeersch, 1987a, b
	50***	One wet year with rapid snowmelt	
Ethiopia / Gelawdiwos	3.3–5.0**	30	Poesen, unpubl. data
Hungary / Kőszeg Mountains	70***	Rainfall event (100 mm)	Veress et al., 2013
Poland / Carpathian	0.08 – 4.13**	4 years	Wałdykowski and Krzemień, 2013

Mountains			
Poland /Lublin Upland	1.5*	Present-day	Mazur, 2008
Poland /Lublin Upland	4.5* (3-9)**	< 50 years	Nowocień, 1996; Nowocień and Podolski, 2008
Poland Lublin Upland	2.5–4.0**	< 50 years	Rodzik et al., 2015
E Romania	1.6**	100	Ionita, 2006
Tanzania /Rondo Plateau	ca. 100***	One rainy season	Poesen, unpubl. data

Table 5 lists reported erosion rates in sunken lanes. Typical medium to long-term average incision rates within bare, unpaved sunken lanes are 1 to 5 cm year^{-1} (or 100 – 500 m³ ha^{-1} year^{-1}). These erosion rates are 10 to 50 times those reported for sheet and rill erosion (Maetens et al., 2012) as well as for ephemeral gully erosion in European croplands (Poesen et al., 2003). According to Zgłobicki (2002) sunken lane incision rates are 5 to 20 times higher than the total denudation rates (2.4-7.0 mm year^{-1}) on nearby agricultural slopes of E Poland. Occasionally much larger rates (i.e. 50 – 100 cm year^{-1}) may occur due to concentrated flow erosion resulting in the formation of gully channels within the sunken lane during extreme climatic events (i.e. heavy rainfall, very wet periods, rapid snowmelt). The formation of potholes with a depth of up to 3 meters has been reported in the bottom of a sunken lane located within loess region of E Poland (Janicki et al., 2002; Figure 9). In the long term, the formation of sunken lanes results in significant regional soil losses and sediment production. Verstraeten et al. (2009) calculated for two study areas (9 km² each) in central Belgium, having sunken lane densities of 0.75-0.91 km km^{-2}, the total soil volume removed in the sunken lanes and obtained a value of ca. 260 m³ ha^{-1}. Zgłobicki (1998a) found for a catchment of 11 km^{2} in East Poland that the total volume of soil lost by the formation of sunken lanes was ca. 60 m^{3} ha^{-1}.

The formation of sunken lanes, as in the case of permanent gullies, can therefore be treated as a human induced hazard for agriculture (Ionita et al., 2015b). Erosion process interactions and conditions controlling the activity or stability of sunken lane banks deserve more research attention so as to improve predictions of the hydrological and soil erosion response of areas with sunken lanes. Sunken lanes may become erosion hotspots and offer thereby unique field laboratories to study the intensity of these processes, their controlling factors as well as suitable erosion control techniques (e.g. Poesen, 1989).

8. Impact and functions of sunken lanes in the landscape

8.1. Ecology/biodiversity

Sunken lanes are important landscape features for ecology and biodiversity. They provide a varied abiotic and biotic environment on small spatial units due to gradients in topography, erosion processes, lithology, soil types, soil moisture, temperature, light availability, insolation and air humidity (Herault et al. 2003; Deckers et al., 2005; Stevens, 1997; Poschlod and Braun-Reichert, 2017; Mor-Mussery and Laronne, 2020). Sunken lane development can promote more stable habitats on the one hand, or encourage disturbance on the other, with consequently differing assemblages of roadside flora and fauna (Martin, 2003). In addition, sunken lanes are excellent wind shelters (RLD, 2004). Especially in monotonous, dynamic agricultural landscapes they are valuable landscape features acting as a refuge for animals and plants. As a result, particularly old/overgrown sunken lanes are important habitats for biota that can serve as biodiversity hotspots in agricultural landscapes that may otherwise support little biodiversity (e.g. Bollen, 2002; Deckers et al., 2005; Pachinger, 2008). They are therefore of crucial importance for nature conservation (Poschlod and Braun-Reichert, 2017; Tukiainen et al, 2019; Heneberg and Bogusch, 2020).

This is especially the case in regions with intensive agriculture (for example the loess belt), that have few nature reserves in between urban areas (RLD, 2004). Furthermore, sunken lanes are an important linear element in the landscape and serve as “infrastructure” for plants and animals. Because of intense urbanisation of Belgium, natural habitats have been lost and sunken lanes function as safe ways connecting distant natural habitats. Well-developed and managed sunken lanes in Belgium can be considered as small-scale forest fragments since the growth conditions are usually suitable for forest species (Deckers et al., 2005; Stevens, 1997). The partial destruction and disappearance (by land levelling) of sunken lanes can lead to the formation of small islands in the remaining sunken lane sections and the reduction of species (Stevens, 1997). Martens (2013) analysed which factors have the largest influence on vegetation growth in Belgian sunken lanes. Land use of the neighbouring areas and soil fertility appeared to have the least impact. The most influential factors are light, controlled by the bank orientation (Stevens 1997; Deckers et al. 2005), the age of the sunken lane and the degree of disturbance of the “natural” environment in the sunken lane. The highest species diversity was found at sites with a lot of light that are also warm and dry (Martens, 2013). A detailed inventory of plant and animal species observed in East and Central Belgian sunken lanes is provided by Herault et al. (2003) and Stevens (1987, 1997). The role of sunken lanes for biodiversity in **Germany** is partly discussed by Dannapfel (2007) and Ambos and Kandler (1999). Sunken lanes, especially overgrown ones, can be valuable habitats for thermophilic and drought-loving plants species and different types of mammals, like rabbits, foxes, birds and insects.

8.2. Microclimate

The varied abiotic environment results in a buffered, temperate microclimate inside the sunken lane. Hillslope sections having a different exposure to the sun will control insolation as well air movement and hence microclimate (Geiger, 1950). The orientation of the sunken lane in the landscape, the vegetation type (resulting in a protective canopy cover) and the depth of incision therefore play a crucial role in the amount of insolation on the sunken lane slopes (Allemeersch, 1987c, Deckers et al., 2005; Stevens, 1997; Lenoir et al., 2017). Solar insolation on the banks is largest when vegetation cover is negligible (i.e. no herbs, shrubs or trees growing) and when the sunken lane is east – west oriented. This orientation causes the sun to directly shine on the south-facing bank leaving the northern bank with almost no sunlight (Allemeersch, 1987c; Stevens, 1997). So far, only one study reported on the microclimatic characteristics of sunken lanes based on measurement data from one day (Allemeersch, 1987c). These unique data on hourly air temperature above (40 cm height) and at the soil surface as well as soil temperature (at 3 cm depth) and air humidity for north- and south-facing grass-covered sunken lane banks and for a sunken lane completely vegetated with trees nicely illustrate these large microclimatic variations. All measurements were done in East Belgium (South Limburg) on a cloud-free day (21 September 1987). At noon both soil and air temperatures could differ by ca. 20°C between north- and south-facing banks. Moreover, on the south-facing slope soil and air temperature differences during the day are also much higher (up to 20 and 30°C respectively) compared to north-facing banks. All observed temperatures in the forested sunken lane are generally lower and very similar to the north bank of the non-forested sunken lane. The air humidity at the start of the day is everywhere almost 100%, but during the day this lowers to 30% for the south-facing slopes (Allemeersch, 1987c). These microclimatic data come from two particular sunken lanes in the same region that were collected during one particular day, they cannot directly be generalized. They illustrate however the very large systematic spatial variations in air and soil temperature as well as in air humidity within sunken lanes. Such significant differences in microclimatic conditions strongly affect the abiotic and biotic components of the sunken lanes.

Also anthropogenic impacts may cause microclimatic changes and hence floral and a faunal diversity in sunken lanes. Examples of such impacts are land use and management of the sunken lane (e.g. grazing or wood extraction, reshaping of the sunken lane banks) or of the nearby cropland (e.g. application of manure and chemicals that affect nutrient and biocide influx from adjacent fields; Kleyer 1991).

8.3. Drainage of hillslopes

Sunken lanes contribute to an enhanced drainage of the nearby hillslopes. Several studies indicated that gully channel formation may lead to a rapid drainage of surrounding areas, resulting in a lowering of water tables, a decrease in base flow as well as the desiccation of the intergully zones (Poesen et al., 2003). In dry climatic environments, this then reduces biomass production, particularly in the vicinity of the gully banks (Frankl et al., 2016; Poesen, 2018).

Sunken lanes cutting down to the groundwater table in landslide-sensitive zones may act as a drainage channel evacuating exfiltrating water from springs and hence contributing to a decrease of the landslide susceptibility of the hillslope by reducing positive pore water pressures in the soils and hence increasing its shear strength. Filling up such sunken lanes reduces the hillslope drainage and may lead to a re-activation of landslides as observed in central Belgium (Van Den Eeckhaut et al., 2007).

8.4. Hydrological and geomorphological connectivity

Linear landscape elements such as rural roads are now well known to have an effect on catchment hydrology, erosion and water quality (e.g. Slupik 1984; Gascuel-Odoux et al., 2011). Sunken lanes, like most roads in rural areas, typically connect runoff and sediment-producing areas with downstream areas, water courses, and settlements. Thereby, they enhance the effective drainage density and sediment flux (e.g. Farres et al., 1993; Froehlich and Walling, 1997; Verstraeten and Poesen, 1999; Steegen et al. 2001; Boardman, 2013, 2014b; Figure 10). Consequently, the negative off-site effects of runoff such as muddy floods, flood damage to roads, sediment deposition, sedimentation in and pollution of water bodies increase with the presence of sunken lanes (Verstraeten and Poesen ,1999; Boardman, 2013; de Walque et al., 2017). The runoff with transported sediments may have different origins. First of all, unpaved, bare sunken lanes can be a source of runoff and sediments themselves (Boardman, 2013; Froehlich and Walling, 1997). A sunken lane that is still incising or extending in an upslope direction generates large volumes of sediments by concentrated flow erosion (see reported erosion rates in table 5). Next, banks of sunken lanes that are insufficiently protected by vegetation often suffer from intense soil erosion by piping, bank gullying or mass movement processes (Poesen, 2018). The absence of a good vegetation cover often results from reshaping of the banks by farmers to widen the sunken lane so as to better access nearby agricultural plots, or from poor bank management. Furthermore, runoff from nearby areas can reach the sunken lane by surface wash, seepage, piping, field drains or via disturbances of the sunken lane where the adjacent cropland can be accessed (Boardman, 2013). When runoff and sediments reach the sunken lane, it is guided by the banks and inevitably flows along the sunken lane since there are no other drainage options.

It should be noted that land use changes such as a decreasing intensity of agricultural activities in some regions may result in a decrease of the density of unpaved roads and as a result a decrease in the number of potential hydrological and sediment transfer routes from slopes to river channels (Latocha, 2014). This also applies to abandoned sunken lanes.

Figure 10. Illustration of the role of sunken lanes in increasing the runoff and sediment connectivity in a landscape. Outlet of a sunken lane with concentrated flow transporting large amounts of coarse sediments that are deposited at the outlet of the sunken lane, typically where the slope gradient drops below 0.04 m m^{-1} (Limburg, The Netherlands, 06.1987) (Photo J. Poesen)

Colluvial/alluvial fans may be formed at the outlet of sunken lanes (Figs. 8c and 9; Rodzik et al., 2014; Latocha, 2014; Superson et al., 2014). Sediment transport intensity within sunken lanes, and sediment accumulation at their outlet may be high, but their geomorphological significance in the landscape also depends on their density. Few studies on this aspect for regions with high sunken lane densities have been made. Research along this line was conducted in the Carpathian Mountains (S Poland), where it was observed that unpaved field and forest roads (not all of them were sunken lanes) are important sources of sediment for fluvial transport (Kroczak 2010, Wałdykowski and Krzemień, 2013; Kroczak et al., 2016). According to Froehlich and Walling (1997) sunken lanes represent the main suspended sediment source due to the fact that most sediments eroded in the bottom of the roads are directly transferred to the stream channels. Froehlich (1982) estimated that unmetalled roads account for ca. 60-70 % of the load in the

Homerka river channel. During storm events not generating overland flow in most of the catchment, unmetalled roads account for ca. 98% of the sediment input to the stream.

The rapid development of sunken lanes during the Anthropocene has significantly enhanced sediment transfer by connecting upper hillslopes in the catchments with valley floor margins. According to Ziegler et al. (2000) sediment production on roads is eight times higher comparing to agricultural lands. This indicates that sunken lanes and unpaved rural roads may significantly contribute to colluvial and alluvial aggradation in many landscapes by strongly increasing hillslope – valley bottom – floodplain connectivity and hence also to the change of valley bottom and floodplain geoecology (Houben et al., 2012; Broothaerts et al., 2014).

8.5. Cultural heritage

Sunken lanes belong to the long-standing heritage of a region (Verdurmen, 2018). This refers to both surface (i.e. visible today: e.g. morphology, fauna, flora, scenic beauty) and embedded values (i.e. those related to practices from the past and that cannot be directly observed today) of sunken lanes. Apart from being geosites (geomorphosites) – elements of geoheritage, sunken lanes testify to important human-environment interactions in prehistorical and historical times (cultural heritage). These lanes provide information on past human movement and historical route networks on both an inter-site and inter-regional level (Wilkinson, 2010) as routes both reflect and influence (large-scale) cultural and landscape processes, and play a crucial role in the exchange of resources, knowledge, and ideas (e.g. Verschoof-van der Vaart and Landauer, 2021). Sunken lanes were also strategic landforms during military conflicts in e.g. Belgium e.g. Ramillies in 1706, Waterloo in 1815, France e.g. Beaumont Hamel in 1916 or during the Civil War in North America e.g. Antietam and Shiloh in 1862 (Ehlen and Whisonant, 2008;

Hippensteel, 2019). Sunken lanes were recognized as nearly ideal defense positions but sometimes they may become a “Bloody Lane” as happened during the battle of Antietam (Hippensteel, 2019). Such landscape features had to be considered for the tactical employment of arms (Donaldson, 1904).

Sunken lanes, together with hedgerows and terraces, are the remnants of past agricultural landscapes in all European countries (Baran-Zgłobicka and Zgłobicki, 2012, Zgłobicki and Baran-Zgłobicka, 2012; Latocha, 2014; Poschlod and Braun-Reichert, 2017). Taking into account their natural and cultural assets it is important to protect sunken lanes with the highest natural heritage values. For example in Poland some sunken lanes are protected as nature monuments.

9. Management of sunken lanes

Erosion in sunken lanes has various effects. It is responsible for the deepening and widening of the sunken lane that provides various functions and services (see above). An ideal sunken lane is in dynamic equilibrium with erosion processes (Mazur et al., 2015; RLD, 2004; Stevens, 1997). Such sunken lane can still evolve and as long as most runoff originates from its own short banks, there is hardly any problem. Intense erosion within the sunken lane threatens various functions of the sunken lane and hence its existence (Mazur et al., 2015; Stevens, 1997). When banks collapse or road surfaces get eroded too fast (e.g. by gully development), vehicle passage becomes difficult or even impossible and the sunken lane loses its traffic function. Therefore, it is important to control the type and intensity of erosion processes within sunken lanes (Stevens, 1997). The occurrence of piping or landsliding on its banks often point to significant runoff volumes crossing the sunken lane bank shoulder. These processes then cause significant soil losses, ecological and economical damage (Mazur et al., 2015; RLD, 2004).

In many regions, the erosion rate of the road surface has been reduced by paving the road (with cobble stones, concrete or asphalt) (Figure 11), but this has often caused excessive erosion at the road sides. Unpaved and often vegetated sunken lanes allow for a reduction of runoff velocity and higher infiltration rates which help to reduce the incidence of muddy floods. Moreover, the dynamic equilibrium of the sunken lane is completely disturbed by paving the road surface (RLD, 2004; Stevens, 1997). What should be done is addressing the origin of the erosion problems which are mostly located within the catchment draining towards the sunken lane (Mazur, 2007; Stevens, 1997). Erosion also occurs during the widening of the sunken lanes when these become too narrow for modern agricultural vehicles. Very steep and even vertical bare walls of sunken lanes are very sensitive to mass movement processes (RLH and Proclam, 2009).

A very common erosion problem in sunken lanes is the development of bank gullies (Poesen, 1989; Poesen et al., 1996). These are mostly initiated when the neighbouring land is cultivated too close to the sunken lanes or landsliding occurs on the banks. Hortonian runoff and possibly also saturated runoff will then flow through and over the banks causing piping and ultimately bank gully erosion. These gullies can rapidly evolve by regressive erosion and then result in deep incisions of the bank shoulder, producing large sediment volumes (Poesen, 1989, 2018; Poesen et al. 2016; RLD, 2004; Stevens, 1997). The solution is to prevent or reduce runoff from neighbouring land to flow through or over the banks into the sunken lanes (Mazur, 2007). This can be achieved by either a land use change or the application of soil and water conservation techniques within the gully catchment and in the zones adjacent to the sunken lane. One effective way to prevent bank gullying, is the application of biological control measures on the bank shoulder and banks (Stokes et al. 2014). The shoulder of a sunken lane is the (vegetated) strip (several meters wide) between the upper part of the sunken lane bank and the nearby cropland or built-up area (Maetens et al., 2012 a, b). The bank shoulder, should be put under permanent grassland to increase rain infiltration, reduce runoff volumes, increase surface roughness and erosion resistance through root cohesion (Poesen, 1989; RLD, 2004; Stevens, 1997). The rooted soil layer below a good grass cover strongly reduces its susceptibility to concentrated flow erosion (De Baets et al., 2006) as well as to piping erosion (Bernatek-Jakiel et al., 2017). The sunken lane banks should be reinforced by suitable deep-rooting plant species to increase their shear strength and hence its susceptibility to landsliding. The vegetated shoulder and bank then function as a buffer between the cropland area and the sunken lane and is crucial for the stability of the banks. Every sunken lane should have both shoulders properly managed (RLD, 2004). This means vegetated by grasses and/or small shrubs and preferably equipped with a ditch (furrow) to evacuate the water parallel to the sunken lane. In this way the shoulder will protect the sunken lanes from runoff flowing across the sunken lane bank as well as from inputs of sediments, nutrients and pesticides. Moreover, this vegetated shoulder has also advantages for biodiversity and safety since there is a lowered probability for sliding of the bank material (RLD, 2004; Stevens, 1997). When bank gully erosion is intense, the sunken lane bank can be protected by installing a geomembrane (Poesen, 1989).

Figure 11. Different methods of paving bottoms of sunken lanes. A - openwork concrete slabs (Nałęczów Plateau, E Poland, loess), B – asphalt (Roztocze Region, E Poland, loess). (Photo: J. Rodzik).

In several countries (e.g. Belgium, The Netherlands, Czech Republic) some sunken lanes have been converted to temporary water retention ponds by the construction of small dams (with a spillway) across the sunken lane (Figure 12; Zlatuska, 2012). Most of such temporary ponds aim at reducing peak runoff rates towards valley bottoms, thereby reducing the flash flooding hazard. In Belgium, several regional organizations produced detailed manuals providing guidelines on how to manage sunken lanes in order to conserve these multifunctional geomorphosites and to use them in a sustainable manner (e.g. RLD 2004; RLH 2009). Criteria to value both surface and embedded values of sunken lanes as long-standing heritage elements in landscapes as a basis to protect them are discussed by Verdurmen (2018).

Figure 12. Sunken lane converted into a temporary flood retention pond by installing a concrete dam and a pipe to allow for bypass flow (Sluizen, Belgium, 2018) (Photo: J. Poesen).

In many regions with intensive agriculture, sunken lanes are under natural and anthropogenic threats. Natural threats comprise excessive water erosion at the lane bottom and mass movement processes on the banks. These often result from particular land use practices in the catchment of the sunken lane or near its bank shoulders. These geomorphic processes may be the result of natural processes (e.g. extreme rainfall or disappearance of particular vegetation types by disease) or mismanagement of the sunken lane (e.g. overexploitation of shrubs and trees on its banks may lead to root decay and hence a lowering of the shear resistance of the banks resulting in bank failure).

Anthropogenic threats result from improper management. Since most old sunken lanes are not adapted to the passage of heavy agricultural machinery, they are often artificially widened, resulting in less stable banks. In various countries (e.g. Poland, Belgium, Germany and UK) the sunken lane bottom is often hardened to prevent further erosion of the road surface and sometimes the slope gradients of the banks are reduced as well to prevent landslides. In some cases, these road works significantly reduced the landscape values of sunken lanes but improved the transport function. In the Lublin Upland, at the beginning of the 21st century, such activities affected ca. 200 sunken lanes (Kołodyńska-Gawrysiak et al., 2011). If there were plans to harden sunken lanes that have high aesthetic values, these cause protests from tourists with variable outcomes. In Poland, a significant problem leading to the degradation of the values of sunken lanes is also their use for intensive traffic of off-road vehicles. They destroy the bottom and slopes of these forms.

Other reported threats to the various functions of sunken lanes in Belgium include digging in the banks (for extracting loess, sand or rock fragments for construction purposes) affecting the cross-sectional shape of the sunken lane, dumping waste, overexploitation of the vegetation on the banks by clear cutting (for e.g. wood extraction), overuse of pesticides and fertilizers on adjacent cropland which negatively affects the biodiversity within the sunken lane (Stevens 1987) or mismanagement of the sunken lane banks and shoulders (RLD 2004).

Ambos and Kandler (1999) reported for Rheinhessen, i.e. the most important German wine growing region, that sunken paths are increasingly disappearing from the landscape due to agricultural intensification or by infilling with waste, rubble or soil materials.

Sunken lanes can also disappear when they are completely filled in to enlarge farmers' plots as part of land consolidation programs or to prepare terrain (bulldozing) for irrigation or constructing buildings and roads following urban sprawl (e.g. De Gruchy and Cunliffe 2020). Large sunken lanes are rather difficult to fill, whereas shallow road incisions have often disappeared by infilling. In some regions, the disappearance of sunken lanes can be extreme. Allemeersch (1987b) reported for four villages in East Belgium that between 26 % and 60 % of the sunken lanes shown on topographic maps of 1950 had completely disappeared in 1987.

After intense erosion of the sunken lane bottom, a new road may be formed near and parallel to it whereas the former road gully may become a large permanent gully after several decades. To maintain the characteristics of a road gully, it is necessary to use it as a road and to remove excessive deposited sediments on its bottom.

Sunken lanes are inherently unstable landforms and therefore their best conservation seems to be their use as a road with moderate traffic. In order to conserve its cross section, it appears to be effective to partially protect the road with openwork concrete slabs, and in the case of old, several-hundred-year-old forms with a smooth longitudinal profile, to harden the road surface and to install drainage gutters on the sides.

Significant runoff volumes flowing through sunken lanes and causing intense erosion in the sunken lane bottom supply water and sediment to valley bottoms, and often cause off-site problems (e.g. muddy floods). On the other hand, these geomorphic features increase geo- and biodiversity in agricultural areas, and have aesthetic and tourist values. Therefore, these forms need protection, and in the case of sunken lanes of outstanding value and size, activities that could lead to changes in their appearance (for example, paving the bottom) should be limited.

10. Tourism and geotourism in sunken lanes

Sunken lanes have a large touristic potential because of their many values and functions: i.e. scenic beauty (reflected among others in paintings), recreational (hiking, biking), scientific (biodiversity, geomorphology), educational and geoheritage. As such they allow for several types of tourism: sports, leisure, ecotourism, geotourism (Figure 13). As to the latter type of tourism, sunken lanes offer geological windows, active geomorphological processes (i.e. various types of water erosion processes, mass movements, animal burrowing activity, windthrow erosion, anthropogenic erosion processes) and could be used as suitable sites to illustrate human-environment interactions in the past and today (Papčo, 2014; Zgłobicki et al., 2019). The number of studies on tourist and geotouristic values of sunken lanes is limited to some parts of Poland. Numerous sunken lanes are included in the Central Register of **Polish** geosites. In **Slovakia** only two such forms were recorded in the Database of the State Geological Institute of Dionýz Štúr, Bratislava (entitled "Important Geological Sites" (Liščák et al., 2012), which is an open map and information set of sites of geological heritage in Slovakia).

Figure 13. Sunken lanes in Poland that are used for recreation (e.g. biking (A), hiking (B) and education (C). (Photo: G. Gajek (A, C), W. Zgłobicki (B)).

In **Poland**, the most famous sunken lane site for tourists are the Root Gully (Kazimierz Dolny, E Poland) and the Queen Jadwiga Gully (Sandomierz, central Poland), which are "must see" attractions. In the summer months, up to 150 people per hour walk them. In Poland, tourist, hiking and cycling trails, sometimes of supra-regional range, are marked in the sunken lanes. There are also educational paths within them. Sunken lanes are often characterized by high geotouristic and geo-educational values (Zgłobicki, Baran-Zgłobicka, 2013; Zgłobicki et al., 2015). For example The Root Gully (Korzeniowy Dół) was the highest rated geo-site among the 57 sites that were part of the loess geoheritage within the planned Małopolski Przełom Wisły Geopark (Warowna et al., 2016). Therefore, sunken lanes are important geosites to disseminate knowledge about geology (rock outcrops in their banks), geomorphology (past and present-day processes and their rates) and human-environment relations (Zgłobicki et al., 2019).

However, even in Poland, the intensity of touristic use of sunken lanes is still rather limited. In the Nałęczów Plateau (E Poland), touristic planning is based on tourist routes running through selected sunken lanes and educational paths, presenting various natural and cultural values of the region. There are no thematic tourist products using the potential of sunken lanes. Sunken lanes located within or near cities or densely populated regions are very popular places for hiking. If, for safety reasons (e.g. fallen trees), access to them is temporarily prohibited (Figure 12b), it causes dissatisfaction among residents and tourists.

While in Poland sunken lanes are undoubtedly attractions described in tourist guides and scientific publications related to tourism and geotourism, in other countries the situation is different. The **Romanian** sunken lanes receive only small attention. Moreover, even for the spectacular gullies in the Moldavian Plateau people are not aware of their beauty and touristic value. In **Russia** sunken lanes are typical landscape elements of old park areas, typically located on valley slopes near rivers in the central part of old cities. Several towns in central **Belgium** advertise hiking trails and biking routes through sunken lanes, by providing detailed maps and booklets, thereby mainly underlining their biodiversity. In some cases geo-biking and geo-hiking routes pass through sunken lanes that allow geotourists to observe particular rock outcrops in the banks. In **Germany,** sunken lanes have partly a regional significance for tourism under the keyword “historical cultural landscape” e.g. in wine growing regions (Ambos and Kandler, 1999). In the Rheinhessen and Kaiserstuhl regions of South West Germany there are occasional display boards for visitors with information about sunken lanes: i.e. their genesis, significance for ecology, and protection state.

11. Future prospects

Given their importance in many rural landscapes worldwide and the limited research conducted so far on these geomorphological features, several aspects related to sunken lanes deserve more research attention in the near future.

1. As sunken lanes are part of our geoheritage, more efforts are needed to map and to better understand spatial patterns of geomorphic features at various spatial scales (from local to regional and national). LiDaR data now allow detailed geomorphological analysis of sunken lanes, particularly in forested areas where traditional topographic maps do not always allow the production of inventories of sunken lanes (e.g. Migoń and Latocha 2018). Such inventories will allow a better understanding of human-landscape interactions during various periods of the Anthropocene, as sunken lanes have influenced both (large-scale) cultural and landscape processes e.g. land use changes (Latocha, 2009). Such analysis may then supplement and expand our knowledge gained from historical written and cartographic sources (Verschoof-van der Vaart and Landauer, 2021).
2. Sunken lanes create a varied abiotic and biotic environment on small spatial units due to strong gradients in topography, erosion processes, lithology, soil types, soil moisture, soil and air temperature, light availability, insolation and air humidity. The magnitude and interactions between the various processes and factors involved are not always known which

is important for a better understanding of the functioning of sunken lanes and their impacts on abiotic and biotic processes.

3. Sunken lanes are part of the Blue-Green Infrastructure (BGI; i.e. an interconnected network of natural and designed landscape components, including water bodies and green and open spaces, which provide multiple functions (.g. enhancing biodiversity and connectivity, decreasing locally global warming effects by moderating the air temperature, improving the aesthetic and social attractiveness of the rural environment, enhancing recreation (tourism) (Ghofrani et al., 2017). We therefore need to better understand and quantify these benefits (ecosystem services) for future environmental management in a changing climate, particularly for regions where there have been considerable nature-based recreation and tourism resources.
4. Sunken lanes are small natural features (SNFs) that can serve as biodiversity hotspots in agricultural landscapes that may otherwise support little biodiversity. More research on their management, restoration, and recreation is required to ensure that they persist and continue to support biodiversity in highly modified landscapes (Poschlod and Braun-Reichert, 2017).

It remains a challenge for the multifunctional conservation management of sunken lanes, like for many minor rural roads, to reconcile all their competing functons (i.e. geotouristic, environmental, cultural, recreational, transport and road safety) and the related management options (Pauwels and Gulinck, 2000; Spooner, 2015).

Conclusions

This review focused on sunken lane research conducted mainly in Europe as very few research papers about sunken lanes in other continents were found. Although few studies about these landforms have been published in the international scientific literature, more papers on various aspects of sunken lanes have been retrieved from the national or regional literature.

Limited data indicate that sunken lanes are very dynamic geomorphic features in rural landscapes with mean sunken lane floor incision rates of 1 to 5 cm/year but occasionally much larger rates (i.e. 50 – 100 cm /year) may occur during years with extreme climatic events (heavy rainfall, very wet periods, rapid snowmelt). In addition, sunken lane banks often experience intense erosion processes by water (piping, bank gullying), mass movement processes or soil removal by burrowing animals or tree fall. Sunken lanes have often been erosion hotspots in the Anthropocene thereby offering unique field laboratories to study the intensity of these processes, their controlling factors as well as suitable erosion control techniques.

The oldest sunken lanes have been reported in the Middle East and Europe and their origin dates back to prehistoric (Neolithic) times. Since then many regions around the globe have seen sunken lanes developing, particularly during periods when human population and trade increased. Sunken lanes are part of a region’s long-standing heritage, testifying to past human-environment interactions. Mapping and analyzing patterns of sunken lanes may therefore supplement and expand our knowledge gained from historical written and cartographic sources.

Sunken lanes perform many important functions in landscapes around the world e.g. (geo)heritage function, ecological function, scientific and educational function, touristic function. Given the ecological importance of sunken lanes and the drastic reduction of biodiversity in intensively cultivated landscapes worldwide, sunken lanes are crucial for supporting biodiversity and maintaining biodiversity hotspots in such landscapes.

The rapid development of sunken lanes during the Anthropocene has significantly enhanced sediment transfer in landscapes by connecting hillslopes in the catchments with valley floor margins. Without doubt, sunken lanes contributed largely to colluvial and alluvial aggradation in such landscapes by an increased hillslope – valley bottom – floodplain runoff and sediment connectivity and hence also to the change of valley bottom and floodplain geoecology.

Unfortunately in several regions, sunken lanes are disappearing due to e.g. urban sprawl, agricultural intensification or land consolidation programs.

An opportunity to conserve these valuable geomorphic features is to promote them for rural tourism and education. Many tourists are not aware of the presence of sunken lanes and their tourist and geotourist values. In some countries (e.g. Poland, Belgium) local authorities have realized that they could be tourist attractions and have therefore started their promotion. Some countries (e.g. Belgium) have prepared manuals for managing sunken lanes to reconcile all their competing functions (i.e. geotouristic, environmental, cultural, recreational, transport and road safety).

Sunken lanes are attractive geomorphosites in many landscapes around the world, providing scenic variety and beauty, a window on the geology and a reminder of past human – environment interactions. It would be a huge loss if they completely disappear or if all potentially unstable banks would be 'engineered' to provide a safe but purely artificial road bank. It remains a challenge for environmental planners to conserve this characteristic geomorphosite for the Anthropocene and to reconcile the various functions sunken lanes play in the landscape.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract

Research highlights

This comprehensive review of sunken lanes highlights their importance in many landscapes.

Sunken lanes significantly affect geomorphological, hydrological and ecological processes.

Given their multifunctional role sunken lanes deserve proper management and protection.