

# Fate of pioneering vegetation patches in a dynamic meandering river

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**ABSTRACT:** Fluvial biomorphodynamics in actively meandering rivers entail interactions between hydromorphodynamics and pioneering tree species that have eco-engineering effects. Here we study spatiotemporal patterns of vegetation patches smaller than 150 m<sup>2</sup> in a 4 km reach of the river Allier in France in order to unravel causes for tree persistence and mortality and identify spatial trends across the river valley. To this end we analysed aerial photographs by object-based image analysis over a period of 56 years and tracked individual patches through time. Furthermore the cover and surface age of the study reach were classified. The large-scale shifts of channels, bars and vegetation are consistent with the meandering process and chute cutoffs. However, the spatiotemporal patterns of the vegetation patches are surprising in that they are ubiquitous and have ages up to decades on the highly dynamic meander belt, but hardly expand into larger vegetation patches. Patches disappear exponentially as a function of their age, and faster so in the last decades. Causes are amalgamation into the riparian forest flanking the meander belt and mortality likely due to desiccation or erosion. Patches have a higher probability of survival when further away from the active channel and closer to high vegetation patches and valley boundary. The window of opportunity of vegetation settlement widens towards the valley boundaries and in floodplain lows of former channels and chutes. These results imply a gradual cross-valley gradient of riparian vegetation settling, survival and succession. © 2019 The Authors. Earth Surface Processes and Landforms Published by John Wiley & Sons Ltd.

**KEYWORDS:** meandering river; pioneer vegetation; object-based image analysis

## Introduction: Problem Definition and Objective

River landscapes are partly structured by fluvial geomorphological processes and partly by biological processes (Gurnell *et al.*, 2012). As riparian plant species affect the hydromorphodynamics and vice versa (Solari *et al.*, 2016), the landscape is a result of biogeomorphological interactions. Moreover, tree species appear to modify their environment such that it improves conditions for settlement and growth in their habitat; in other words, they are eco-engineering species (Jones *et al.*, 1994; Corenblit *et al.*, 2015).

Dynamics in riparian ecotopes or habitat mosaics arise mainly from two sets of processes: succession by vegetation development and rejuvenation by river morphodynamics (Geerling *et al.*, 2006; Gurnell *et al.*, 2012; Garófano-Gómez *et al.*, 2017). Succession starts by settling of pioneer vegetation and is succeeded by growth and mortality of multiple species. It leads to increased biomass, vegetation height and average vegetation age over time. This paper is concerned with the pioneering stage of riparian vegetation, during which environmental variables only determine where species settle on a bare sediment surface, as opposed to later stages of succession where the spatial structure of vegetation partly

determines through facilitation and competition where new vegetation settles. Recent literature on observations and models of fluvial biogeomorphology emphasized that succession proceeds from pioneer vegetation that colonizes the bare soil and is gradually replaced by postpioneer species as islands build up and eventually form a dense floodplain forest cover (Geerling *et al.*, 2006; Camporeale *et al.*, 2013; Solari *et al.*, 2016; Garófano-Gómez *et al.*, 2017).

Rejuvenation is largely induced by vegetation mortality, as at least part of the juveniles and trees in the bushy phase disappear quickly in subsequent floods (Pasquale *et al.*, 2014; Kui *et al.*, 2014; Surian *et al.*, 2015; van Oorschot *et al.*, 2016) and droughts (Bätz *et al.*, 2016). In some cases this vegetation turnover is determined by channels that migrate laterally into vegetated bars, such as observed in the braided Tagliamento river (Surian *et al.*, 2015). Here, 'rejuvenation' entails complete resets by river channel migration that destroys older floodplain and creates new, bare soil, partial vegetation removal by uprooting or mortality due to inundation stress during floods, and partial soil creation by sedimentation during floods that can cover low vegetation such as grass, herbs and pioneer trees in the seedling stage. The effect is that a range of ages of vegetation occurs depending on the age of the surface they formed on, which implicitly suggests that bare

soil is colonized after formation and remains vegetated until removed by erosion during floods. The bank erosion mechanism is also assumed to be the main process in meander simulation models (Camporeale *et al.*, 2013). In other cases, however, the vegetation itself is mainly uprooted due to bed, rather than bank, erosion (Kui *et al.*, 2014), by the flood flow itself (Pasquale *et al.*, 2014), or mortality through inundation or drought stress. For rivers dominated by chute cutoff, the persistence or removal of vegetation on the inner-bend bar is much more important for the meandering pattern than the outer-bank stability (Kleinhans *et al.*, 2018). The processes of vegetation removal are well known (e.g., Gurnell *et al.*, 2012) but there remains a gap between spatial biogeomorphological modelling at resolutions much coarser than individual plants (e.g., van Oorschot *et al.*, 2016; Solari *et al.*, 2016) and the physical relations available for individual plant uprooting (e.g., Schnauder and Moggridge, 2009; Aberle and Järvelä, 2013). Hence we do not know how pioneers initially settled in patches are to be modelled.

In particular, for locations other than eroding banks, we do not know whether all individual plants at one location are uprooted by bed erosion during floods or by drought. Individuals may survive until a later stress period or make it into a next succession stage. In line with this idea we assume in our modelling that a fraction, rather than the entire population, of trees in a patch dies off under stress (van Oorschot *et al.*, 2016), but this hypothesis remains untested. We do not know what fraction of the pioneers disappears, grows out to riparian forest, or stays in a pioneer state without expansion. The objective of this paper therefore is to quantify temporal dynamics and spatial relations of pioneer vegetation with the active river channel and the riparian forest, in order to understand the main causes of pioneer disappearance, persistence, or succession.

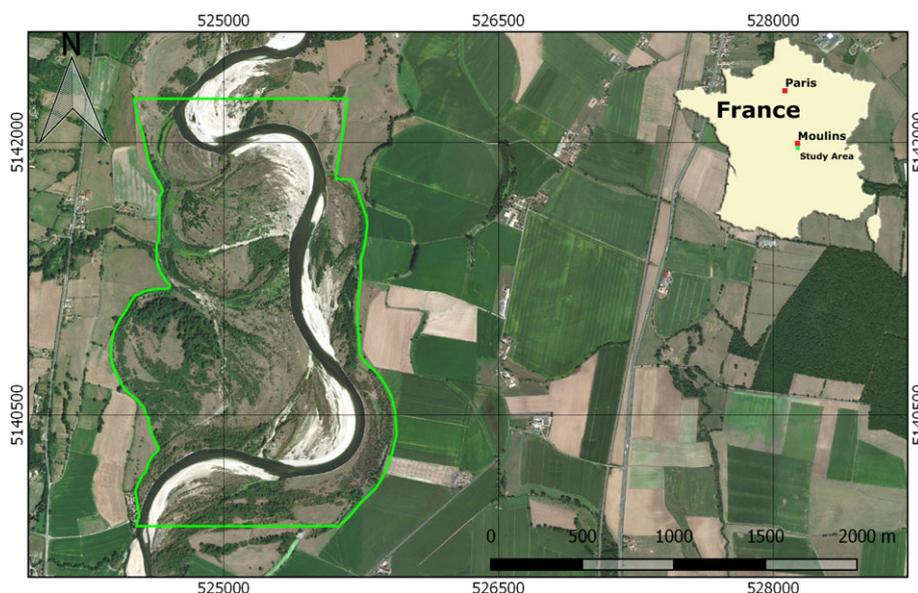
To this end we focus on the River Allier, southern France, which is a sandy gravel-bed river with a strong interaction between pioneering riparian trees and the meandering process (Geerling *et al.*, 2006; van Oorschot *et al.*, 2016; Kleinhans *et al.*, 2018). This river is the only one in Western Europe that is allowed to meander freely and is, as such, an ecologically valuable system and an example for river renaturalization projects elsewhere. The scientific interest in the River Allier is that it takes a middle ground between braided rivers such

as the Tagliamento, where the morphodynamics mainly determine the landscape structure but are affected by riparian vegetation (Bertoldi *et al.*, 2011), and rivers such as the sinuous, but not actively meandering Nqoga River, where the landscape is determined by vegetation (Tooth and McCarthy, 2004). In the River Allier, the landscape is structured both by riparian vegetation patches and by the perpetually changing morphology due to the active meandering with chute cutoffs. As a result, the River Allier exhibits a mosaic of habitats that shifts over the years while maintaining approximately the same surface fractions, on average, over the reach scale (Geerling *et al.*, 2006; Garófano-Gómez *et al.*, 2017). The changes and shifts in the mosaic are mostly caused by dynamic meandering through bend migration and sudden shifts during floods (Kleinhans and van den Berg, 2011; van Dijk *et al.*, 2014; van Oorschot *et al.*, 2016). Likewise, the scale of the patches in the mosaic patterns of Geerling *et al.* (2006) and Garófano-Gómez *et al.* (2017) ranges from the typical length of meander bends to an order of magnitude smaller. To bridge the scale gap between these large-scale mapped mosaics and the dynamics of vegetation as modelled, we focus on patches of pioneer tree species.

## Methods

### Aerial photographs

Many past studies of rivers in general and the River Allier specifically were conducted on the basis of aerial photographs. A number of these proceeded from manual digitization of surface units founded on some ground truth (Geerling *et al.*, 2006; Garófano-Gómez *et al.*, 2017). A recent study applied the structure from motion technique, an improvement on stereo photogrammetry, to obtain detailed digital terrain models and vegetation height models (Vautier *et al.*, 2016). Here we are interested in the recognition and fate of small pioneer tree vegetation patches. To this end we will identify isolated vegetation patches and track these through time by object-based image analysis (OBIA) on subsequent aerial photographs.



**Figure 1.** Study area in the River Allier, France. Background image from Google Earth (accessed December 2017). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

**Table 1.** Aerial photographs used in the image-based object analysis. All images were obtained from the Institut National de l'Information Géographique et Forestière

Image date	Color	Resolution	Resampling
(dd/mm/yyyy)		(m)	resolution (m)
13/07/1946	BW	0.92	0.3
09/05/1954	BW	0.92	0.3
03/06/1960	BW	0.92	0.3
30/06/1968	BW	0.264	—
28/07/1975	BW	0.188	—
02/08/1980	BW	0.323	—
09/07/1985	BW	0.34	0.3
31/07/1992	BW	0.32	—
20/06/1998	BW	0.275	—
19/07/2000	RGB	0.265	—
31/05/2002	RGB	0.76	0.3

The study area comprised about four to six meander bends (Figure 1), which is probably sufficient to cover the full range of floodplain histories and settings with isolated vegetation patches that can be found in this river. The extent was chosen for full coverage in all sets of available aerial photographs. The total area is  $2.86 \times 10^6 \text{ m}^2$  or 286 ha. The flanking terraces with agriculture were cropped off before analysis.

A time series of 11 orthophotos was created, which included all photos that are available for the study area between 1946 and 2002 (Table 1). The orthophotos were stitched together from individual prints, which were available as hard copy or in digital format depending on the year of purchase. All photos were retrieved from the French Institut National de l'Information Géographique et Forestière (IGN). The series included black and white and full-colour hard copies, as well as black and white digital copies. All hard copies were scanned at 2400 dpi; the digital copies were digitized at 1200 dpi by IGN. For each time step an orthophoto was created by Agisoft (2017 version) and Erdas (2017 version), with pixel sizes varying from 19 to 32 cm. Average geometric accuracy was 3.47 m. All orthophotos were clipped to the extent of the study area (Figure 1).

## Image classification and map analysis

The orthophotos were classified using object-based image analysis (OBIA; Figure 2) as the photos provide too little information for a pixel-based distinction of the land cover classes. Aerial photos contain limited spectral information, particularly the black and white photographs. Moreover, the spatial arrangement of pixels is hardly taken into account, so that a pixel-based classification would result in very noisy maps without reliable information about patches. In OBIA, pixels are first grouped into objects, which have many spectral, geometric and context features to characterize them (Addink *et al.*, 2012; Blaschke *et al.*, 2014). This is particularly relevant in sparsely vegetated surfaces where bare soil may be visible in between plants, and pixels may be partially filled by different types of surfaces and other sources of spatial variation. Such variation is an inherent part of vegetation patches. The internal spectral variation, the shape – for instance, circularity or elongation – and context – e.g., contrast with neighbouring objects – are valuable characteristics available in OBIA. Analysis of vegetation in orthophotos on the basis of spectral information is so limited that the added features from OBIA are indispensable. Finally, the supreme characteristic of OBIA is that it merges single square pixels that have no spatial meaning in reality into a meaningful group of pixels that together represent an observable entity in nature.

The target class of this study was the isolated vegetation patch, which after initial testing was defined as  $150 \text{ m}^2$  or less, while most isolated patches of simple rounded forms are an order of magnitude smaller in surface area. This size cutoff also allows us to study merging of small vegetation patches into larger patches and with the forest. To identify this class of isolated vegetation patches, segmentation was applied to the photos to create objects. In this process neighboring pixels that are spectrally similar are grouped into objects. Here, spectral information refers to the greyscale information in each pixel in the aerial photographs. The maximum heterogeneity within an object was set such that the objects optimally delineated vegetation from bare soil and water. Contiguous vegetation patches could be split into multiple objects. Given the varying pixel size and the differences in illumination conditions, the heterogeneity threshold was set for each year individually and was confirmed by visual inspection.

Next, all objects were classified into the classes *water*, *bare soil*, *low vegetation* or *high vegetation*. Objects representing water are characterized by low brightness values. They were labelled manually, as the outline of the channel is easy to recognize visually, whereas spectral confusion between water and high vegetation is high due to the low brightness values of both classes. The other classes were retrieved fully automatically as follows. The remaining (non-water) objects were merged into contiguous objects if they met three conditions: (1) they shared at least 5% of their border; (2) average brightness differed less than 12 (on a scale of 0–255); and (3) the standard deviation of brightness within the objects differed less than 2. The third condition was included to avoid merging of objects with different textures. The three classes bare soil, low vegetation and high vegetation have different brightness values, where bare soil has the highest and high vegetation the lowest value. Here, we know from field site visits that bare soil is mostly sandy gravel, low vegetation is mostly herbs and grasses, while high vegetation is dominantly trees (also see (Geerling *et al.*, 2006); (Garófano-Gómez *et al.*, 2017)). These can very clearly be distinguished on the images because the brightness of trees is considerably lower than that of herbs on account of its canopy structure, with leaves and branches absorbing much more of the incoming radiation. Furthermore, the isolated vegetation patches are not individual trees, but are groups of trees in the seedling stage, bushy or full-grown poplar and willow trees, likely somewhat cluttered with driftwood, with occasional patches of herbs and grasses. For each year thresholds were calibrated by visual inspection to optimally assign each object to these three classes. Finally, all low vegetation and high vegetation objects that were smaller than  $150 \text{ m}^2$  and were fully surrounded by brighter objects were labelled as isolated vegetation patches.

The classification resulted in 11 maps showing the isolated vegetation patches. The maps were intersected and when patches in consecutive photos overlapped they were identified as surviving patches (Figure 3). Two other categories are the newly emerged patches and the disappeared patches. This last category combines the result from different processes: the patches could have died from flooding or drought, they could have been swiped away by river erosion, or they could have grown into a larger patch. For each isolated vegetation patch the shape was quantified to explore the effect on its development. A convenient shape index is defined as the ratio of patch perimeter and  $4\sqrt{\text{area}}$  of the patch, where a value of 1 indicates perfect resemblance to a compact square object. Furthermore, an approximate age of the isolated vegetation patches was determined from their first appearance.



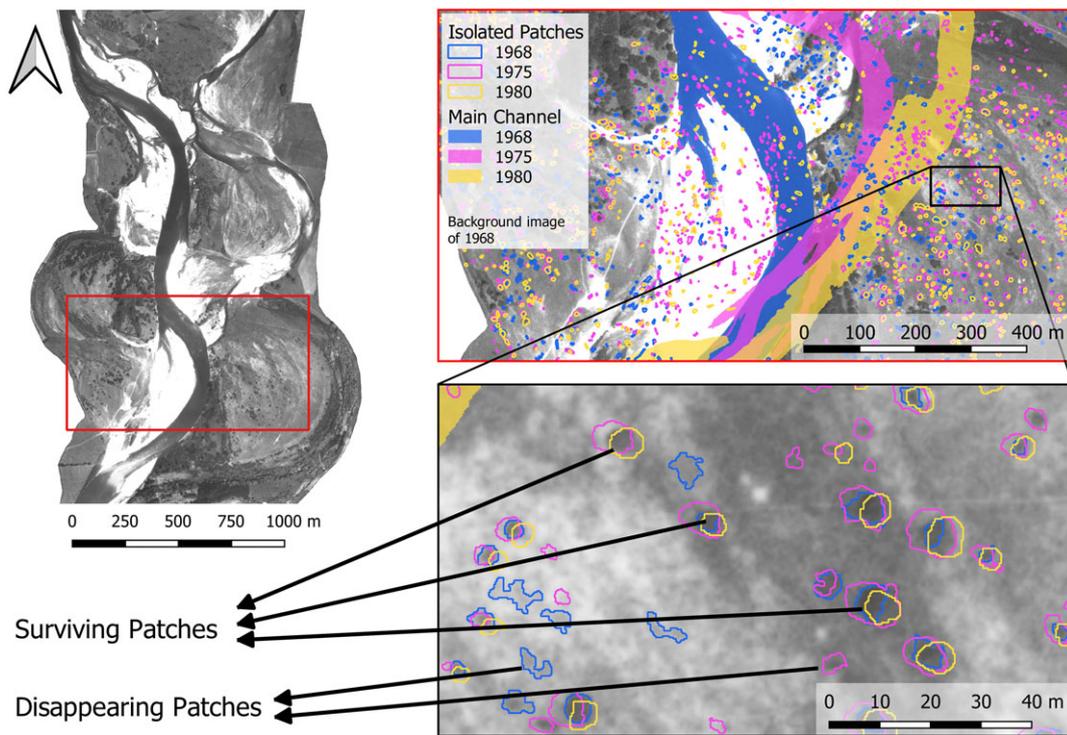
**Figure 2.** Workflow of the object-based image analysis conducted to obtain pioneer vegetation patches. The legend for box types and colour is given at lower right. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

## Hydromorphological data

Stage and discharge data were retrieved from <http://www.hydro.eaufrance.fr> (accessed December 2016) for four stations (Table II), none of which had both variables for the entire period of interest. Data were compared and merged by averaging to obtain an approximate but continuous time series of stage and discharge between 1955 and 2015. This was of sufficient accuracy for our purposes of semi-quantitative linking of hydromorphological data with vegetation dynamics. Water level was calculated relative to an arbitrary datum such that the lowest water levels were just above 0 m depth.

The most downstream station Moulins was not used for water-level analysis because of the backwater effect of the weir and bridge. The two upstream stations Billy and Saint-Yorre had somewhat lower stage and discharge ranges and were transformed to match that of station Chatel-de-Neuvre, which is closest to the study area.

We use annual peak discharge and annual peak water level as indicators for uprooting and inundation stress, the 25% lowest discharge as an indicator for potential desiccation stress depending on bed elevation relative to local groundwater level, and a moving average to indicate water availability in general.



**Figure 3.** Example of patches recognized to appear and disappear in three available images spanning 12 years. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

**Table II.** Data of stage and flow discharge

Station	Period	Stage	Discharge	$QH$ -rel.
Chatel-de-Neuvre	1986–2016	Yes	Yes	$Q = 0.02(H + 170)^{1.8}$
Moulins	1968–2016	Yes	Yes	$Q = 0.2(H + 70)^{1.6}$
Billy	1955–1966	Yes	No	Chatel-de-Neuvre
Saint-Yorre	1967–2016	Yes	Yes	

*Note:* Approximate  $QH$  relation is given for stage  $H$  in cm above arbitrary datum. The unavailable stage for station Billy was back-calculated from the  $QH$  relation for Chatel-de-Neuvre. Stations Billy and Saint-Yorre were corrected by empirical multiplication factors ( $1.32Q$  and  $1.44H$ ) based on correlation between Saint-Yorre and Chatel-de-Neuvre. Stage data of Moulins before 26 July 1968 was corrected by subtraction of 100 cm.

## Results

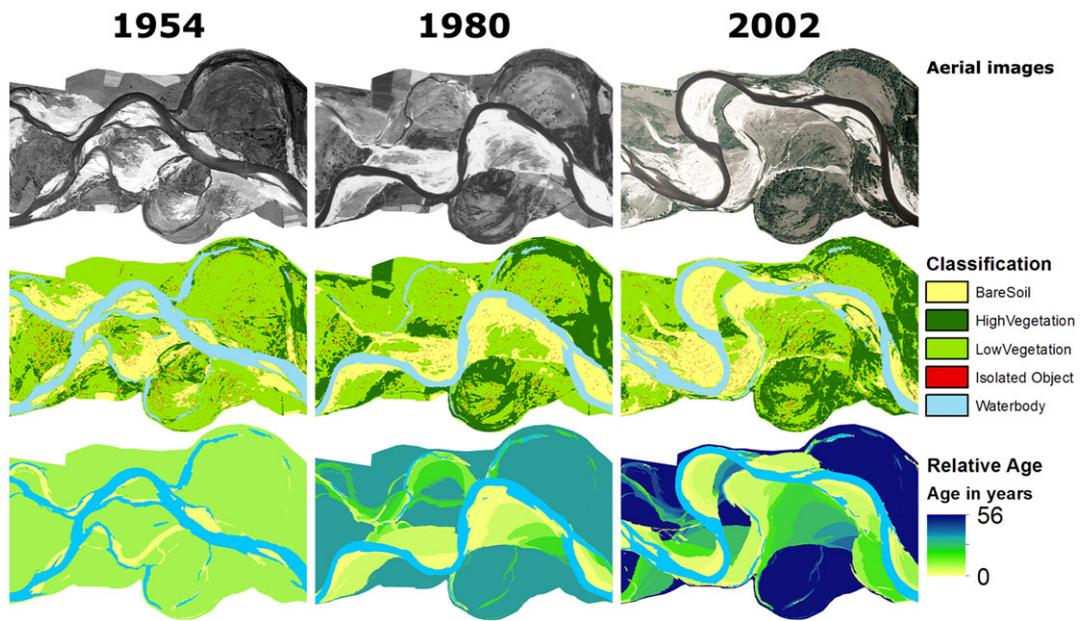
### Surface cover and isolated vegetation patches

The classified cover of the River Allier shows the expected dynamics: as the meanders migrate and cut off, older floodplain is eroded and new bare soil is formed close to the river channel (Figure 4). Some of the bare soil, mostly further away from the low-water channel, transforms to low vegetation and high vegetation over time. The resulting landscape is patchy, with the largest recognizable units at the length scale of meander bends, and the smaller units of bare soil, low and high vegetation an order of magnitude smaller. Furthermore, a range of landscape ages is found. These age differences were calculated from the first available image and represent a minimum age for existing areas and a maximum age for new areas. The area fraction of the covers remains about constant over time (Figure 5A). This shows that the river is dynamic in the sense of frequent flooding and active meandering, and that the river is in large-scale planform equilibrium in the sense of cover on the timescale of our observations.

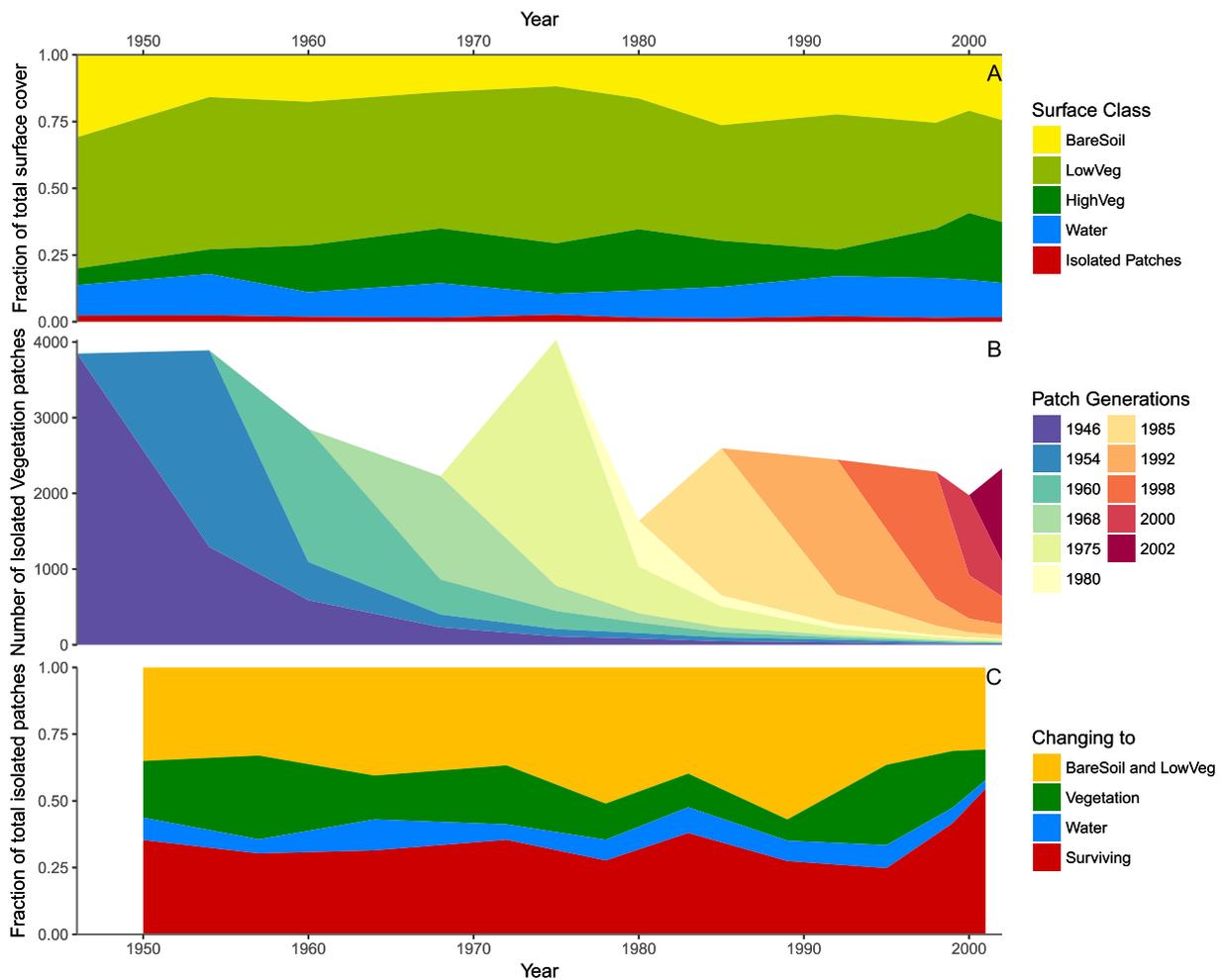
The surprising results are that the isolated vegetation patches smaller than  $150 \text{ m}^2$  occur ubiquitously in the zone that is changing rapidly due to the meandering processes, and, moreover, that the patches are quite persistent over time. This contrasts with the classic image of riparian vegetation settling as seedlings to either die off again or expand into forest. The vegetation in the patches ages considerably but many patches neither expand nor disappear over several years. Below we detail these findings.

The isolated vegetation patches can occur only in the bare soil and low vegetation areas (Figure 4). Although many patches line up on curves delineating former channel banks or minor channels cutting across the bars, they are found all over the valley. Once grown or merged beyond  $150 \text{ m}^2$  or amalgamated with a high vegetation patch, it is classified as high vegetation. Many patches remain recognizable in subsequent images, meaning that their age could be determined since their first appearance or since the first image. The number of patches decays with age (Figure 5B). The total number fluctuates by almost a factor of two over the observation period.

About one-third of the patches survive long enough to be observed in the next image. Other patches disappear in a



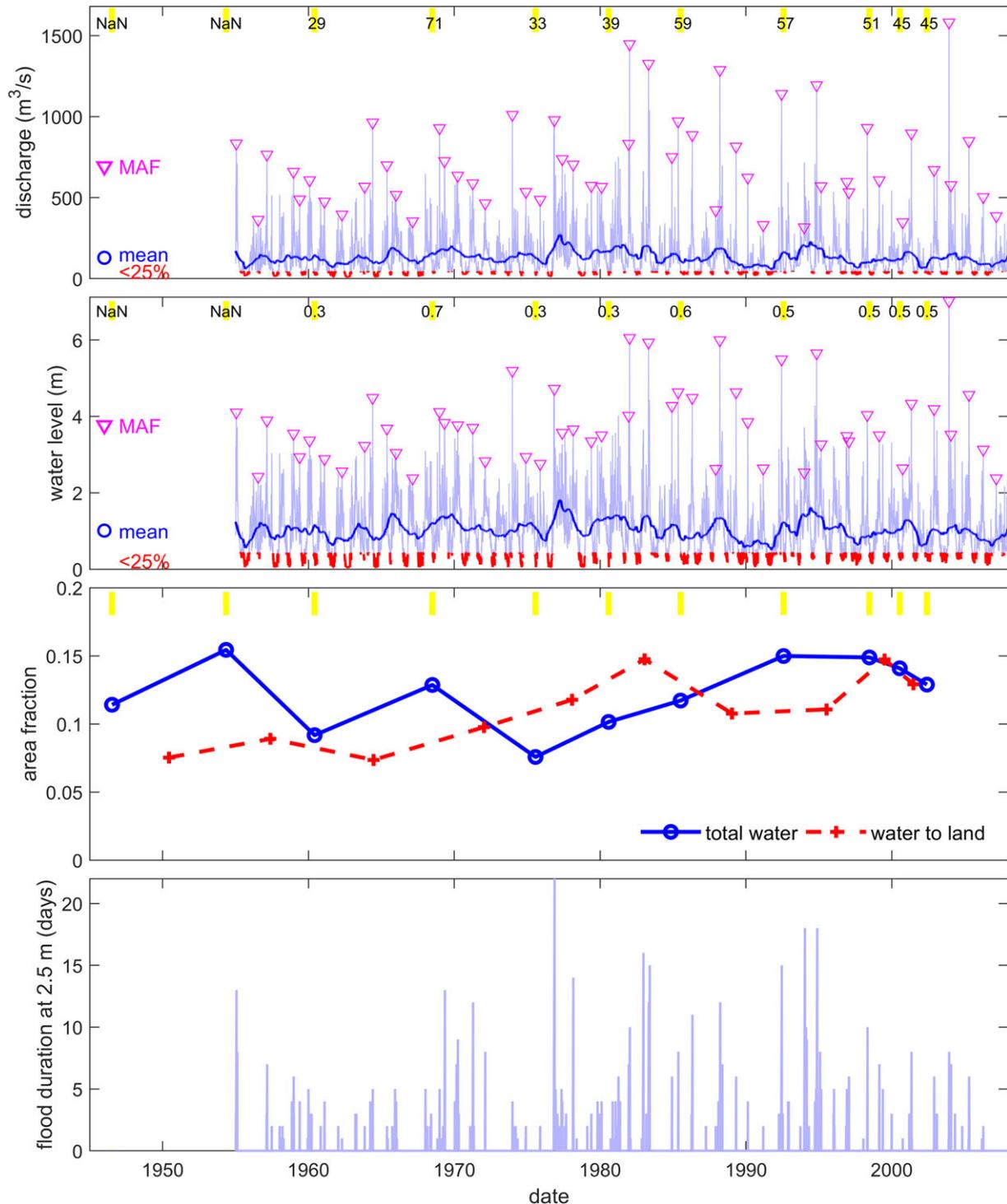
**Figure 4.** Example of aerial photographs (top row), classified cover with patches (middle row) and surface age (bottom row) for three time steps. See online supplementary movie (supporting information) for all time steps. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**Figure 5.** Time series of cover, number of vegetation patches and patch disappearance. (A) Area of classified cover. Isolated vegetation patches are surrounded by bare soil and low vegetation classes. (B) Number of isolated vegetation patches in the study area through time since the year of first appearance. (C) Fraction of isolated vegetation patches surviving, merging with vegetation cover, disappearing through channel migration or disappearing for other reasons. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

number of ways (Figure 5C). The first cause is that about one-quarter of the patches transform to high vegetation cover, sometimes by amalgamation but mostly due to merging with existing high vegetation cover. Less than a tenth of the patches disappear into the low-water channel, but this is a conservative estimate as the river channel is much wider in flood stage. The number of patches disappearing into bare soil and low

vegetation mirrors the change in the total number of patches; for example, the largest drop in patch numbers from 1975 to 1981 coincides with a larger fraction of change into the bare soil and low vegetation class. Here, the bare soil class is an indication of the river channel width during flood because much of the active river bed belongs to this class. However, this class also contains new flood deposits from suspended



**Figure 6.** Time series of hydromorphodynamics. (A) Daily flow discharge and (B) flow stage above arbitrary level. The calculated mean annual flood discharge and water level are indicated to the right. A moving average discharge and values below 25% of the time, as an indication for low water availability, are indicated. The running mean is calculated with a window of a year. Timing of aerial photography is indicated, with values of  $Q$  and  $H$  at the top of the respective panels showing that low flow conditions were not significantly different, meaning that the aerial photographs are well comparable. (C) Water surface fraction of total surface area indicative of active channel area, and fraction of water surface area that changed to land, indicative of channel displacement between images. (D) Inundation duration calculated for an arbitrary level of 2.5 m. For reference, the mortality threshold for black poplar seedlings is 60 days of inundation (Geerling *et al.*, 2006; van Oorschot *et al.*, 2016). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

bed material over the low vegetation cover and in between the higher vegetation (for example, in the outer bend at the bottom left of the 2002 image; Figure 4).

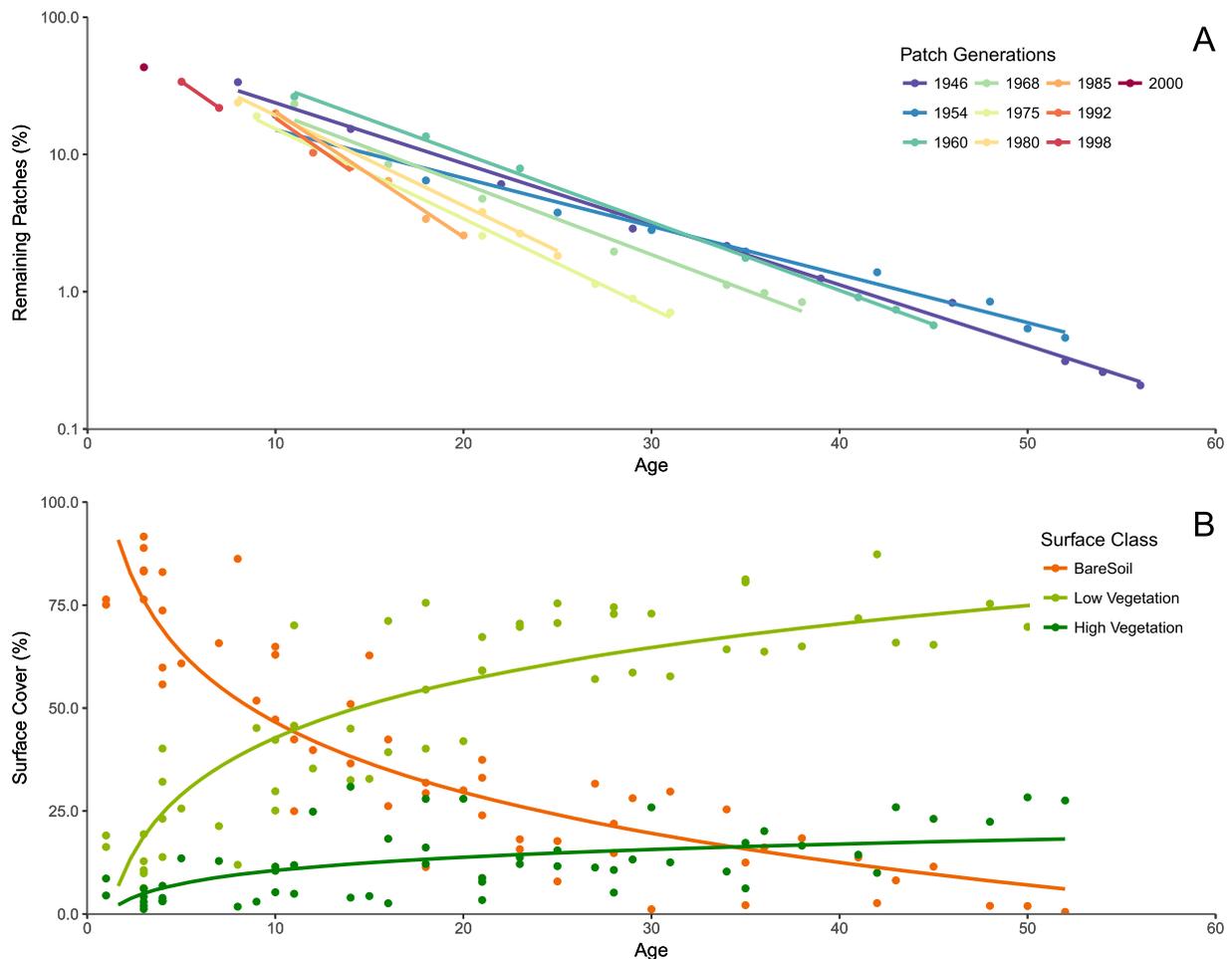
A typical cross-section of the valley (Figure 4) shows a channel, bare soil in the inner bend, and bordered by low vegetation before the first high vegetation is encountered. This landscape structure follows the outward movement of the channel, but revegetation of the areas reset by hydromorphodynamics is slow. The transition from bare soil to low vegetation takes a long time: after 10 years 50% of the new bare soil areas are still bare and after 30 years this is still almost 20%, indicating that the conditions for settling are unfavourable.

## Hydromorphodynamics

The above observations can be attributed to noise effects such as image quality and natural dynamics, in particular vegetation succession and hydromorphodynamic causes of mortality. Given the consistent spatial arrangement of land cover patches, we assume that image quality only plays a minor role in this study. The natural dynamics are apparently such that hydromorphodynamics limit succession and largely prohibit succession in the ecosystem; otherwise the patches of pioneer vegetation would have expanded. Hydromorphodynamic causes of mortality can generally be attributed to

flooding, drought during summer, bend migration and chute cutoffs. Mean flow discharge is fairly constant throughout the observation period, with slightly wetter years around 1978 and 1995 (Figure 6), although measurement issues with the stages cannot be excluded. The mean annual flood discharge is about four times the mean discharge. Water levels above arbitrary datum are on average about 1 m. During annual floods most of the study site is submerged. Inundation duration for arbitrary water level of 2.5 m, 1.5 m above the average water level, is of the order of days to at most 3 weeks during floods. Mean discharge is well below bankfull discharge, meaning that the morphologically active river bars are entirely dry during most of the year. We have no data on local groundwater level in the bars but some observations in pits dug during field site visits indicate that the subsurface is as coarse grained and permeable as the surface, and the groundwater surface is at about the same elevation as the water level in the channel.

The wetter year in 1978 coincides with the fastest disappearance of patches but no such reduction was observed in 1995, which was almost as wet. However, the 1978 period has no low flow and continuous relatively higher discharge, which could mean inundation stress for the vegetation. Furthermore, the bare soil cover is largest from the 1980s onward (Figure 5A), when the five highest floods are also much higher than the five highest floods in the period before. Also, the transformation of water into bare soil is highest in this period, where this transformation is a measure for thalweg migration



**Figure 7.** Changes in patch disappearance rate and surface cover. (A) Exponential decay of the number of remaining patches as a function of time, with year of appearance indicated. The steepening slope indicates a shorter characteristic timescale of decay. (B) Change in cover type of floodplain as a function of age, showing that 90% of the bare floodplain transforms to vegetated floodplain in about 42 years, of which only 15% becomes high vegetation. The vegetation patches, not shown here, only occupy a minor fraction and merge partly with high vegetation over time. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

and shifting. A statistically significant correlation could perhaps be found but it is not entirely certain that the hydrodynamic data can be trusted because this was composed from multiple observation sets from multiple locations in the river.

### Isolated vegetation patch dynamics

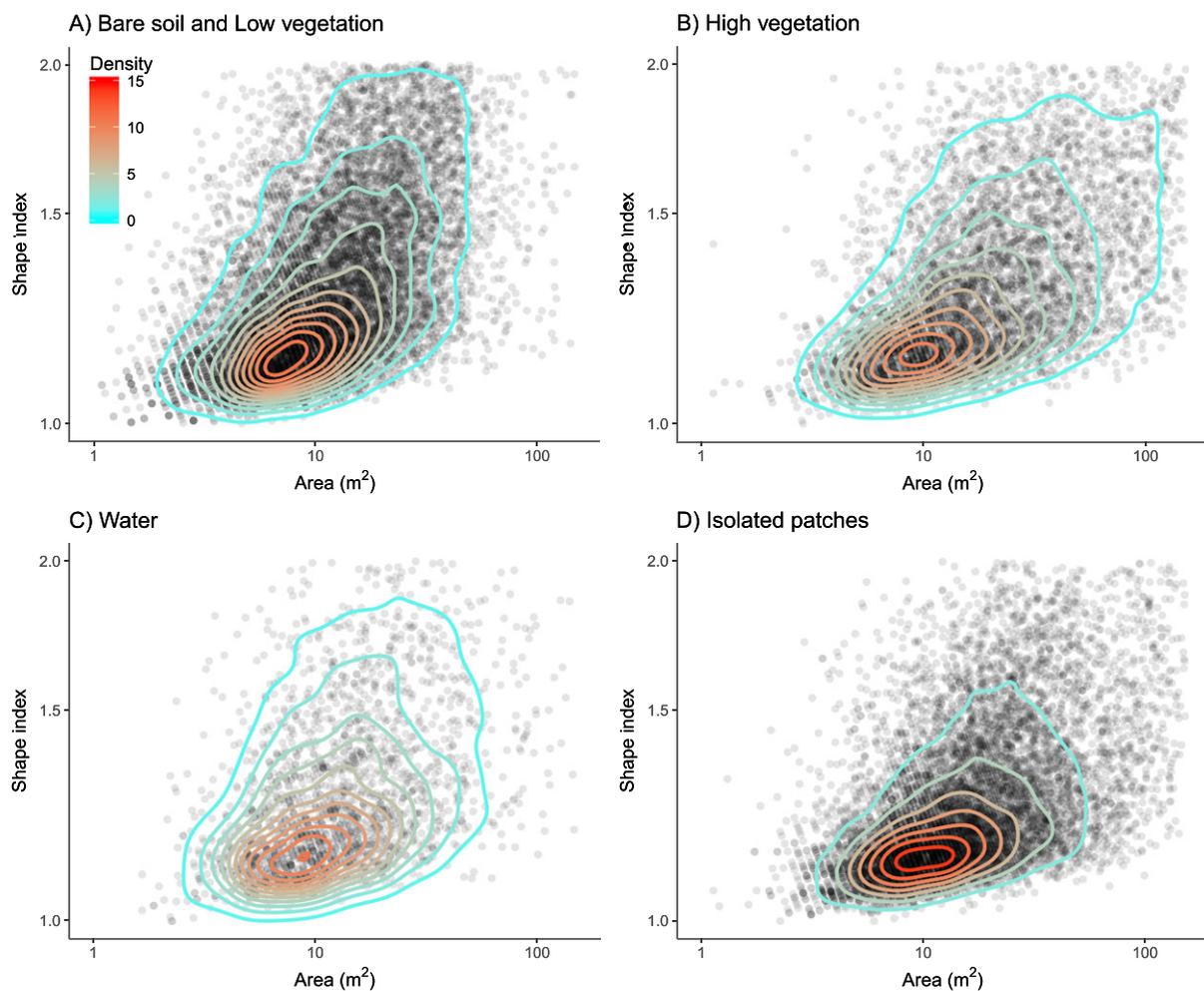
The observed disappearance of vegetation patches proceeds remarkably uniformly (Figure 5B). The age analysis of landscape and the coupling of vegetation patches through time allows us to calculate the characteristic timescale of patch disappearance. We plotted the observed fraction of patches remaining as a function of age for each set of new patches observed in a certain year (Figure 7A). We fitted exponential functions  $y = \alpha e^{\beta x}$  of the remaining fraction against patch age, from which a characteristic timescale of disappearance of 90% of the patches was calculated as  $T = -2/\beta$  (Table III). Exponential fits had  $R^2 > 0.98$  for nearly all generations and the lowest  $R^2 \approx 0.93$  for the 1992 generation, meaning that for practical purposes the decay and characteristic timescale can well be described by an exponential function. The characteristic timescale for 90% patch disappearance is about two decades for the first half of the generations (before 1980) and drops to one decade for the second half of the generations (after 1980). This shows in the first place that the frequency

of image availability is, although low, sufficient and not limiting to capture the trends. Moreover, the reduction of survival coincides with a reduction in total number of patches and an increase of the patches changing into bare soil or low vegetation. This means that the vegetation patches are under

**Table III.** Exponential fits to the remaining fraction of isolated vegetation patches of a certain age class after their first appearance

Year	$\alpha$	$\beta$	$T_{90}$	$R^2$	$n$
1946	0.657	-0.102	20	0.993	10
1954	0.245	-0.081	25	0.98	9
1960	0.709	-0.115	17	0.998	8
1968	0.409	-0.119	17	0.981	7
1975	0.379	-0.151	13	0.996	6
1980	0.557	-0.152	13	0.992	5
1985	0.886	-0.21	10	0.99	4
1992	0.692	-0.221	9	0.93	3
1998	0.526	-0.22	9	1	2

*Note:* The characteristic timescale for 90% disappearance of number of patches is calculated from  $\beta$ . The  $R^2$  is given as an indication of fit quality, but note that the number of points  $n$  on which the exponential fits was determined decreases through time.



**Figure 8.** Area and shape index of isolated vegetation patches on bare soil and low vegetation (A), disappearing into high vegetation (B), disappearing into water (C) and patches that are surviving (D). Shape index is defined as the ratio of patch perimeter and  $4\sqrt{\text{area}}$  of the patch, where a value of 1 indicates perfect resemblance to a compact circular object rather than, for instance, an irregular object that could be two merged objects. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

increased stress since the 1980s, such that their life expectancy halved.

The transformation from bare soil to low vegetation and high vegetation also proceeds exponentially with age, but on a much longer timescale than the individual patches and with a much larger spread. Bare soil cover reduces by 90% after about four decades (Figure 7B), whereas low vegetation and high vegetation covers increase. This transformation most likely occurs by settling, growth and expansion of vegetation as low-water channel cover remains about the same (Figure 5C).

We tested whether survival of isolated vegetation patches is related to their size, here expressed as surface area (Figure 8), assuming that larger patches perhaps survive more frequently. However, this is contradicted by the observations: patches that disappeared in bare soil and low vegetation or into water are, at best, 10–20% smaller than patches that survived as patches or merged with high vegetation. Also the shape between surviving and disappearing patches is not clearly different, meaning that patch irregularity or compactness is not clearly correlated with survival or disappearance.

### Spatial trends and facilitation

To unravel possible causes of patch dynamics, in particular causes for disappearance, we calculated distributions of selected patches over distance from water or high vegetation cover, measured at the last observation time of patch existence (Figure 9). The skewed distribution of the distance to the low-water channel shows that most patches are at a distance of about 100 m from the low-water channel, except those that disappeared into the channel (Figure 9A). The surviving patches are the furthest away. Patches closer to high vegetation are more frequently merged with high vegetation (Figure 9B) and also closer together (Figure 9C). There is no clear difference between the distributions of surviving patches and patches disappearing on bare soil or on low vegetation. This lack of trend is apparent both as a function of distance to the low-water channel and as a function of distance to the nearest other patch.

This behaviour was confirmed when the patches were subdivided into surviving patches, patches transforming to high vegetation, and true mortality of patches that disappeared on bare soil and low vegetation cover. The disappearance of patches into the low-water channel was likely caused by mortality due to uprooting and/or inundation stress. This subset represents a minor fraction and is therefore not further analysed. The frequency of the subsets of patches was plotted against distances for a number of possible combinations (Figure 10). Important trends are as follows. Many patches merging with high vegetation were close to the high vegetation (Figure 10A) and close to other patches but far from water (Figure 10E). Surviving patches are located further from water than from high vegetation (Figure 10B) and survive more frequently when closer to other patches (Figure 10F). Patches mainly disappear that were further away from water and on bare soil and low vegetation (Figures 10C and 10D). This occurred more frequently when the distance to adjacent patches was larger (Figure 10G and 10H). In other words, isolated vegetation patches have a higher chance of survival when they are more closely spaced and closer to the riparian forest, and when they are further away from the river channel. In addition, some patches concentrate at lower bed elevations in residual channels on the bars.

To summarize, the isolated vegetation patches in the River Allier have shown remarkably constant properties and dynam-

ics over the past half century. The patches are fairly rounded and circular in shape and have surface area ranges between 4 and 100 m<sup>2</sup>, which means they have characteristic patch diameters between 2 and 10 m. Patch survival probability decays exponentially with age and patches have a characteristic lifetime of 20 years in the first half of the observation period, which rapidly reduces to 10 years in the second half. Patches close to existing vegetation are likely to survive as, or to transform into, high vegetation, but the majority of the patches will disappear on the covers of low vegetation, bare soil or water after a surprisingly long period without expansion.

## Discussion

### Life and death of pioneer vegetation patches

The observed trends can be rephrased in terms of succession and setbacks. The fraction of patches changing into high vegetation reflects progress in succession, while changes into water, bare soil or low vegetation indicate a setback in succession. Surviving patches reflect a status quo. Figure 11 shows that chances of continued succession are highest especially when close to existing high vegetation patches and also when close to other isolated vegetation patches. Chances of a status quo are largest when located far from water. On the other hand, a short distance to water means higher chances of a setback. With increasing distance from existing vegetation, chances of a setback in succession increase, while chances of a status quo are independent from this distance. In short: succession is more likely close to dense vegetation and is strongly hampered by the active water channel.

Before possible causes of patch disappearance are inferred, the vegetation settling patterns must be understood. Spatial variations between patch density, expressed here as distance between patches, are minor. Firstly, patches are spaced closer together near the forest, suggesting vegetative propagation from propagules directly from the forest. Second, patches are located on the lower residual channels and former bank lines, suggesting seedling setting at the waterlines. A possible cause for the latter settling pattern is that lower locations have better access to the groundwater. This results in better chances of surviving droughts and, given the higher probability of lower water levels, a higher probability of propagule dispersal and settling from the slow flow in side channels (van Oorschot *et al.*, 2016). As a consequence, a larger window of opportunity is ensured for hydrochorous tree settling from seedlings. Although a valid hypothesis, the closer spacing of patches close to the forest is more likely explained by anemochorous propagule dispersion.

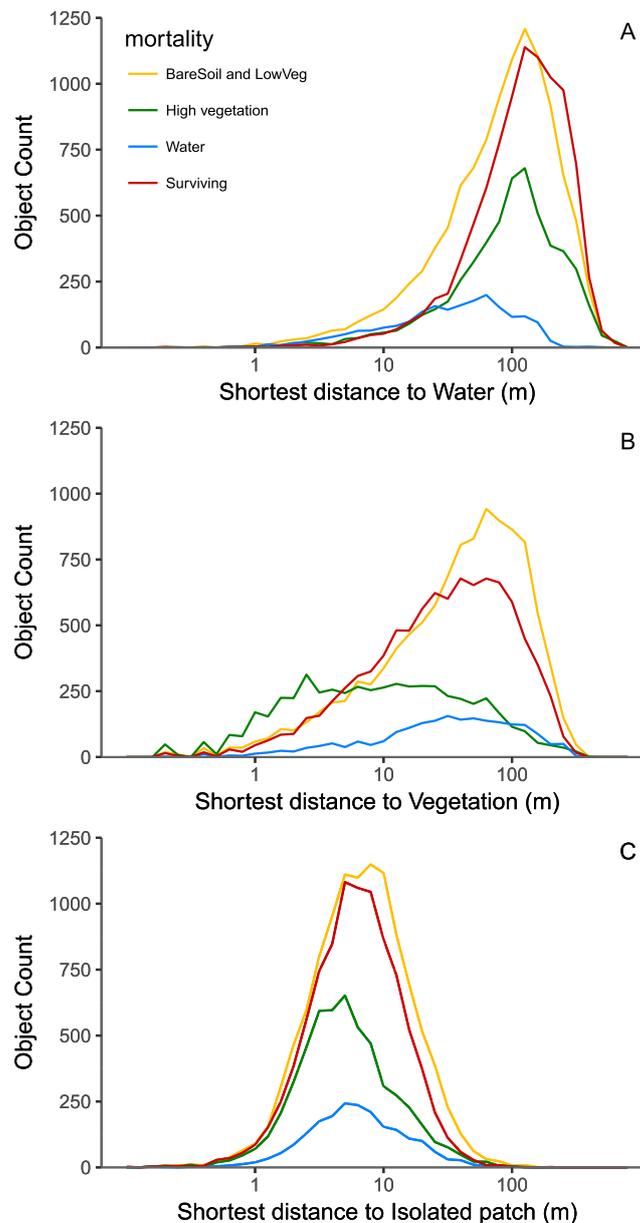
The most surprising observation is that the vegetation is able to settle in patches and survive the stresses for decades but at the same time fails to expand these patches. This apparent stasis contradicts the usual observation that patches of pioneer vegetation either die or quickly grow into larger vegetation patches. The fact that the pioneer species settle on the active bars despite large environmental stresses is not surprising. Also, it would not be surprising if the patches facilitated vegetation settlement in their lee sides and through clonal growth and propagule dispersion, but this, surprisingly, only occurs close to the riparian forest. Apparently the pioneer species fail to eco-engineer their environment. This stasis is in contrast to characteristic behaviour of saltmarsh vegetation, where vegetation settling in patches leads to salt marsh expansion, while tussocks of grasses shrink and disappear in the case of eroding salt marshes (Temmerman *et al.*, 2007; van Belzen *et al.*,

2017). In the Allier River, the patches form and persist, so apparently there is an equilibrium between patch growth and disappearance. To unravel what causes the lack of expansion and disappearance of the vegetation patches we discuss four processes that may affect survival.

A first process causing vegetation patch disappearance is desiccation during low flow (Gurnell *et al.*, 2012). The bare soil consists of coarse sand and gravel, which drains well, meaning that the groundwater table is close to the water surface elevation in the channel (Shope *et al.*, 2012). If desiccation were a main cause of patch disappearance, most of the surviving patches would be expected relatively close to the low-water channel because of the lower bed elevation and proximity to local groundwater. Nevertheless, patch survival is higher for larger distances from the channel. The soil is finer grained on the upper floodplain (Kleinhans *et al.*, 2018), so

that moisture from floods and rain is perhaps long lasting (Bätz *et al.*, 2015; Corenblit *et al.*, 2016). Furthermore, the sides of the valley supply groundwater independently of the river floods.

A second process causing patch disappearance is that the plants die because of inundation stress on the bare soil surrounding the patches that is clearly active as channel bed during floods (Gurnell *et al.*, 2012). Black poplar seedlings begin to die after about 60 days of inundation (Geerling *et al.*, 2006; van Oorschot *et al.*, 2016), a condition that is hardly reached at water levels 2.5 m above the considered datum (Figure 6). The halved patch survival rates observed since the 1980s are associated with higher discharge and water-level flood peaks (Figures 6A and 6B), while low flow and mean flow remain almost the same. At the same time, a higher cover fraction of bare soil is observed in this period in conjunction



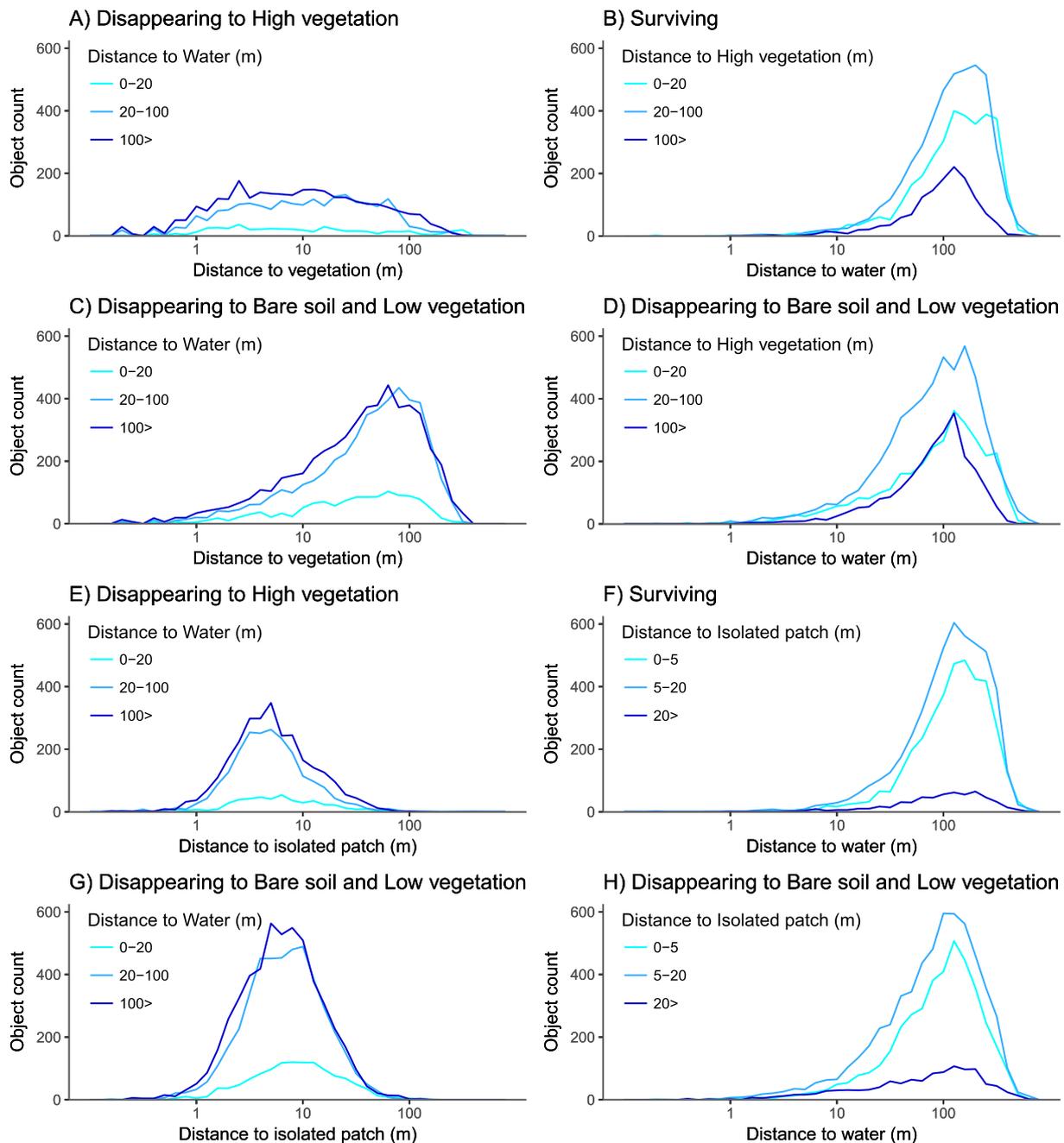
**Figure 9.** Number of isolated vegetation patches surviving, merging with vegetation cover, disappearing through channel migration or disappearing for other reasons on bare soil and low vegetation cover as a function of distance to other entities, averaged for all years. (A) Effects of distance to the low waterline, showing a low number of patches disappearing due to channel migration and high survival far away from the water. (B) Effects of distance to high-vegetated covers to which patches could amalgamate, showing a considerable fraction of patches merging with high vegetation but a surprisingly large number of patches surviving far away from the high vegetation. (C) Effect of minimum distance between patch and the closest adjacent vegetation object, showing no different facilitation effects on any cover type other than patches being closer together when they merge with the high vegetation cover. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

with low and high vegetation cover, and a higher area fraction of water transforming to land as a consequence of channel migration and shifting. These findings suggest that vegetation patches in the Allier mainly disappear during floods, especially closer to the river channel and further away from high vegetation cover. This evidence is complicated by a large number of chute cutoffs observed in 1980 (Kleinhans and van den Berg, 2011; van Dijk *et al.*, 2014), resulting in a straighter river, a large area fraction of residual channels as well as more dry floodplain during and below mean flow conditions.

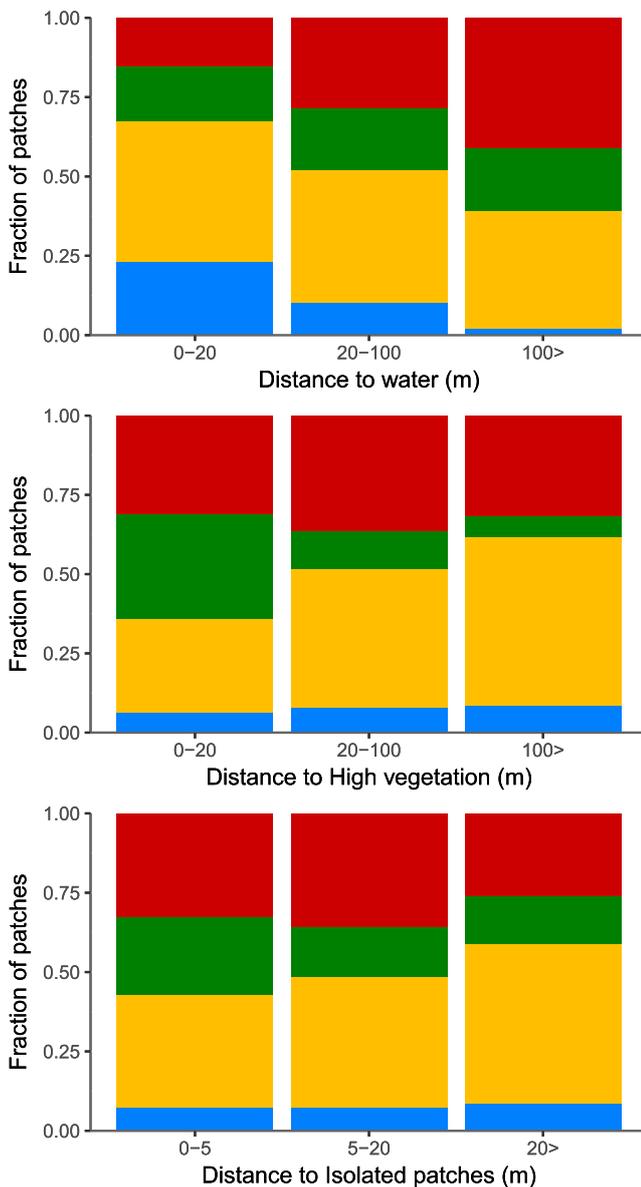
A third process is plant uprooting that likely occurs in combination with bed lowering. Uprooting of seedlings begins at  $0.55 \text{ m s}^{-1}$  (van Oorschot *et al.*, 2016), a condition that recurs with almost yearly frequency. However, many vegetation patches are much older than 1 year and more mature plants only die of inundation stress after about 240 days and are uprooted at a flow velocity threshold of  $7 \text{ m s}^{-1}$ , which

does not occur at all in the observation period (van Oorschot *et al.*, 2016). This means that bed erosion is required to uproot older vegetation. Given the lateral dynamics of the Allier River and the ubiquity of chute cutoffs, bed elevations are more likely to change in the center of the valley, which is not directly related to bend migration and therefore not clearly observable on aerial imagery. Clearly there is scope for further analysis in combination with bed elevation models (Vautier *et al.*, 2016).

The above processes refer to the disappearance of patches. A fourth process is related to the spatial arrangement of patches that may enhance their survival. Perhaps patches facilitate other patches in settling and survival, which is suggested by the positive correlation of survival and proximity to other patches or forest cover (Gurnell *et al.*, 2012; Corenblit *et al.*, 2016) (Figure 11). A possible mechanism for survival is that the combined flow resistance of multiple patches forces the main flow into the channel and elsewhere



**Figure 10.** Distributions of numbers of disappearing or surviving isolated vegetation patches as a function of distance from water or vegetation, subdivided in other distance classes. Also see Figure 9. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**Figure 11.** Summary of isolated vegetation patch survival and disappearance as a function of distance classes. See Figure 9 for legend. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

on the floodplain. Modelling indicates that multiple flow paths in a complex pattern of vegetation patches exist during floods (van Oorschot *et al.*, 2016; Kleinhans *et al.*, 2018). This implies that measuring the inter-patch distance as a function of proximity to the low-water channel or the forest is too simplistic since also the groups of patches concur to modify the flow pattern.

Two additional processes that may partly explain vegetation patch survival without expansion must be mentioned, even though we have no substantial evidence but only limited observations. The first is removal of vegetation by man and by cattle. During field site visits we observed cows, and also Garófano-Gómez *et al.* (2017) observed pastured grassland. This means we cannot exclude grazing as a cause for the lack of lateral expansion of isolated vegetation patches and the mortality on the bare soil and low vegetation covers. Furthermore, several authors observed considerable dead wood present in the form of logs and log jams, also in association with patches of pioneering tree seedlings (Gurnell and Petts, 2002). Possibly the dead wood protects the vegetation patches that would otherwise have been removed during floods.

In summary, a combination of processes causes the lack of patch expansion. In the most active part of the river valley, vegetation is uprooted following bed erosion during floods in combination with desiccation on the upper portions of bars. Away from the active channel the influence of fluvial dynamics decreases and the proximity of (high) vegetation patches offers some protection, such that patches may merge into larger patches. However, this explains only part of the observed patch behaviour, as some patches close to the active channel survive whereas some patches close to (high) vegetation disappear. On the other hand, expansion of the large vegetation cover and the formation of striping patterns, obvious to the unaided eye but not yet detectable automatically, require future research into processes of propagule production and transport by the flow.

### Comparison of mapped landscape patterns by different methods at different scales

The few studies that report data on our study area had different mapping methods, raising the question to what degree a comparison is possible. A landscape mosaic of patches in the Allier valley was observable on aerial photographs and digitized manually by Garófano-Gómez *et al.* (2017) on a recent image and then modified back in time on subsequent earlier images. In their analysis, Garófano-Gómez *et al.* (2017) distinguished six succession phases, excluding agriculture: bare soil on 5% of the area, 4% pioneers, 29% grasslands that partly result from their function as pasture, 14% riparian forest of mostly black poplar, 3% riparian forest of white willow flanking residual channels, 11% shrubs that are also affected by grazing, and 6% hardwood forest. In our analysis we find much larger bare soil cover than Garófano-Gómez *et al.* (2017), even more low vegetation cover that is at least partly grassland, and a similar fraction of high vegetation that corresponds to their riparian forest (Figure 5a). In a similar analysis, Geerling *et al.* (2006) observed a decrease in bare soil and grassland vegetation between 1954 and 2000, whereas we find an increase in bare soil and a decrease in low vegetation.

Clearly, the largest differences between our and earlier classifications are found in the bare soil class. The method of Garófano-Gómez *et al.* (2017) was checked by ground truth but is to an unknown degree inherently subjective in interpretation and conservative in observing changes. Furthermore, while the minimum patch size in Garófano-Gómez *et al.* (2017) was 52 m<sup>2</sup>, most of their patches were much larger and our isolated vegetation patches smaller than 150 m<sup>2</sup> generally lack in their final map for generalization purposes. Likewise, the minimum mapping unit in Geerling *et al.* (2006) was 1600 m<sup>2</sup> and 20% coverage by canopy was the minimum for classification as open shrub or open forest, which in our method would partly be classified as bare soil or low vegetation with isolated vegetation patches. The differences are therefore entirely due to the differences in methods, where ours is automated and objective and focused on much smaller vegetation patches than the previously published maps.

The surprising results of our analyses were the ubiquitous occurrence and persistence in time but general lack of expansion of vegetated patches in the highly dynamic meander belt. These observations were not possible with large-scale mapping reported in the literature. Map generalization in manual digitization at a certain scale means that small pioneer patches that we identified as isolated vegetation patches are either ignored, or, above a certain number per hectare, classified as pioneers or shrub. The same is likely the case for pioneer herb and grass patches. Our bare soil cover is much larger because

of the small pixels we used in the object-based classification in covers. We could not uncover at what patch density per unit area the succession phase classification changed to shrubs in Garófano-Gómez *et al.* (2017) and likewise were unable to compare the ecotope transitions in Geerling *et al.* (2006) to our cover transitions. While Geerling *et al.* (2006) find a decrease in bare soil and we find an increase, we also find a decrease in the number of vegetation patches. We suggest that this difference could be due to the larger-scale classification of spatially more uniformly but less dense distribution of patches on the newly formed bare soil in 1980 following an exceptional number of chute cutoffs.

This means that the two mappings – Geerling *et al.* (2006), Garófano-Gómez *et al.* (2017) – and ours are complementary in scale rather than contradictory, where their larger-scale mapping is informative about the landscape mosaic scale and our vegetation patch analysis is informative about pioneer dynamics. The difficulty in comparing these different scales and somewhat subjective classes also means that the absolute numbers and fractions of cover need to be interpreted with great care, while the numbers and sizes of patches recognized in our analysis are objective and should be much better than order-of-magnitude accuracy, which also makes our spatiotemporal patterns and dynamics reliable.

### Meander bend-scale landscape dynamics

A comparison of dynamics with previous studies is more informative for our understanding than absolute numbers. Geerling *et al.* (2006) estimated that 59% of the surface covered by pioneer vegetation transitioned to another ecotope. In general, this high turnover agrees with our results. Garófano-Gómez *et al.* (2017) confirm this in general, but suggest that the landscape has an equally high turnover between 1967 and 2005, and indicate that this number reduces after the year 2005 and attribute this to a change in flow regime, in particular the floods with recurrence intervals above 2 years. Qualitatively, this link with floods agrees with our results and the available literature, since rejuvenation requires active river meandering and floodplain formation, both of which take place mostly during floods. Quantitatively, these results differ as we observe a lower turnover before the 1980s and a higher turnover until the end of our observation period. While Geerling *et al.* (2006) and Garófano-Gómez *et al.* (2017) focused on transitions between years of entire patches in the landscape mosaic, we stress that such patches do not have one single age since they are composed of isolated pioneer vegetation patches that have a range of ages.

Our covers and patches show exponential trends in time. Most of the pioneers disappear in a decade, meaning that they failed to pioneer the bare soil and turn it into forest. Notably, a minority of the patches persist throughout the observation period, while not expanding. Thus a balance emerges between yearly settling of a great number of vegetation patches and mortality spreading out over decades, which leads to a total number of isolated vegetation patches varying at most by a factor of two. Only a quarter of the vegetation patches amalgamate or merge into the larger vegetation cover to contribute to the large-scale cover succession, while more than a third disappear in the retrogression to bare soil and low vegetation. Perhaps a similar exponential decay can be seen in the vegetation age distributions of Surian *et al.* (2015), but here the dominant process of vegetation removal is bank erosion, due to lateral channel dynamics rather than vertical dynamics and desiccation processes inferred from our data.

Counterintuitively, this fits the idea of pioneers that are eco-engineering species: these patches persist, but most fail to engineer their environment precisely because of the risks associated with pioneering (Jones *et al.*, 1994). A pioneer plant could engineer its environment through hydraulic resistance, which causes the flow to be focused elsewhere, mainly in the channel. The resulting local flow stress reduction implies a favourable environment for the establishment of new individuals of the same and other species (van Oorschot *et al.*, 2016) and leads to local sedimentation that may further reduce inundation stress (Kleinhans *et al.*, 2018). However, in order to have these effects, the plant should not be flushed out, which requires rooting (Kleinhans *et al.*, 2018). Only vegetation patches closer together, or relatively close to denser riparian forest, eventually survive the disturbance by floods. If our inference that high floods are the main mortality cause is correct, then the specific eco-engineering effect likely is the enhanced hydraulic resistance by denser vegetation as also found in van Oorschot *et al.* (2016). Hydraulic resistance alone is, however, not sufficient: patches close to the low-water channel are highly susceptible to hydrodynamics and, perhaps even more importantly, morphodynamics. Further away from the channel and higher up on the floodplain, a set of patches with the same hydraulic resistance has a much higher chance of survival since the flow strength is much reduced and possibly the flood frequency is also lower, implying a reduction in mortality by inundation stress. Likewise, seedling survival increases because of soil formation (Bätz *et al.*, 2015). In rivers other than the Allier, with higher mud concentrations, significant layers of mud may deposit to form a floodplain soil that also reduces the desiccation stress, while interaction between mud and vegetation may lead to levees (Kleinhans *et al.*, 2018). Although desiccation may well explain part of the dynamics (Bätz *et al.*, 2016), all our observations together show a decreasing influence of the river away from the lowest and morphologically most active part of the valley.

The gradual reduction of mortality and increase in survival and merging to large-scale vegetation cover are at odds with the alternative stable states observed in other aquatic biogeomorphological systems, for example saltmarsh systems along an estuary (van Belzen *et al.*, 2017). In such systems, positive feedbacks lead to either a densely vegetated landscape or a bare landscape. A significant number of pioneering plants and tussocks is required in order to transition the bare tidal flats to saltmarsh, while a saltmarsh, once collapsing under wave attack, continues to collapse and shift considerably landward. These shifts may even take place periodically. Neither of these situations applies to the river system, however. Although channel migration suddenly transitions riparian forest into water and bare soil, much more of the vegetation patches disappear due to desiccation and local bed erosion. No situations were observed where sufficient pioneers settled and survived to transition the bare soil close to the river to riparian forest. Rather, a gradual increase in succession chance is observed away from the river channel onto the higher floodplain.

### Conclusions

Ubiquitous patches of pioneer tree species in an actively meandering river were successfully identified at the metre scale and tracked through time over a period of nearly six decades. Object-based image analysis was applied to a series of 11 aerial photomosaics of a reach with several meanders. Most isolated vegetation patches persisted surprisingly long but did not expand in size. This means that the patches of vegetation survived many stresses, with 90% disappearing after

one to two decades due to amalgamation with the riparian forest or disappearance, but were unable to eco-engineer their environment. The probability of persistence of the patches is higher away from the main channel and closer to the denser vegetation flanking the river, with which patches often merged. Likely causes of disappearance are desiccation during low flow and undercutting and uprooting by erosion during floods.

The scale of this study allowed the recognition of small individual patches, which allowed tracking over time. This will be a valuable addition to modelling studies once spatial resolution has increased sufficiently. The dynamics observed in our data demonstrate a surprising persistence and ageing of pioneer patches that has not yet been observed in modelling studies. This shows the potential for the combination of imagery and biogeomorphological models in understanding and prediction of processes shaping riparian floodplains.

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## References

- Aberle J, Järvelä J. 2013. Flow resistance of emergent rigid and flexible floodplain vegetation. *Journal of Hydraulic Research* **51**(1): 33–45.
- Addink E, van Coillie F, de Jong S. 2012. Introduction to the GEO-BIA 2010 special issue: From pixels to geographic objects in remote sensing image analysis. *International Journal of Applied Earth Observation and Geoinformation* **15**: 1–6.
- Bätz N, Colombini P, Cherubini P, Lane SN. 2016. Groundwater controls on biogeomorphic succession and river channel morphodynamics. *Journal of Geophysical Research: Earth Surface* **121**(10): 1763–1785. <https://doi.org/10.1002/2016JF004009>.
- Bätz N, Verrecchia E, Lane S. 2015. The role of soil in vegetated gravelly river braid plains: more than just a passive response? *Earth Surface Processes and Landforms* **40**: 143–156.
- Bertoldi W, Gurnell A, Drake N. 2011. The topographic signature of vegetation development along a braided river: Results of a combined analysis of airborne lidar, color air photographs, and ground measurements. *Water Resources Research* **47**: W06525.
- Blaschke T, Hay GJ, Kelly M, Lang S, Hofmann P, Addink E, Feitosa R Q, van der Meer F, van der Werff H, van Coillie F, Tiede D. 2014. Geographic object-based image analysis: Towards a new paradigm. *ISPRS Journal of Photogrammetry and Remote Sensing* **87**(Suppl. C): 180–191.
- Camporeale C, Perucca E, Ridolfi L, Gurnell A. 2013. Modelling the interactions between river morphodynamics and riparian vegetation. *Reviews of Geophysics* **51**(3): 379–414.
- Corenblit D, Davies N, Steiger J, Gibling M, Bornette G. 2015. Considering river structure and stability in the light of evolution: feedbacks between riparian vegetation and hydrogeomorphology. *Earth Surface Processes and Landforms* **40**: 189–207.
- Corenblit D, Steiger J, Charrier G, Darrozes J, Garófano-Gómez V, Garreau A, González E, Gurnell A, Hortobágyi B, Julien F, Lambs L, Larrue S, Otto T, Roussel E, Vautier F, Voltaire O. 2016. *Populus nigra* L. establishment and fluvial landform construction: biogeomorphic dynamics within a channelized river. *Earth Surface Processes and Landforms* **41**: 1276–1292.
- Garófano-Gómez V, Metz M, Egger G, Díaz-Redondo M, Hortobágyi B, Geerling G, Corenblit D, Steiger J. 2017. Vegetation succession processes and fluvial dynamics of a mobile temperate riparian ecosystem: The lower Allier River (France). *Géomorphologie* **39**(3): 247–250.
- Geerling G, Ragas A, Leuven R, van den Berg J, Breedveld M, Liefhebber D, Smits A. 2006. Succession and rejuvenation in floodplains along the river Allier (France). *Hydrobiologia* **565**: 71–86.
- Gurnell A, Bertoldi W, Corenblit D. 2012. Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. *Earth-Science Reviews* **111**: 129–141.
- Gurnell A, Petts G. 2002. Island-dominated landscapes of large floodplain rivers, a European perspective. *Freshwater Biology* **47**(4): 581–600.
- Jones C, Lawton J, Shachak M. 1994. Organisms as ecosystem engineers. *Oikos* **69**: 373–386.
- Kleinhans M, de Vries B, Braat L, van Oorschot M. 2018. Living landscapes: muddy and vegetated floodplain effects on fluvial pattern in an incised river. *Earth Surface Processes and Landforms* **43**: 2948–2963.
- Kleinhans MG, van den Berg JH. 2011. River channel and bar patterns explained and predicted by an empirical and a physics-based method. *Earth Surface Processes and Landforms* **36**: 721–738.
- Kui L, Stella J, Lightbody A, Wilcox A. 2014. Ecogeomorphic feedbacks and flood loss of riparian tree seedlings in meandering channel experiments. *Water Resources Research* **50**(12): 9366–9384. <https://doi.org/10.1002/2014WR015719>.
- Pasquale N, Perona P, Francis R, Burlando P. 2014. Above-ground and below-ground salix dynamics in response to river processes. *Hydrological Processes* **28**(20): 5189–5203. <https://doi.org/10.1002/hyp.9993>.
- Schnauder I, Moggridge H. 2009. Vegetation and hydraulic–morphological interactions at the individual plant, patch and channel scale. *Aquatic Sciences* **71**: 318–330.
- Shope C, Constantz J, Cooper C, Reeves D, Pohl G, McKay W. 2012. Influence of a large fluvial island, streambed, and stream bank on surface water–groundwater fluxes and water table dynamics. *Water Resources Research* **48**: W06512.
- Solari L, van Oorschot M, Belletti B, Hendriks D, Rinaldi M, Vargas-Luna A. 2016. Advances on modelling riparian vegetation–hydromorphology interactions. *River Research and Applications* **32**: 164–178.
- Surian N, Barban M, Ziliani L, Monegato G, Bertoldi W, Comiti F. 2015. Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitude. *Earth Surface Processes and Landforms* **40**: 542–558.
- Temmerman S, Bouma T, van de Koppel J, van der Wal D, de Vries M, Herman P. 2007. Vegetation causes channel erosion in a tidal landscape. *Geology* **35**: 631–634.
- Tooth S, McCarthy S. 2004. Controls on the transition from meandering to straight channels in the wetlands of the Okavango delta, Botswana. *Earth Surface Processes and Landforms* **29**: 1627–1649.
- van Belzen J, van de Koppel J, Kirwan M, van der Wal D, Herman P, Dakosand V, Kefi S, Scheffer M, Guntenspergen G, Bouma T. 2017. Vegetation recovery in tidal marshes reveals critical slowing down under increased inundation. *Nature Communications* **8**(15811).
- van Dijk W, Schuurman F, Van de Lageweg W, Kleinhans M. 2014. Bifurcation instability and chute cutoff development in meandering gravel-bed rivers. *Geomorphology* **213**: 277–291.
- van Oorschot M, Kleinhans M, Geerling G, Middelkoop H. 2016. Distinct patterns of interaction between vegetation and morphodynamics. *Earth Surface Processes and Landforms* **41**: 791–808.
- Vautier F, Corenblit D, Hortobágyi B, Faournoux L, Steiger J. 2016. Monitoring and reconstructing past biogeomorphic succession within fluvial corridors using stereophotogrammetry. *Earth Surface Processes and Landforms* **41**: 1448–1463.

## Supporting Information

Supporting information may be found in the online version of this article.