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Changes in floodplain geo-ecology in the Belgian loess belt during the first millennium AD

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Original Article

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Abstract

Variation in human activities has greatly impacted the processes and intensities of erosion, sediment transport and storage throughout the Late Holocene, and many lowland rivers around the world have responded to these variations. Although this long-term process–response relationship has been established before, the effects of short-term (*c.*200-year) changes in human impact on lowland rivers are less well studied. Here, we followed an integrated approach whereby observations of floodplain changes are evaluated against detailed data on human impact for three lowland rivers in the Belgian loess belt: Dijle, Mombeek and Gete rivers. Pollen data were used to reconstruct changes in local and regional vegetation and to calculate human impact scores. Corings along transects and a database of *c.*160 radiocarbon ages were used to reconstruct geomorphic changes in the river valleys. Our results show a decrease in human impact between 200 and 800 AD, which can be related to the decreased population density in Europe during the first millennium AD. During this period, forests in the studied catchments regenerated, soil erosion decreased, hillslope–floodplain connectivity decreased due to the regeneration of valley-side vegetation barriers, and sediment input in the floodplain decreased. A reaction to this decreased human impact can be observed in the river valleys during the first millennium AD, with a regrowth of the alder carr forest and an increase in the organic matter content of the alluvial deposits with a local reactivation of peat growth. The observed trajectories of Belgian river valleys during the first millennium AD provide more insight into the sensitivity of these river valleys to short-term variations in human impact. These results can in turn be used to better estimate the effects of future changes in the catchments on the fluvial system.

Introduction

Variation in human activities has greatly impacted the processes and intensities of erosion, sediment transport and storage throughout the Late Holocene, and many lowland rivers around the world have responded to these variations (Notebaert & Verstraeten, 2010; Brown et al., 2018; Macklin & Lewin, 2019). The process–response relationship on a long timescale has been well established: The general concept of fluvial response following human disturbances in NW Europe is that of continuously increasing human impact since Neolithisation which caused a continuous aggradation in the floodplain, although delayed (e.g. Houben, 2007; De Moor et al., 2008; Dotterweich, 2008; Lespez et al., 2008; Notebaert & Verstraeten, 2010; Fuchs et al., 2011; Verstraeten et al., 2017). Changes in climate and land use in the river catchment could also cause changes in river channel patterns (e.g. De Moor et al., 2008; Słowik, 2015; Candel et al., 2018). Other studies point to the importance of infrastructural works in the floodplain (e.g. watermills and bank protection measures) for changes in floodplain morphology and channel pattern (e.g. Walter & Merritts, 2008; Słowik, 2013; Hobo et al., 2014; Maaß and Schüttrumpf, 2019). For the Dijle catchment, located in the Belgian loess belt, Broothaerts et al. (2014b) have studied the floodplain response to human disturbance and have shown how the Dijle floodplain changed from a natural to a human-dominated environment. By evaluating detailed data on floodplain changes with detailed data on human impact and regional vegetation changes, they showed that natural floodplains of the Dijle valley consisted of strongly vegetated marshy environments dominated by an alder carr forest. This changed when human impact in the catchments crossed a threshold, such that sediments eroded on cultivated hillslopes entered the floodplains. As a result, floodplain geomorphology and ecology (hereafter called 'geo-ecology') changed from a marshy, forested environment towards a more open floodplain dominated by clastic overbank deposits (Broothaerts et al., 2014b).

Superimposed on these long-term trends of increasing human impact and the fluvial response to it, short-term fluctuations (*c.*200 years) are also present. The effects of such shorter-term changes in climate and human impact on the fluvial system during the Holocene period are harder to study, due to preservation and resolution issues. Insight into these effects is needed, however, to fully understand the process–response relationship on shorter timescales, and to understand the possible effect of future changes in human impact or climate

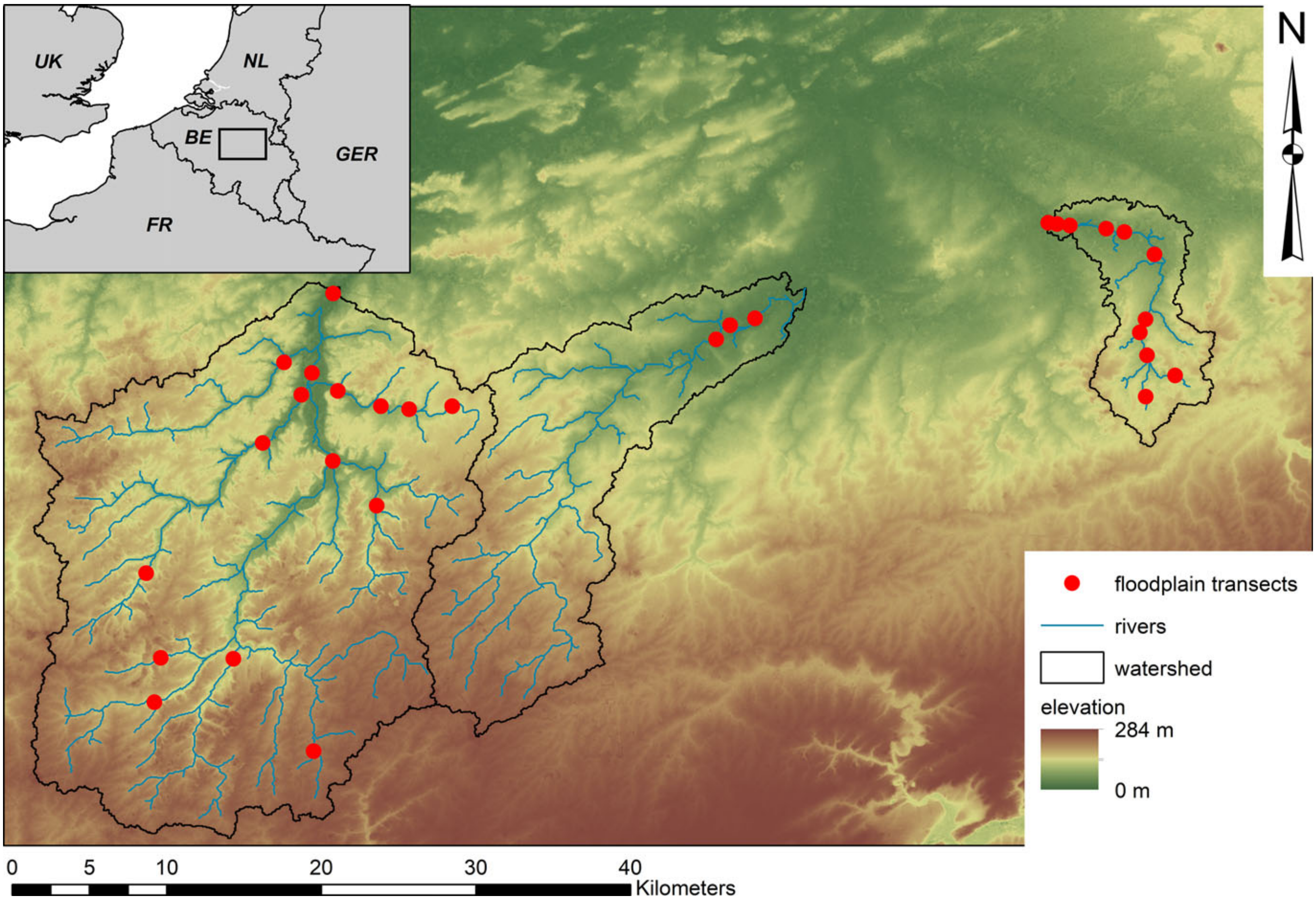

Figure 1. Location of the studied catchments, with indication of the locations of the coring transects. From west to east: Dijle, Gete and Mombeek catchments.

on river systems. For instance, it can be questioned whether short-term climate oscillations in the Late Holocene are intensive enough to trigger changes in fluvial systems or whether these impacts are buffered in the catchment. The first millennium AD in NW Europe is characterized by such short-term changes in human impact and climate. Particularly between 250 and 700 AD, cultural change, population decline and widespread forest regeneration are observed in NW Europe (e.g. Zolitschka et al., 2003; Cheyette, 2008; Wickham, 2009; Forster, 2010) and therefore this period is often called the 'Dark Ages'. In Belgium, forest regeneration and recovery started between 250 and 700 AD (Tack et al., 1993). In France, the Netherlands and Belgium, overall population decline is estimated at *c.*40% between 500 and 650 AD compared to the Roman period (Russell, 1972). In the Rhine–Meuse delta (the Netherlands), Groenewoudt and Van Lanen (2018) and Van Lanen et al. (2018) estimated the population decline between 270 and 725 AD at *c.*80%. Moreover, the first millennium AD in NW Europe was characterised by climate variability with consecutively a warmer period (between *c.*1 and 250 AD), a colder period (between *c.*250 and 700 AD) and another warmer period (between *c.*700 and 1000 AD) (Riechelmann and Gouw-Bouman, 2019), although there is no consensus about their precise temporal and spatial extent (see e.g. Helama et al., 2017; Neukom et al., 2019; Riechelmann and Gouw-Bouman, 2019).

Only a few previous studies have been done on the effect of these changes in human impact and climate, during the first millennium AD, on changes in river systems in NW Europe (e.g. Lang and Nolte, 1999; Houben et al., 2013; Pierik et al., 2016; van Dinter et al., 2017). In the Belgian loess belt, indications of decreasing human impact during the first millennium AD come from pollen records in Dijle (Broothaerts et al., 2014c) and Mombeek catchment (Heyvaert, 1983), and are briefly linked with changes in the river system (Broothaerts et al., 2014b). A detailed understanding of these links is not yet available. Therefore, this research seeks to study the changes in floodplain geo-ecology in the Belgian loess belt during the first millennium AD and the role of changing human impact in it. For this purpose, an integrated approach is needed, and detailed data on floodplain changes need to be evaluated against detailed data on human impact (see e.g. Foulds and Macklin, 2006; Broothaerts et al., 2014b; Verstraeten et al., 2017). Several studies (Diriken, 1981; Heyvaert, 1983; Rommens et al., 2006; Notebaert et al., 2011a, b; Broothaerts et al., 2013, 2014b) have previously presented data on floodplain changes and vegetation changes in the Belgian loess belt. In the present study we combine these data, together with newly collected data, to provide an understanding of the significance of the changes in human impact during the first millennium AD on the river valleys in the Belgian loess belt.

Study sites

This study focuses on three river catchments (Fig. 1), the Dijle catchment south of Leuven (*c.*750 km^2), the Gete catchment (*c.*800 km^2) and the Mombeek catchment (*c.*100 km^2), all part of the Scheldt catchment (*c.*20,000 km^2). The catchments are located in the Belgian loess belt, characterised by an undulating

Table 1. Archaeological periods in the Belgian loess belt. Based on CAI (2019)

Archaeological period	Start date	End date
Neolithic period	5200 BC	1900 BC
Bronze Age	1900 BC	700 BC
Iron Age	700 BC	50 BC
Roman period	50 BC	250 AD
Early Medieval period	250 AD	1000 AD
Medieval to Modern period	1000 AD	present

Table 2. Lithostratigraphical units identified in the Dijle, Mombeek and Gete catchments. Based on Notebaert et al. (2011a) and Broothaerts et al. (2013)

No.	Unit	Texture	Interpreted deposition environment
1	Braided river deposits	Compact silty loamy, or sandy sediments	River channel and overbank deposits
2	Organic-rich open water deposits	Gyttja deposits	Shallow lake
3	Peat	Peat	Marshy floodplain
4	Overbank deposits	Silty clay loam to loam	Overbank
5	Organic-rich overbank deposits	Organic silty clay loam to silt loam	Organic overbank
6	River bed sediments	Sandy loam and sands	River channel and point bar
7	Colluvial sediments	Alternating silty clay loam to sandy deposits, arranged in layers	Alternation of colluvium and overbank

plateau in which several rivers are incised. Soils are mainly Luvisols, developed in Pleistocene loess deposits. The elevation of the Dijle catchment ranges from 25 m a.s.l. at the outlet to 165 m a.s.l. in the south of the catchment. The Dijle River has at the outlet a base discharge of 4 $m^3 s^{-1}$ and a peak discharge of 25 $m^3 s^{-1}$. The elevation of the Gete catchment ranges between 160 and 21 m a.s.l.; base discharge at the outlet of the Gete catchment is *c.*2 $m^3 s^{-1}$ and peak discharge *c.*22 $m^3 s^{-1}$. In the Mombeek catchment the elevation ranges between 112 and 34 m a.s.l.; base discharge at the outlet of the Mombeek catchment is *c.*0.1 $m^3 s^{-1}$ and peak discharge *c.*3 $m^3 s^{-1}$. Floodplain slope gradient in all three catchments ranges between 0.1% in the main valleys and 1.5% in the headwaters. Floodplain width in the headwaters does not exceed 150 m; in the downstream part of the catchments, floodplains can reach 1000 to 1500 m.

The current land use is dominated by cropland (*c.*40%), built-up area (*c.*25%) and grassland (*c.*20%). Floodplains are mainly dominated by grassland and plantation forests. Previous palynological studies in the Dijle and Mombeek catchments show that the catchments were mainly forested during the first half of the Holocene (Heyvaert, 1983; Broothaerts et al., 2013, 2014c). The Neolithic Linearbandkeramic arrived in the Belgian loess belt around 5200 BC (Vanmontfort, 2007, 2008). During the Neolithic period (5200 BC until 1900 BC; Table 1) human impact in the catchment was probably limited to local disturbances and small-scale forest clearance (Heyvaert, 1983; Broothaerts et al., 2013, 2014c). From the Bronze Age (1900 BC until 700 BC; Table 1), vegetation gradually changed under the influence of increasing human impact in the catchment. Human impact first peaked during the Roman period (50 BC until 250 AD; Table 1). During the Medieval period (from 1000 AD; Table 1) human impact increased further to reach its highest values in the Modern period (Heyvaert, 1983; Broothaerts et al., 2014c). Archaeological and historical data for the Belgian loess belt are limited and fragmented. For the Flemish part, an extensive database is available (Van Daele et al., 2004; CAI, 2019); but for the larger Walloon part, such a detailed database is missing.

Materials and methods

Previous studies have provided data on past changes in floodplain morphology, local floodplain vegetation, regional vegetation and human impact in the Dijle, Mombeek and Gete catchments. In this study, we chronologically combine these data on local floodplain vegetation with the available reconstructions of floodplain morphology to reconstruct the floodplain geo-ecology in these catchments. In a next step, these data on floodplain geo-ecology are chronologically evaluated with detailed data on human impact and regional vegetation changes, to provide insight into the temporal relation between human impact and changing floodplain geo-ecology. The temporal focus in this study is on the first millennium AD. As such, for the first time, an integrated approach is provided in which detailed data on floodplain changes are evaluated against detailed data on human impact for the first millennium AD. The temporal details of the available data allow this evaluation to be made on a 200-year resolution.

An overview of how the floodplain morphology, local floodplain vegetation, regional vegetation and human impact were reconstructed in the Dijle, Mombeek and Gete catchments is given below. For a more detailed description of these methods and datasets, we refer to the original papers.

Reconstructing floodplain morphology

Floodplain transects are available for the Dijle catchment from Rommens et al. (2006), Notebaert et al (2011a,b) and Broothaerts et al. (2013, 2014a); for the Mombeek catchment from Diriken (1981) and Vervoort (2018); and for the Gete catchment from Quintens (2019). Altogether, 16 transects are available for the Dijle catchment, 11 transects for the Mombeek catchment and 3 transects for the Gete catchment (Fig. 1). Coring density is around one coring every 20 m for most of the transects. The alluvial architecture was reconstructed based on this data set of, in total, *c.*400 corings. For each coring, a lithological field description is available with a vertical resolution of 5 cm, containing texture and sorting determined by palpation, colour description, description of soil horizons and identification of inclusions, following United Nations Food and Agriculture Organization (FAO) guidelines (Jahn et al., 2006). Based on the detailed field descriptions, textural data and organic matter content, the sediments were grouped in lithostratigraphical units, using floodplain architecture concepts (Houben, 2007; De Moor and Verstraeten, 2008) and following Notebaert et al. (2011a) and Broothaerts et al. (2013) (Table 2).

Chronology of floodplain changes

A detailed chronology of the floodplain changes in the Dijle catchment is provided by Broothaerts et al. (2014a) and Verstraeten et al. (2017). Radiocarbon dates are available for the Mombeek valley from Diriken (1981), Heyvaert (1983) and Vervoort (2018). For the Gete catchment, radiocarbon dates are available from Quintens (2019). In total, 160 radiocarbon dates are available for the studied catchments for the entire Holocene period, and provide a chronological framework for the floodplain changes and lithostratigraphical units. All ages were calibrated using the IntCal13 calibration curve (Reimer et al., 2013) and *Oxcal 4.3* software (Ramsey, 2009). The calibrated radiocarbon dates were used to obtain a chronology for the floodplain changes during the Holocene period and more specifically during the first millennium AD. Timescales for the available pollen sequences and floodplain accumulation rates were made based on four to seven radiocarbon dates for each pollen sequence, dating each important change in lithology and pollen signal. Finally, the organic-rich overbank deposits observed in the studied floodplains were dated using 14 available radiocarbon dates from this layer (Table 3).

Reconstructing vegetation changes and human impact

Holocene vegetation changes in the Dijle catchment were reconstructed based on pollen data of six alluvial sites by Broothaerts et al. (2014c). Reconstruction of Holocene vegetation changes in the Mombeek catchment comes from pollen data of one alluvial site analysed by Heyvaert et al. (1983). Pollen data for the Gete catchment are currently not available.

In this study, data on human impact in the Dijle and Mombeek catchments are extracted from the regional pollen signal based on non-metric multidimensional scaling (NMDS), a statistical ordination technique. NMDS has successfully been applied to pollen data in previous studies (Ghilardi and O′Connell, 2013; Broothaerts et al., 2014c, 2018; Woodbridge et al., 2019). Full explanation of NMDS can be found in Legendre & Legendre (1983) and McCune & Grace (2002). In this study, NMDS was applied to the pollen data of the Dijle catchment (six sites; Broothaerts et al., 2014c) and Mombeek catchment (one site; Heyvaert, 1983) respectively, using *R*-package *vegan* (Oksanen et al., 2012). Bray–Curtis dissimilarities were used to calculate the distance matrix for ordination. All regional pollen taxa that occurred in more than 5% of the samples were included. Wisconsin double standardisation and a square-root transformation were performed in *vegan*, if the pollen values were larger than common abundance class scales. A two-dimensional solution was used, since the measure of fit of the data versus the number of dimensions shows that two axes provide a greater reduction in stress than a higher number of axes. Broothaerts et al. (2014c) showed that scores on NMDS axis 1 can be used as a proxy for human impact in the catchment: low negative scores correspond to tree pollen types such as *Ulmus*, *Tilia*, *Corylus* and *Quercus* and indicate forested landscapes, while high positive scores correspond to cultural indicators such as *Centaurea cyanus*, *Plantago lanceolata* and cereal types and indicate deforested landscapes and human activities. The scores on NMDS axis 1 were plotted as a function of time, using the timescale constructed for the pollen data by Broothaerts et al. (2014c) and Heyvaert (1983) for the Dijle and Mombeek catchments respectively. Average NMDS scores were calculated with a time step of 200 years, and trends are discussed on a 200-year resolution. Plotting the scores on NMDS axis 1 in function of time can be used as an indication of the evolution of human impact through time, as shown by Broothaerts et al. (2014c).

In addition, the available pollen data for Dijle and Mombeek were also used to reconstruct changes in local floodplain vegetation throughout the Holocene and the first millennium AD.

Results

Regional vegetation changes and human impact

The pollen records from the Dijle and Mombeek catchments indicate that these catchments were forested during the Mid-Holocene, dominated by deciduous trees, and that human impact indicators were absent or low (Fig. 2). This deciduous forest is considered as the natural vegetation of the catchments in the Belgian loess belt (see Heyvaert, 1983; Broothaerts et al., 2014c). A clear decrease in forest cover is observed from the Bronze Age onwards, with an increase in grasses and anthropogenic indicators (Fig. 2). The trend of increasing human impact and deforestation is interrupted after the Roman period (Figs 2 and 3). More specifically the scores on NMDS axis 1, an indicator for human impact, show a decrease in human impact between 200 and 400 AD in the Dijle catchment and between 200 and 800 AD in the Mombeek catchment (Fig. 3). During that time, the pollen data and regional vegetation reconstructions show an increase in tree taxa and a decrease in human impact indicators (Fig. 2). Within the Dijle catchment there are some local variations, with a more pronounced signal in the downstream part of the catchment, as for example in Archennes (Fig. 2A), and a less pronounced signal in the upstream part (Broothaerts et al., 2014c). The period of decrease in human impact and renewed forest growth is, however, rather short, only 200 to 600 years. By *c.*400 AD, at most study sites in the Dijle catchment and by 800 AD in the Mombeek catchment, forest cover is again decreasing (Fig. 2) and human impact is increasing (Fig. 3). Human impact finally reaches its highest values during the Medieval to Modern period (Fig. 3).

Floodplain geo-ecology

Reconstructions of the floodplain morphology (Fig. 4; Table 3) show a complex of organic-rich deposits and peat at the base of the Holocene deposits. These organic-rich deposits are overlain by clastic overbank deposits, which are linked to increased erosion on the hillslopes due to increasing human impact (Broothaerts et al., 2013). In turn, these clastic overbank deposits contain organic-rich overbank deposits locally grading into peaty units (Fig. 4). These peat and peaty units are *in situ*, as determined in the field and described in the original publications (Diriken, 1981; Broothaerts et al., 2014b). These organic-rich overbank deposits indicate a phase with increased accumulation of organic material or even regrowth of peat in the distal parts of the floodplains. Radiocarbon dates from these organic-rich deposits range between *c.*1 and 1300 AD, with a peak between 600 and 800 AD (Fig. 5). During that time, we also see a decrease in sedimentation rates at the well-dated sites in the Mombeek catchment (Fig, 4B). Such a decrease is not observed in the data of the Dijle catchment (Fig. 4A), probably due to the rather limited time resolution of the sediment stratigraphy and averaging effects (see e.g. Notebaert et al., 2011a). These peaty deposits are mainly found in the distal parts of the floodplain and backswamps, and do not cover the entire floodplain width. Near the river channel, clastic overbank deposits can still be found (Fig. 4).

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Table 3. Radiocarbon dates for the organic-rich overbank deposits, in Dijle, Mombeek and Gete catchments (total: 14)

No.	Sample ID	Lab code	Conventional age (^{14}C a BP)	Calibrated radiocarbon age (cal a BP) (±1σ error)	Location	Coordinates	Depth (m)	Dated material	Source
1	Arch 57-4	Beta-257378	1320 ± 40	1243 ± 41	Dijle, Archennes	50.744731, 4.652402	3.4–3.5	wood remains	Notebaert et al., 2011b
2	Arch 57-3	Beta-257377	890 ± 40	818 ± 57	Dijle, Archennes	50.744731, 4.652402	2.7–2.75	wood remains	Notebaert et al., 2011b
3	NB-ARC-D21	Beta-352396	1230 ± 30	1164 ± 55	Dijle, Archennes	50.750670, 4.661315	3.78–3.80	wood remains	Broothaerts et al., 2014a
4	NB-ARC-D20-3	Beta-352395	780 ± 30	705 ± 20	Dijle, Archennes	50.750670, 4.661315	3.21–3.23	wood remains	Broothaerts et al., 2014c
5	HMW	Beta-192000	1300 ± 40	1229 ± 43	Dijle, Hamme-Mille	50.781781, 4.702193	2.30–2.40	Organic C residue	Rommens et al., 2006
6	KOR_04C	UtC 14830	1280 ± 36	1219 ± 44	Dijle, Korbeek	50.848349, 4.657364	3.3	charcoal	Notebaert et al., 2011b
7	KOR110-D4	Beta-323482	1470 ± 30	1355 ± 39	Dijle, Korbeek	50.849254, 4.655310	2.08	plant remains	Broothaerts et al., 2014c
8	KOR110-D2	Beta-321656	1670 ± 30	1580 ± 46	Dijle, Korbeek	50.849254, 4.655310	1.84	wood remains	Broothaerts et al., 2014c
9	KOR110-D6	Beta-321657	1340 ± 40	1260 ± 40	Dijle, Korbeek	50.849254, 4.655310	2.32	plant remains	Broothaerts et al., 2014c
10	SAR-100-D5-2	Beta-309758	1490 ± 30	1373 ± 36	Dijle, Sint-Agatha-Rode	50.788730, 4.630917	2.4	wood remains	Broothaerts et al., 2014c
11	GETE-T2B10-193-197	RICH26864	1278 ± 24	1227 ± 31	Gete, Transect 2	50.825583, 5.025833	1.93–1.97	Organic C residue	This study
12	GETE-T2B10-246-249	RICH-26860	1293 ± 23	1234 ± 32	Gete, Transect 2	50.825583, 5.025833	2.46–2.49	wood remains	This study
13	Mombeek-150	Lv1071	1670 ± 45	1580 ± 65	Mombeek, Vliermaal	50.829444, 5.406389	1.50–1.55	Organic C residue	Heyvaert, 1983
14	Mombeek-165	Lv1070	2015 ± 35	1970 ± 42	Mombeek, Vliermaal	50.829444, 5.406389	1.65–1.70	Organic C residue	Heyvaert, 1983

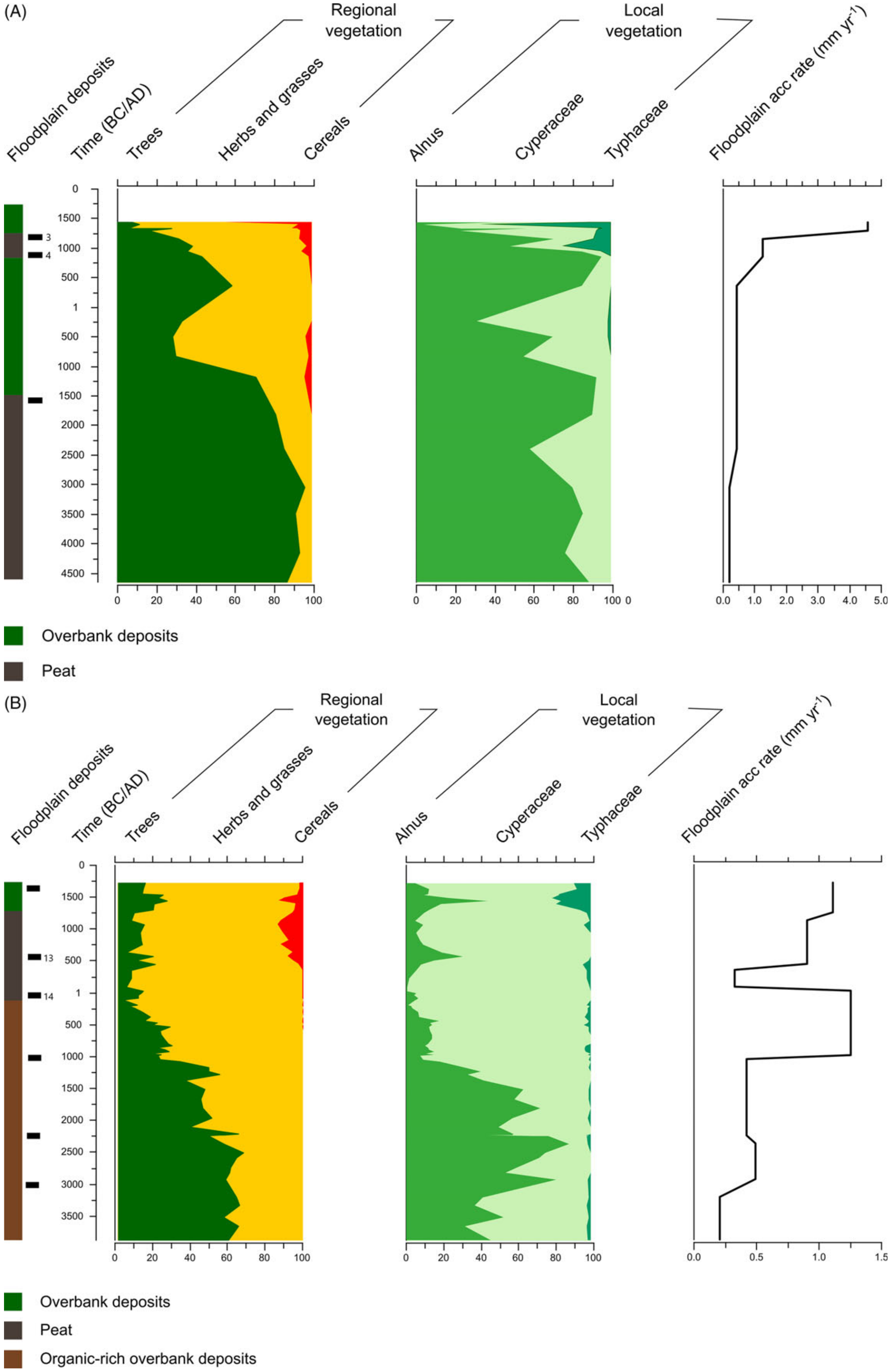

Figure 2. (A) Typical pollen diagram in Dijle catchment, near Archennes (based on Broothaerts et al., 2014c). Black rectangles indicate location of the available radiocarbon dates; numbers refer to Table 3. (B) Typical pollen diagram in Mombeek catchment, near Vliermaal (based on Heyvaert, 1983). Black rectangles indicate location of the available radiocarbon dates; numbers refer to Table 3.

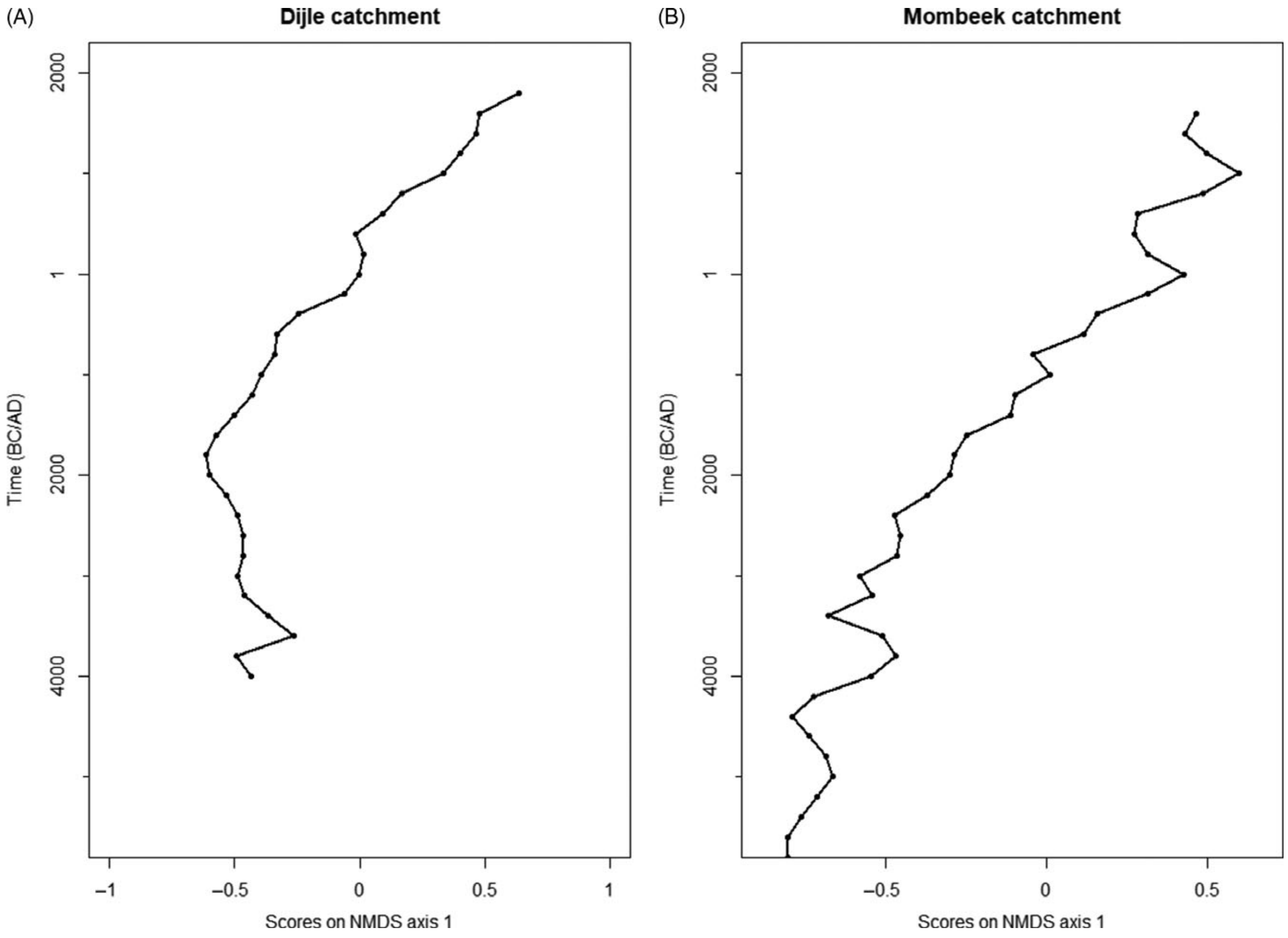

Figure 3. Human impact scores for Dijle catchment (updated from Broothaerts et al., 2014c) and Mombeek (Vliermaal, based on pollen data of Heyvaert, 1983).

Also in the first millennium AD, the local pollen data clearly show a regrowth of the alder carr forest at several study sites (Fig. 2). In Archennes, Dijle catchment, this regrowth is dated between 300 and 900 AD, and in Mombeek catchment, between 400 and 750 AD (Fig. 2). Similar observations are made at the other sites in the Dijle catchment (Broothaerts, 2014).

Discussion

Changes in floodplain geo-ecology during the first millennium AD

The general pattern of increasing human impact and consequent changes in floodplain geo-ecology is interrupted during the first millennium AD. Whereas from the Bronze Age onwards the strongly vegetated marshy floodplain environment dominated by an alder carr forest changed under the influence of increasing human impact towards a more open floodplain dominated by clastic overbank deposits, this trend is reversed during the first millennium AD. During the first millennium AD, the floodplain geo-ecology changed again (Fig. 6) with a regrowth of the alder carr forest (Fig. 2), organic-rich deposits and locally a regrowth of peat (Fig. 5), and a decrease in sedimentation rates (Fig. 2). We attribute these changes in floodplain geo-ecology to changes in human impact in the catchment during the first millennium AD. The observed decrease in human impact between 200 and 400 AD in the Dijle catchment and between 200 and 800 AD in the Mombeek catchment (Fig. 3) is suggested to cause a decrease in soil erosion. Similar changes in human pressure on the landscape during the first millennium AD were observed in the Netherlands (van Dinter et al., 2017; Pierik et al., 2018; Van Lanen et al., 2018) and SW Germany (Lang & Nolte, 1999; Houben et al., 2013). De Brue & Verstraeten (2014) showed for the Dijle catchment the non-linear relation between human impact and sediment delivery to the fluvial system. It is likely that even a minor decrease in agricultural practices and local soil erosion resulted in an important decrease in runoff and sediment delivery to river channels. This can be related to the regeneration of valley-side vegetation reducing hillslope–floodplain connectivity again, as is also demonstrated for the Wetterau catchment in Germany (Houben et al., 2013). As a result, flood frequency and sediment input in the floodplain decreased, leading to more stable floodplain environments in which the organic matter content could increase again and alder carr forests could re-establish.

However, the current dataset is too limited to identify the exact mechanism behind these local geo-ecological changes. Indeed, next to changes in sediment input, reduced intensities of human impact may also have resulted in subsequent changes in groundwater fluxes leading to a rewetting of the floodplain and, as such, promotion of organic matter sequestration. Hydrological and sedimentological modelling studies at the catchment scale (e.g. Notebaert et al., 2011c; De Brue and Verstraeten, 2014; Swinnen, 2020) may be better suited to identify causal factors and to study the sensitivity of floodplain geo-ecology to the different changing factors.

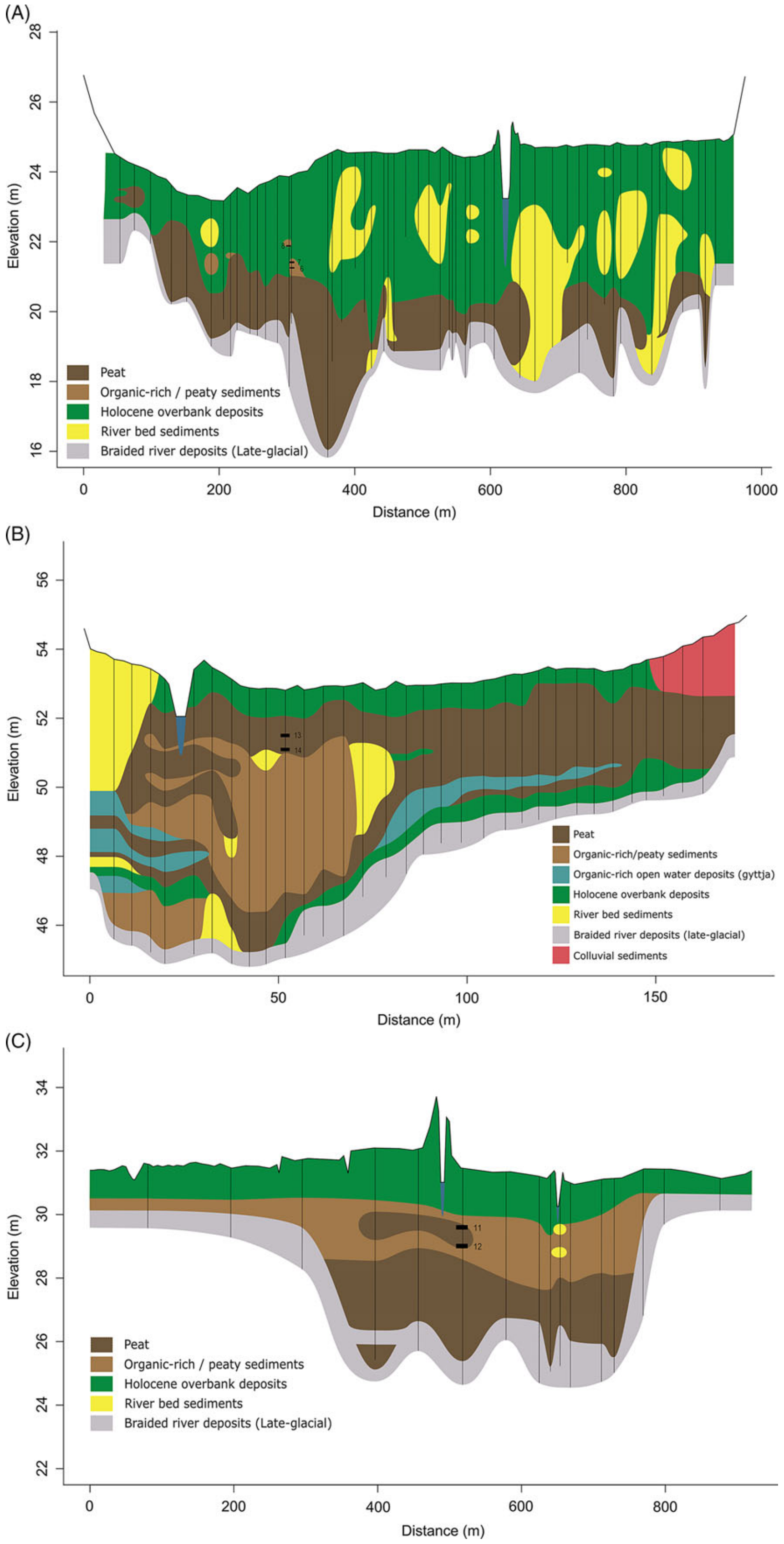

Figure 4. Typical lithostratigraphical transects of the studied floodplains. (A) Dijle (based on Broothaerts, 2014); (B) Gete (based on Quintens, 2019); (C) Mombeek (based on Diriken, 1981). Black rectangles indicate location of the available radiocarbon dates of the organic-rich layer; numbers refer to Table 3.

Organic-rich deposits from the first millennium AD are mainly found in the distal parts of the floodplain and are not continuously observed in the floodplain transects (Fig. 4). As such there is not a complete return to the original, natural state of the floodplains, i.e. marshy environments without a clear river channel. There is rather an increased accumulation of organic material in the distal

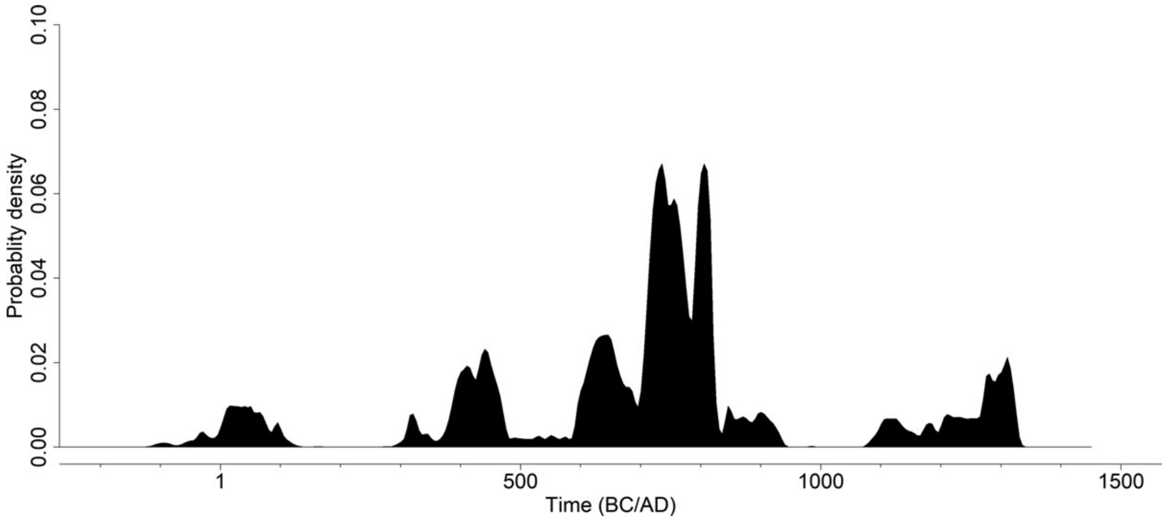

Figure 5. Probability density function (PDF) of all radiocarbon ages of Unit 5 (organic-rich overbank deposits) in Dijle, Gete and Mombeek catchments ($n = 14$).

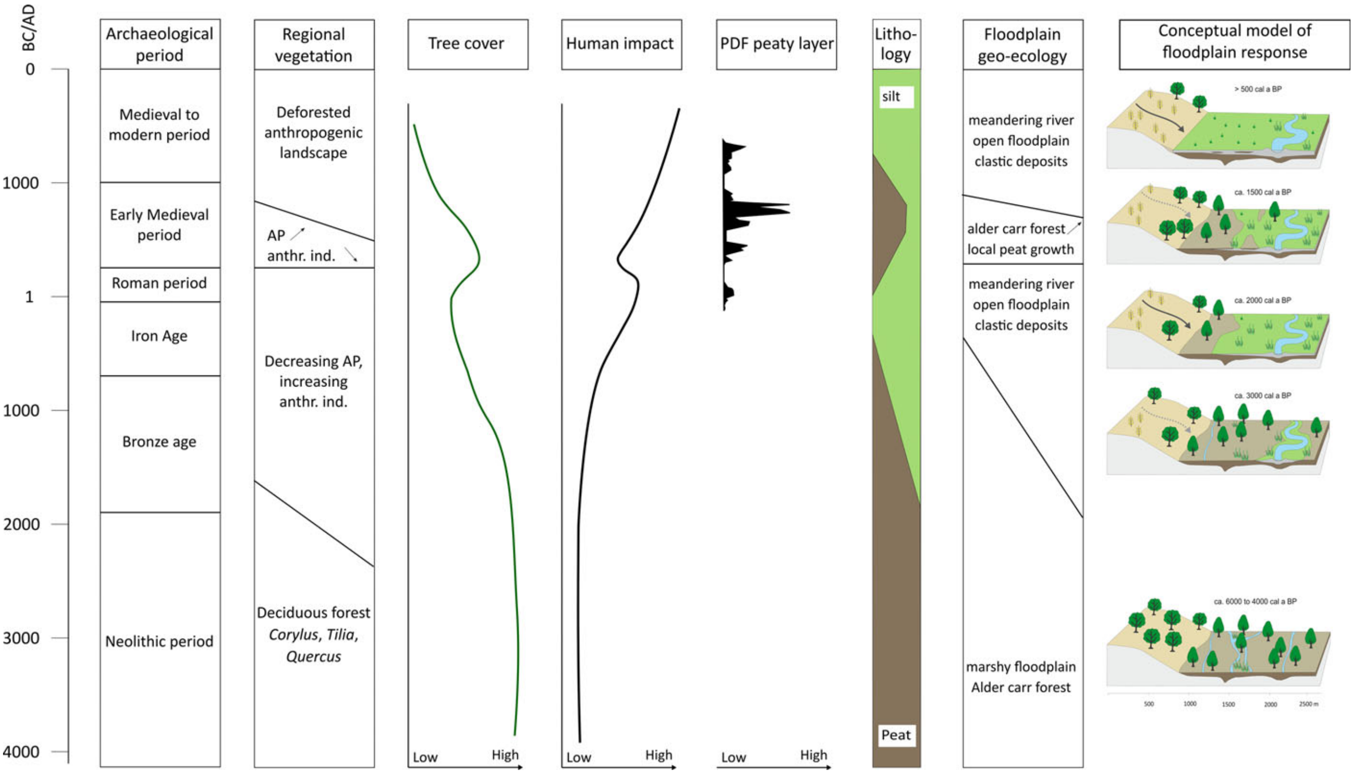

Figure 6. Conceptual overview of the main regional changes (vegetation, tree cover and human impact) and local floodplain changes (probability density function (PDF) of radiocarbon ages of Unit 5, lithology, and floodplain geo-ecology) for river catchments in the Belgian loess belt for the last 6000 years. The conceptual model of floodplain response is partly based on Broothaerts et al. (2014b).

parts of the floodplain. Moreover, there is also a high variability within the studied catchments: the described changes in floodplain geo-ecology are observed in 21 out of the 30 studied floodplain transects (70%) and do not show a continuous pattern (Diriken, 1981; Broothaerts, 2014). As a result, extrapolation of local trends to the whole catchment is not always justified. A catchment-wide approach, with results from multiple corings within one cross-section and cross-sections from different study sites in the catchment, is needed to gain full insight into the effect of short-term changes in human impact on the fluvial system.

Time lag in floodplain response during first millennium AD

For the Dijle catchment, human impact decreased between 200 and 400 AD whereas the renewed expansion of the alder carr forest is seen in the period 300 to 900 AD (Figs 3 and 6). In the Mombeek catchment, human impact decreases between 200 and 800 AD, whilst alder carr forests return between 400 and 750 AD (Figs 2 and 6). Thus, a time lag of 100 to 200 years can be observed between regional catchment changes (decrease in human impact, regrowth of the forest) and local floodplain changes (renewed peat formation, regrowth of the local alder carr forest). Such a temporal offset between changes of human impact and local floodplain changes is observed in several catchments in West and Central Europe (Lang & Nolte, 1999; Trimble, 1999; De Moor & Verstraeten, 2008; Macklin et al., 2010; Houben et al., 2013) and has been demonstrated for the Dijle catchment by De Brue & Verstraeten (2014), Verstraeten et al. (2017) and Notebaert et al. (2018). The observed time lag can indicate that floodplain changes are only triggered when changes in human impact in the catchment are large enough and thus reach a threshold. Once the threshold is reached, even a minor decrease in agricultural practices can result in an important decrease in runoff and sediment delivery to the fluvial system (see Verstraeten et al., 2017; Notebaert et al. 2018). For this, also the regeneration of valley-side vegetation and the abandonment or less intensive use of the network of dirt roads and sunken lanes are important, as they reduce hillslope–floodplain connectivity (see e.g. Houben et al., 2013). However, the observed time lag can also indicate that changes in floodplain geo-ecology during the first millennium AD are not only caused by changes in human impact but also driven by other factors such as climate change. Indeed, during the first millennium AD, fluctuations in temperature and precipitation are observed in NW Europe (see e.g. Riechelmann & Gouw-Bouman, 2019) which can cause changes in both catchment and floodplain hydrology. However, there is currently no consensus about the precise temporal and spatial extent of the climate variability (see e.g. Helama et al., 2017; Neukom et al., 2019; Riechelmann & Gouw-Bouman, 2019). To identify the exact role of climate change, a more detailed temporal framework (<200 years) and more detailed and independent databases on climate, land cover and fluvial changes are needed, as well as hydrological and sedimentological modelling studies at the catchment scale (see previous subsection).

Also, with the increase in human impact at *c.*400 AD (Dijle) and *c.*800 AD (Mombeek) and the associated floodplain changes towards a more open floodplain dominated by clastic overbank deposits, there is a delay in the floodplain response (Fig. 6). Again, this can be attributed to the threshold that needs to be crossed before floodplain changes are triggered (see also Verstraeten et al., 2017; Notebaert et al. 2018;). Moreover, in the wide floodplains in the downstream parts of the studied catchment, the peaty layer from the first millennium AD can be found, especially in the distal parts of the floodplains. A small increase in sediment input will trigger floodplain sediment deposition close to the river channel, while peat growth continued for the more distal parts of the floodplain. Only when human impact in the catchment becomes overwhelming the massive floodplain sedimentation will be triggered and the entire floodplain will become dominated by clastic overbank deposition (Broothaerts et al., 2014b).

Significance of the Dark Ages in the Belgian loess belt

This study demonstrates clear changes in the landscape during the first millennium AD in the Belgian loess belt (Fig. 6). The regional vegetation reconstructions show an increase in tree cover and decrease in human impact between 200 AD and 400 AD, respectively, and 800 AD, in the Dijle and Mombeek catchments. These regional changes in vegetation and human impact are suggested to cause a decrease in soil erosion, a decrease in hillslope–floodplain connectivity and a resulting decrease in sediment delivery to the fluvial system. These regional changes are therefore suggested to be linked to changes in local floodplain geo-ecology, i.e. a regrowth of the alder carr forest and an increase in the organic matter content of the alluvial deposits with a local reactivation of peat growth (Fig. 6). These changes can still be recognised in the current floodplain transects (Fig. 4), although discontinuously. The observed changes in floodplain geo-ecology during the first millennium AD are, however, not observed in the downstream part of the Scheldt catchment (Meylemans et al., 2013; Storme et al., 2017), probably due to the larger catchment area and the accumulated human-induced sediment supply in the downstream part of the catchment (Broothaerts et al., 2014a).

Quantitative estimates of forest regeneration or population decline during the first millennium AD cannot be made based on the data presented in this study. The presented reconstruction of human impact is semi-quantitative and cannot be considered as an absolute quantification of human population or percentage of deforestation (see also Broothaerts et al., 2014c). Such quantitative reconstructions of population densities and deforestation are, however, needed in order to fully understand human–environment interactions in this period, and to discuss in quantitative terms how ‘dark’ this period really was for the Belgian loess belt. To come up with quantitative reconstructions of population densities, the current fragmented archaeologic and historic datasets in the Belgian loess belt should be integrated and analysed in depth (see e.g. Shennan, 2017; Van Lanen et al., 2018). Moreover, more archaeological and historical data are needed to understand the nature of the changing human impact signal in terms of subsistence economy and land use strategies.

The signal of decreasing human impact and increasing forest cover in the Belgian loess belt during the first millennium AD is rather short and took only 200 to 600 years. From 400 AD (Dijle catchment) and 800 AD (Mombeek catchment), human impact increases again and, as a result, forest cover decreases again, with lowest forest cover and highest human impact during the Medieval to Modern period (Fig. 6). This relatively short signal of 200 to 600 years was, however, enough to trigger changes in the floodplains. Once the threshold in the landscape system was crossed, changes in floodplain geo-ecology were triggered rather quickly and floodplains responded to limited changes in the catchment. Defining such threshold values of human impact or vegetation cover in quantitative terms remains problematic. To do so, there is a need for a more detailed temporal framework, more information on the processes involved, such as the hillslope–floodplain connectivity and the sedimentological and hydrological responses to changes in human impact, as well as a more detailed archaeological and historical dataset.

The observation that short-term fluctuations in human impact can have an important impact on the fluvial system and can trigger changes in floodplain geo-ecology has important implications for future floodplain management. Our results show local floodplain managers and restoration projects that rewetting of the floodplain or an increase in carbon storage can be attained even with a limited decline in human impact in the catchment. Exactly how large this decline should be and how future changes in the catchments will trigger changes in floodplain geo-ecology, however, should be quantified with hydrological and sedimentological modelling studies – for which the data presented in this study can be very useful.

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