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Sediment budget for five millennia of tillage in the Rockenberg catchment (Wetterau loess basin, Germany)

Peter Houben

Department of Physical Geography, Goethe University, Altenhoeferallee 1, 60438 Frankfurt a.M., Germany

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ABSTRACT

The long-cultivated loess landscapes of central Europe provide the opportunity to explore the long-term perspective on the evolution human-natural sediment systems that are driven by human-caused soil erosion processes. A balance of spatially non-uniform sediment production, sedimentation and delivery was developed to highlight the quantitative dimensions and functioning of anthropogenic sediment redistribution in an undulating loess catchment of temperate Europe. The presented long-term perspective relies on analysing pedostratigraphic and lithostratigraphic field data from 728 corings across ~10-km^2, GIS-based data processing, and the analysis of data uncertainty. For a period of 5000 years of tillage, anthropogenic sediment production equals ~9425 t ha^{-1}, of which 62% still reside as colluvial sediment on the catchment's hillsides. The valley floors fulfil a sediment-conveyor function through transporting 77% of the sediment received from the hillsides. Whole-catchment yield to the contiguous higher-order valley is 29% of the amount of anthropogenic sediment production. The average catchment-scale depth of soil truncation is 0.64 m while the remaining anthropogenic sediment cover has an average thickness of 0.46 m (effective surface denudation: ~0.18 m). The long-term integral net erosion rate is ~0.5 t ha^{-1} a^{-1} because of extensive sediment retention on hillsides. The inherited human imprint on the soilscape, eventually, can be judged as beneficial rather than detrimental: the ubiquitous cover of humic colluvia generally is more suitable for intense cultivation than pristine pedostratigraphies. The sediment budget, although build from a historic perspective, also provides a plausible reference for realistic objectives of managing the soil erosion problem in human-natural sediment systems.

1. Introduction

The low-relief landscapes of central Europe are marked by a millennial-scale legacy of varied intensities, types, and patterns of cultivation resulting in a highly variable palimpsest of truncated pedostratigraphies, colluvial burial, and alluvial sedimentation because of anthropogenic sediment redistribution (e.g. Lang et al., 2003; Dreibrodt et al., 2010; Notebaert and Verstraeten, 2010). Thereby, cultivation-related processes of soilscape change have gained their stratigraphic significance through the fact that they occur at rates 5–100 times higher than natural rates of erosion and sedimentation (e.g. Wilkinson, 2005; Hoffmann et al., 2010).

Accordingly, qualitative information about human-caused changes to the stratigraphies of soils and alluvial sequences has long been used to explain the evolution of soilscapes, floodplains, or palaeoenvironmental settings (e.g. Bork et al., 1998; Lang, 2003; Berger et al., 2008). Quantitative information is required to develop the understanding of human-driven sediment redistribution change in a watershed systems context. In watershed systems, different topographic units (e.g., hillslopes, valley floors) produce and retain sediment at variable rates, which inherently leads to a spatio-temporally imbalanced sediment redistribution within the system. Therefore, sediment budgets (see overview by Slaymaker, 2003) are employed to understand complex watershed system response to agricultural activities as they highlight the quantitative significance of sediment fluxes among different system components (e.g. Trimble, 1983; Fryirs and Brierley, 2001). Sediment budgets also allow for comparing the efficacy of anthropogenic sediment redistribution in different settings (e.g. Walling et al., 2002) and can be used as a reference for validating soil erosion data derived from modelling or plot-scale monitoring (e.g. Trimble and Crosson, 2000; Peeters et al., 2008).

In some central European loess watersheds arable cultivation and associated sediment redistribution began ~7500 years ago with the first sedentary Neolithic cultures (e.g. Gronenborn, 1999; Dotterweich, 2008; Kadereit et al., 2010). The millennial-scale history of cultivation in central Europe, hence, provides the

E-mail address: p.houben@em.uni-frankfurt.de.

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opportunity to study the morpho-stratigraphic significance of human-natural sediment systems that have evolved over more than three millennia. Bork (1983) set up the first landscape-scale accounting of anthropogenic soil truncation, sedimentation, and net delivery in a German, 280-km^2-large loess watershed for the last 800 years. van Hooff and Jungerius (1984) presented a sediment budget for cultivation-related sediment redistribution for 4000 years in a 3.5 km^2 large loess catchment in Luxembourg. Since then, others explored long-term sediment budgets in meso-scaled agricultural loess watersheds (Macaire et al., 2002; Rommens et al., 2006; Notebaert et al., 2009; Verstraeten et al., 2009), while some relate to small watersheds or the hillslope scale (Rommens et al., 2005; Leopold and Völkel, 2007; Moldenhauer et al., 2010). Nevertheless, when relying on pedostratigraphic field data, these studies hardly have more than 10 data points per km^2 (Bork, 1983: ~3 data points km^{-2}; Notebaert et al., 2009: ~1 data point km^{-2}). To tackle the scaling problem, some scholars developed GIS-oriented and/or numerical modelling methodologies. De Moor and Verstraeten (2008) presented a sediment budget of the Dutch Geul watershed (380 km^2) by combining model data about hillslope sediment redistribution with field data about alluvial sedimentation. Hoffmann et al. (2007) quantified Holocene overbank sediment stored on the valley floors of the River Rhine watershed (125,000 km^2) based on modelling topographic and geologic geodata (see also Erkens et al., 2006; Hoffmann et al., 2009); Seidel and Mäckel (2007) used a combination of geologic and pedostratigraphic information from small-scale maps and field data to derive budgets of Holocene anthropogenic sediment fluxes in subwatersheds of the upper River Rhine area (1730 km^2).

This paper highlights sediment fluxes and specific functioning of hillslopes, hillslope hollows, and valley floors in a classic, 7500-year-long cultivated loess landscape of central Germany. About 70 data points km^{-2} have been obtained to reveal the quantitative and spatial nature of anthropogenic changes to near-subsurface litho- and pedostratigraphies in the 10-km^2 catchment. The rates of soilscape change can be compared with findings from other loess watersheds in central Europe and the north-eastern America. Finally, the long-term human imprint on the Rockenberg soilscape serves as a reference for discussing issues of past and future sustainable agricultural production by weighting beneficial aspects against effective losses to the soil resource.

2. Study area

2.1. General setting

The Rockenberg catchment forms part of the Wetterau loess basin (central Germany; Fig. 1). Total catchment area encompasses 10.24 km^2. Because anthropogenetically altered ground (backfilled sand, quartzite, or basalt pits, and built-up area; Fig. 1b) was not considered, the budgeted catchment surface is 9.93 km^2. The topography is characterised by near-level to gently sloping hillsides. Hillslopes show a simple and slightly variable topography with a few branching hillslope hollows (Figs. 1b, 2). The smooth hilltops culminate with elevations of about 240–251 m asl; the catchment outlet lies at 140 m asl. A small, only ~1 m wide 2nd order channel occupies the main valley floor and connects with the receiving Wetter River valley south of the town of Rockenberg. Over the Holocene, the study area has been marked by a humid temperate climate with mild winters and warm summers (Stobbe, 1996). For the recent decades, mean annual temperature is 9 °C; the mean annual precipitation (MAP) of ~550 mm a^{-1} is the lowest of the Wetterau basin because of the catchment's position in the rain shadow of the adjacent Taunus upland (Müller-Westermeier, 1996).

2.2. Bedrock, near-subsurface strata, and soils

Miocene siliclastic sediments (so-called Rockenberg Beds) dominate local bedrock geology (Kümmerle, 1981). The Rockenberg Beds chiefly consist of unlithified, horizontally bedded, non-calcareous, sands, gravels, conglomerates, muds, silts, and clays. Local heights correlate with the occurrence of more resistant Miocene basalts. The Miocene strata are ubiquitously covered

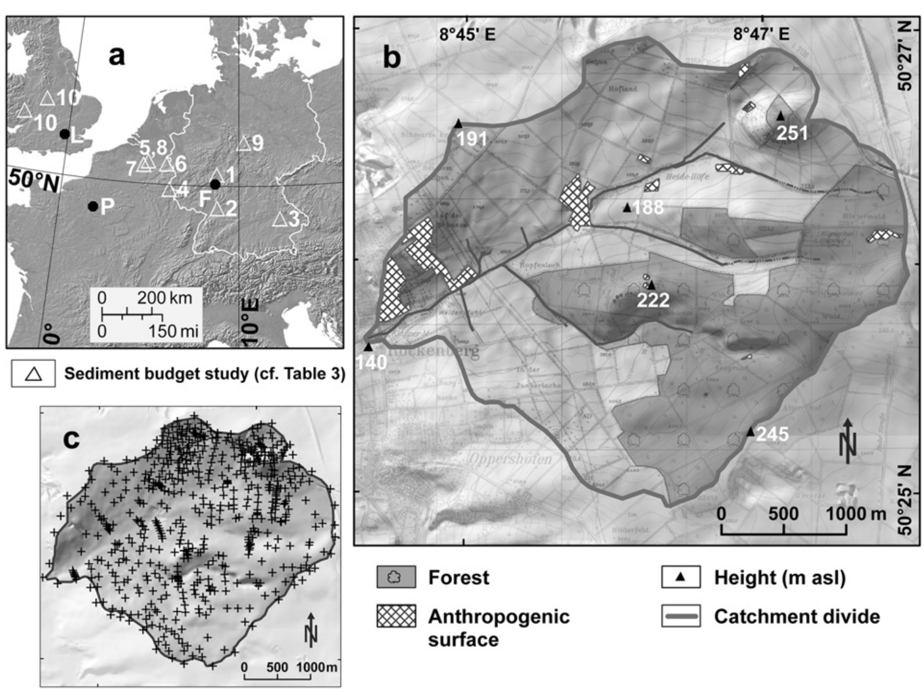

Fig. 1. a. Location of the Rockenberg catchment in central Europe. F = Frankfurt a.M., L = London, P = Paris; locations and numbers of other sediment budget studies refer to Table 3 (white line = state border of Germany). b. Topographic overview of Rockenberg catchment. c. Sketch map of coring sites (crosses).