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Grow With the Flow? Impact of Experimental Floods on Riparian Vegetation in an Alpine River

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ABSTRACT

Experimental floods have been proposed as a measure to mitigate effects of river flow regulation, primarily vegetation encroachment, streambed colmation, and loss of bed and channel mobility. In this study, we investigated the short- and long-term biogeomorphic effects of an experimental flood programme conducted in the Spöl River (Swiss Alps) since 2000. Based on a GIS analysis of orthoimages between 1991 and 2023, we characterize the past and current state of fluvial biogeomorphic succession. From field surveys, we describe the current distribution of riparian vegetation in the lower Spöl. Lastly, we investigate the impact of experimental floods on riparian trees through dendrogeomorphological indicators. Over the study period, we identified a significant increase in active channel width and an associated reduction of vegetation encroachment. However, no significant colonization of gravel bars by pioneer species was observed. Tree-ring widths showed a general decrease in riparian tree growth since the beginning of the experimental flood programme. We show that this apparent control of hydrogeomorphic processes on biogeomorphology and the corresponding absence of vegetation succession patterns is due to high aggradation rates of sediment delivered by an unregulated tributary. We discuss the implications of these findings for future management of the river and experimental flood programme and raise caveats regarding the future developments of river morphology in the lower Spöl.

1 | Introduction

1.1 | Interactions Between Fluvial Processes and Riparian Vegetation

Landscape dynamics in riparian environments are driven by the physical disturbance regime resulting from variations in discharge, sediment transport, and sediment erosion and deposition (Ward et al. 2002; Naiman and Décamps 1997; Baker 1977). The frequent reworking of the riverscape through floods of varying intensities creates a *shifting habitat mosaic* (e.g., Gurnell and Petts 2002), as a response to 1. mechanical stress caused by flooding, burial, and scouring, and 2. physiological stress caused by long periods of inundation or drought (Corenblit et al. 2024a, 2024b; González Del Tánago et al. 2021; Poff and Zimmerman 2010; Corenblit et al. 2009; Steiger et al. 2005; Tabacchi et al. 2000).

Riparian plants have developed different strategies to colonize and grow vigorously in such disturbed environments (Corenblit et al. 2024a, 2024b; Tabacchi et al. 2019). In turn, some may contribute to riverscape morphogenesis by trapping sediment, stabilizing landforms, and diverting flow (Krzeminska et al. 2019; Polvi and Sarneel 2018; Gurnell et al. 2012; Simon and Collison 2002). Corenblit et al. (2007) generalize these *biogeomorphic feedbacks* between vegetation and hydrogeomorphology in their four-phase *fluvial biogeomorphic succession* model (hereafter *FBS*), which consists of:

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1. a *geomorphic* phase, where hydrogeomorphic processes alone drive riverscape morphogenesis, and disturbances are too intense for new vegetation to develop;
2. a *pioneer* phase, still controlled quasi-unilaterally by hydrogeomorphic processes, where plant propagules are recruited and the first young plants appear;
3. a *biogeomorphic* phase, where pioneer communities have become sufficiently robust to influence both sediment transport and flow dynamics, that is take on an engineering function in biogeomorphic feedbacks;
4. an *ecological* phase, where vegetation becomes increasingly disconnected from hydrogeomorphic disturbance, and autogenic successional processes become dominant in shaping the community structure.

1.2 | Flow Regime Alterations and Experimental Floods

Motivated by flood risk mitigation, land gain, and hydropower production, humankind has often heavily engineered rivers worldwide (Wohl et al. 2015; Décamps et al. 1988). Zeh Weissman et al. (2009) found 46% of streams in Switzerland in a non-natural ecomorphological state. A major pressure on aquatic and riparian environments is hydropower production (57.6% of Swiss electricity production; SFOE 2024), due to the disruptions of ecological connectivity it causes (Lane et al. 2022).

In particular, regulated discharges downstream of dams or water intakes are limited to a low, constant *residual flow*, limiting hydrogeomorphic activity. As a result of this, vegetation often encroaches towards the channel (e.g., Tonolla et al. 2021; Gabbud et al. 2019; Jourdain 2017; Molnar et al. 2008). This in turn disrupts biogeomorphic feedbacks, and therefore ultimately leads to the reduction or disappearance of the riparian ecotone (Bejarano et al. 2020).

In response to this degradation, various adaptations of regulated flow regimes have been implemented worldwide (Yarnell and Thoms 2022; Loire et al. 2021). One of these, the release of controlled floods to reduce colmation and promote morphogenic dynamics (hereinafter *experimental floods*) is the focus of the present study. Assessing to which extent and how experimental floods may participate in restoring habitat dynamics is necessary for informed river management practices integrating biogeomorphology (O'Briain et al. 2024; Tonolla et al. 2021). Biogeomorphological case studies thus far have predominantly focused on larger lowland rivers (e.g., Corenblit et al. 2020; Jourdain 2017), or on unregulated and relatively natural montane rivers (e.g., Corenblit et al. 2010), and the long-term biogeomorphic response of regulated mountain rivers to experimental floods remains to be investigated.

The effect of flooding on vegetation is often quantified through dendrogeomorphological methods such as abrupt changes in tree ring width or eccentric growth (e.g., Tichavský et al. 2020; Quesada-Román et al. 2020; Ballesteros-Cánovas et al. 2015). These indicators are generally used as proxies to reconstruct the date and magnitude of palaeofloods. Conversely, they may offer insights into the short- and long-term effects of experimental floods on riparian trees. To the best of our knowledge, however, we have found no application of dendrogeomorphological methods to this effect. Jourdain (2017) focuses on the effects of experimental floods on riparian vegetation and documents vegetation mortality associated with geomorphic changes in the Isère catchment, but makes use of vegetation maps to address this without considering effects on individual trees.

1.3 | Goals of the Present Study

In order to characterize the long-term effects of the experimental flood program on biogeomorphology in the lower Spöl (Section 2.1), this study addresses the following questions:

1. What is the current biogeomorphic state of the lower Spöl, and how has it changed over time? Can a restoration of quasi-natural FBS dynamics be observed (reduction of vegetation encroachment, development of pioneer communities on landforms reworked by the experimental floods)?
2. What is the current distribution, vitality, and species composition of riparian vegetation in the riparian corridor of the lower Spöl? Has the prevalence of non-riparian species decreased near the channel? If FBS phases can be distinguished, do they display distinct species compositions?
3. How are riparian trees affected by flooding in the experimental flood program? Are there differences in sensitivity between species?

2 | Materials and Methods

2.1 | Study Area

This study focuses on a 1.5 km long reach of the Spöl, a fifth-order stream (Consoli et al. 2023) near Zernez in Eastern Switzerland. The main area of interest is located downstream of the confluence with the Ova da Cluozza (1507 m a.s.l.; Figure 1). The Spöl catchment is 434 km^2 (FOEN 2015) and mostly lies within the Stelvio National Park in Italy and the Swiss National Park (hereinafter *SNP*). The river originates at Forcola di Livigno (approx. 2600 m a.s.l.), and flows over 38 km to its confluence with the En/Inn River in Zernez (1470 m a.s.l.).

Two dams were built along the course of the Spöl as part of a hydropower scheme which came into operation in 1970. The lower Spöl, where the study area is located, flows from the Ova Spin dam (crest at 1633 m a.s.l.; yellow polygon in Figure 1b) to the confluence with the En/Inn River. It has one major tributary, the Ova da Cluozza (27 km^2 catchment), which delivers large amounts of sediment to the Spöl (cf. Figure 1d).

Before regulation started in 1970, the Spöl had a glacio-nival regime with periodic floods from heavy precipitation reaching

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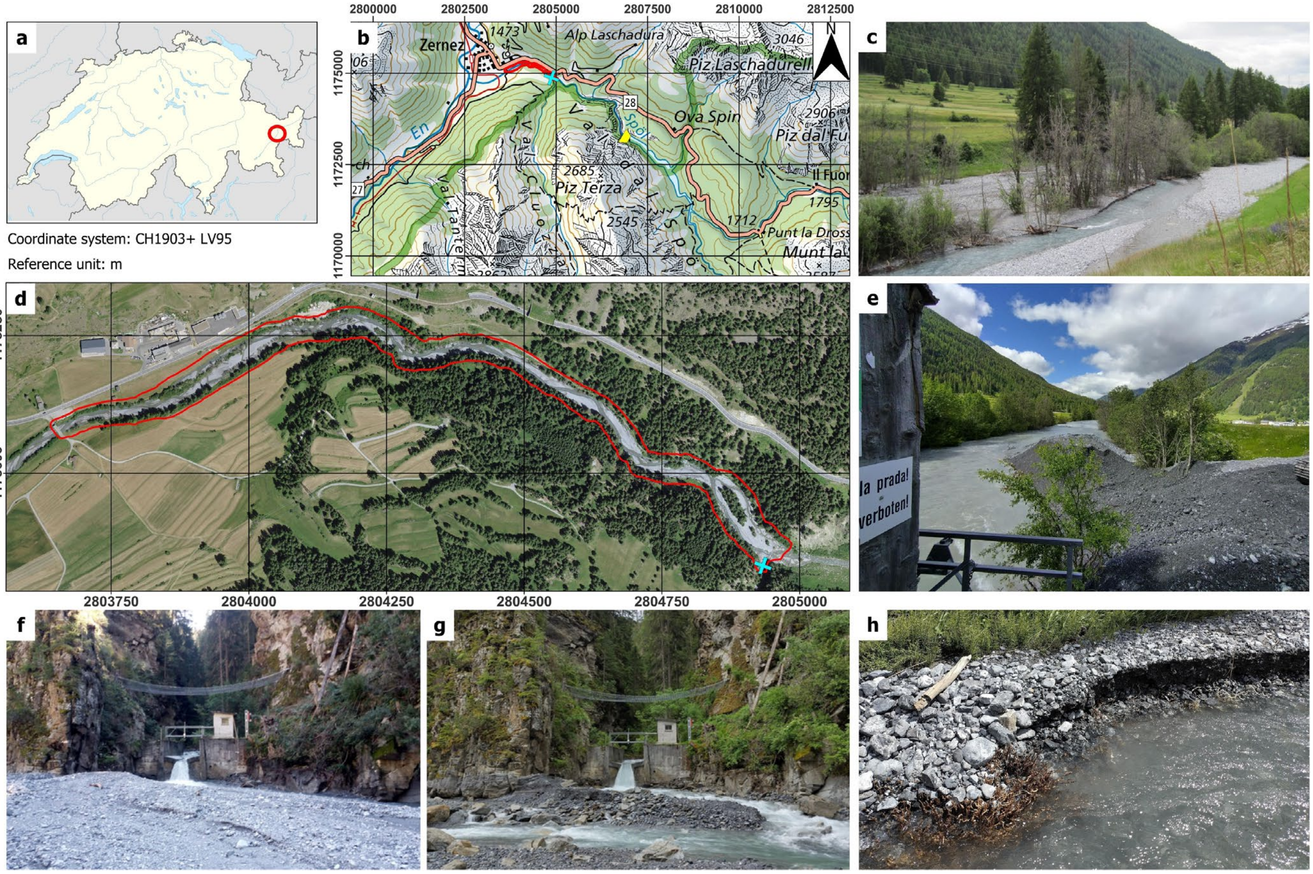

FIGURE 1 | (a) Location of the study area within Switzerland. (b) Extract of NM 1:100,000 (Swisstopo 2022a) showing the Spöl from the Ova Spin lake to the confluence with the En/Inn. (c) Riparian vegetation dieback in reaction to channel widening and migration (2023-06-27). (d) Orthoimage of the study reach in 2022 (Swisstopo 2022b). (e) Sediment removed in anticipation of the 2024 experimental flood, temporarily deposited atop riparian vegetation (2024-06-12). (f) Confluence with the Ova da Cluozza on 2023-09-25 and (g) on 2024-06-14. (h) Patch of *Equisetum sp.* pioneers buried under approx. 20 cm of sediment (2024-06-13). Red polygons in (b, d) delineate the study reach, blue crosses show confluence with the Ova da Cluozza. Yellow polygon in (b) shows Ova Spin dam. [Color figure can be viewed at wileyonlinelibrary.com]

from 20 to 60 $m^3 s^{-1}$, while the mean annual discharge was 8.6 $m^3 s^{-1}$ (Robinson et al. 2018). The residual discharges at both dams ($\leq 1.0\ m^3\ s^{-1}$; Scheurer and Molinari 2003) led to loss of channel mobility, vegetation encroachment (primarily from Pinaceae), and streambed colmation. Pioneer vegetation was described as "strongly reduced" (Mürle et al. 2003).

Attempts to restore hydrogeomorphic dynamics in the upper Spöl have been the subject of several other studies (e.g., Consoli et al. 2023; Robinson et al. 2023, 2018) and will not be discussed here. In the lower Spöl, they started with a single flushing flow released from Ova Spin in 1995. The riverscape was considerably affected, but the effects of the flood were soon lost after the return to the residual flow regime (Molinari et al. 1996). Governmental, hydropower, and SNP authorities agreed on a three-year (2000–2002) experimental flood programme, hereinafter termed *pilot project*, encompassing both the lower and upper Spöl (Mürle et al. 2003). An enterprise of this scale constituted pioneering work in regulated alpine streams (Scheurer 2014). Results were encouraging (Mürle et al. 2003; Ortlepp and Mürle 2003), and the yearly experimental flood regime was continued.

Works focusing on long-term developments in the lower Spöl are scarce (e.g., Mathers et al. 2021; Kevic et al. 2018), and none has studied riparian vegetation extensively since Mürle et al. (2003). Soto Parra et al. (2024), Consoli et al. (2022) and Pellegrini et al. (2022) showed that the high sediment loads delivered by the Ova da Cluozza were redistributed, but not removed, during experimental floods and caused observable morphological changes (cf. Figure 1f,g).

Since 2000, the experimental flood programme had led to the release of 21 experimental floods in the lower Spöl until the end of 2023 (Figure 2). They all were released during the vegetation period, with the earliest in the season being released on 2016-06-08 and the latest on 2018-09-04. The median total duration was 10 h 15 min, and the median peak discharge 28.6 $m^3 s^{-1}$. Hashemi et al. (2024) indicate that the peak discharges of the experimental floods correspond to an approx. 2 year return period flood, but that greater magnitudes are difficult to implement due to floodplain land-use. A considerably larger flushing flow with a peak discharge of 80 $m^3 s^{-1}$ was released for dam maintenance purposes on 2009-06-21 (Kevic et al. 2018). According to available official information, this discharge can be estimated to correspond to a return period of 100–300 years. This estimate is based on regulated discharges between 2000 and 2020, however. No official data is available to estimate the return period of this event prior to regulation, but it would presumably be < 100 years (see FOEN 2024).

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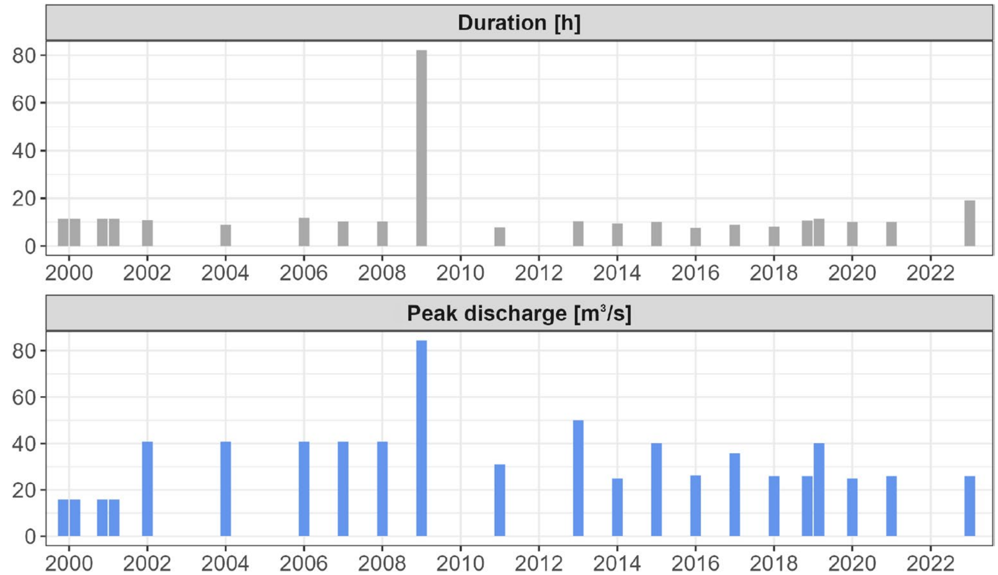

FIGURE 2 | Summary of experimental floods conducted in the lower Spöl since 2000 (updated from Kevic et al. 2018). The large 2009 flood is a flushing flow. [Color figure can be viewed at wileyonlinelibrary.com]

2.2 | Biogeomorphic Mapping

Since 2018, changes in the riverscape have been documented by the SNP in a set of drone orthomosaics, usually before and after each experimental flood (e.g., Hashemi et al. 2024; Consoli et al. 2022). These in turn were used to build land cover maps (Finch et al. under review), from which biogeomorphic maps were elaborated, with the addition of the 1991 SWISSIMAGE orthomosaic (Swisstopo 2022b) to document the biogeomorphic state of the river before the start of the experimental flood program.

Five FBS phases were defined: the four phases described in sec. 1.1, and *permanent inundation* for the location of channels and pools at the time of orthoimage capture. The distinction of FBS phases was primarily based on the degree of vegetation development, as proposed by Betz et al. (2023), Han et al. (2022) and Corenblit et al. (2010).

Where the coverage of vegetated gravel bars without clear pedogenesis consisted of trees, we assigned 1. the biogeomorphic phase if the trees were predominantly live or 2. the geomorphic stage if the trees were dead or dying. This distinction was motivated by the difference in stress levels exerted by flooding between these two phases (cf. Corenblit et al. 2011). An exception was made in cases where dead trees had trapped large wood jams (cf. Ruiz-Villanueva et al. 2022) and were therefore contributing to structural heterogeneities in the active channel. Such cases were assigned to the biogeomorphic phase even if tree mortality was high. Fallen trees were considered part of the geomorphic phase, even if they were still foliated or had trapped wood and sediment (Gurnell et al. 2012). Live trees standing in low-flow channels were considered part of the permanent inundation phase, independently of their fitness and of water depth. Parts of the floodplain inundated during the experimental floods but not displaying any major signs of erosion or sedimentation remained designated as the ecological phase.

The diachronic analysis of FBS dynamics was performed through the establishment of transition matrices in SAGA GIS (Conrad et al. 2015). These were aggregated into *trajectories of change* (cf. e.g., Garófano-Gómez et al. 2017), namely:

1. *Stable*: no change in FBS phase. This was divided into separate classes by FBS phase, whereby permanent inundation and geomorphic phases were aggregated into an *active channel* class;
2. *Progression*: transition to a more mature FBS phase;
3. *Retrogression*: change to a less mature stage after total or partial resetting through flooding or burial;
4. *Anthropisation*: transition to agricultural land or other anthropogenic structures.

Additionally, the FBS maps were used to compute the active channel width (defined as the sum of widths of the permanent inundation and geomorphic phases, i.e., without vegetation) along transects every 50 m. The significance of differences in active channel widths over time was assessed by a Kruskal-Wallis rank sum test, with a post hoc Dunn's test using a Bonferroni correction.

2.3 | Vegetation Survey

Trees within the active floodplain (or its immediate vicinity, in locations that could plausibly be reached by an experimental flood or flushing flow) were surveyed in August 2023, using the 2023-06-16 post-flood SNP orthoimage for field mapping. Trees atop confining margins such as bedrock scarps, or otherwise ostensibly disconnected from the floodplain, were not considered. Well-established shrubs with substantial ground coverage, e.g., *Myricaria germanica* (L.) Desv., were included in the tree survey.

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Riparian trees were mapped by grouping them into 156 stands (ranging from 3.5 m^2 for isolated trees to 759 m^2, median 75.1 m^2) exhibiting homogeneous characteristics regarding species composition, tree size and spatial distribution, and proportion of dead trees. Only species incidence and a visual estimation of the dominant species was recorded. Three categorical variables, namely stand mortality, stand density and average stem diameter at breast height (DBH; Table S1), were recorded based on visual estimations.

The herbaceous and shrub strata were only mapped in areas where no higher vegetation was present. They were not surveyed at the species level, but grouped into broad categories following Garófano-Gómez et al. (2017); cf. also Steiger et al. (2005). The assemblages used for vegetation mapping are defined in Table S2.

In order to assess the differences in tree species composition between FBS phases, we computed the Sørensen dissimilarity (Sørensen 1948) of tree stands and conducted an analysis of similarities (ANOSIM; Clarke 1993) on the resulting matrix.

2.4 | Dendrogeomorphology

In order to quantify the short- and long-term effects of experimental floods on riparian trees, and particularly growth disturbances (Díez-Herrero et al. 2013; Ruiz-Villanueva et al. 2010), we sampled 24 trees along the study reach (listed in Table S3, map in Figure S5). Only trees that had been visibly affected by flooding were chosen for sampling, that is, they had exposed roots, were buried under sediment, or were close to or inside low-flow channels. As many dead or dying trees as possible were sampled to reconstruct the date of last ring formation, but this was often rendered impossible by wood decay. Trees were considered dead if they had reached total crown transparency (Bigler and Rigling 2013).

Samples were extracted using a 5 mm increment corer during a field campaign in September 2023. For optimum capture of the latest tree rings, cores should theoretically be extracted at the root collar (Villalba and Veblen 1997), especially since the date of last ring formation can vary strongly with sampling height (Bigler and Rigling 2013). Sampling near the ground is impractical, however, if not impossible with a manual corer, and coring heights of approx. 1 m, intentionally below standard breast height, appeared to be a suitable compromise. In line with Šilhán (2015), Ruiz-Villanueva et al. (2010), and Stoffel and Bollschweiler (2008), cores were generally extracted in the direction of flow, if possible from both sides. A total of 40 cores was extracted (Table S3).

Ring widths were measured bark-to-pith with 1/100 mm resolution, using a LINTAB 6 positioning table (Rinntech 2020). Live trees were initially assumed to have formed their outermost ring in 2022, and dead trees were considered undated. During the measurement of the coniferous samples, all occurrences of traumatic resin ducts (TRDs) were marked, except for *Pinus* samples due to their tendency to form large amounts of resin ducts with no traumatic cause (Stoffel and Corona 2014). Series from dead trees were dated by cross-matching their skeleton plots with nearby trees from the same species, and the result was verified in COFECHA (Holmes 1983).

Pointer years were investigated using the bias-adjusted standardised growth change method (BSGC; Buras et al. 2022). The resulting list of pointer years was combined with the list of TRDs, and with eccentric growth observed from width differences between up- and downstream-facing cores ($\frac{upstream - downstream}{upstream + downstream}$; cf. Wistuba et al. 2013), into a dataset of growth disturbances (GD). Following Ruiz-Villanueva et al. (2010), weights (wGD) were applied to different GD types and intensities (Table 1). The proportion of trees affected by each event in relation to the sample depth at the time (%D) was calculated, and each event was assigned a weight of 2 if affected trees were spread along the reach, or 1 if they were only concentrated in a limited area (SD). For each disturbance event, the Growth Disturbance Index ($GDI = wGD \times \%D \times SD$) was calculated.

Monthly precipitation sums and monthly mean temperatures were retrieved from Buffalora (16 km E of Zernez, 1971 m a.s.l.; MeteoSwiss 2024), which is the closest station to the study area and covers the entire time span of the tree ring width series. They were summarized over the growing season, that is, May to September of each year (after Moser et al. 2010). In order to better identify trends despite elevation differences, values are presented as deviations from the 1991 to 2020 mean.

3 | Results

3.1 | Biogeomorphology of the Lower Spöl

In the 2023 post-flood orthoimage, the active channel (including low-flow channels and gravel bars) took up most of the study reach, as shown in Figure 3a. Vegetated areas in the ecological phase were the second most prominent class. Pioneer vegetation was scarce. Figure 3b shows the relative coverage of each phase across time.

Active channel widening between 1991 and 2023 can be divided into two main phases (Figure 3c). Between 1991 and 2018, channel widening up to a maximum of 18.8 m (median 8.0 m) occurred in the upstream two thirds of the study reach. The second phase of channel widening occurred during the 2019 experimental floods (cf. Figure 1c), and affected mostly the downstream third of the study reach, where a maximum channel

TABLE 1 | Weights (wGD) used for the quantification of growth disturbance (GD) intensities (modified from Ruiz-Villanueva et al. 2010).

GD	wGD
Injury/TRD	1
Intense growth decrease	0.75
Intense eccentric growth	0.25
Weak eccentric growth	0.1

Note: Intense GDs are defined as those that can be identified through visual inspection of the core, and *weak* GDs require magnification, but remain clearly recognisable.

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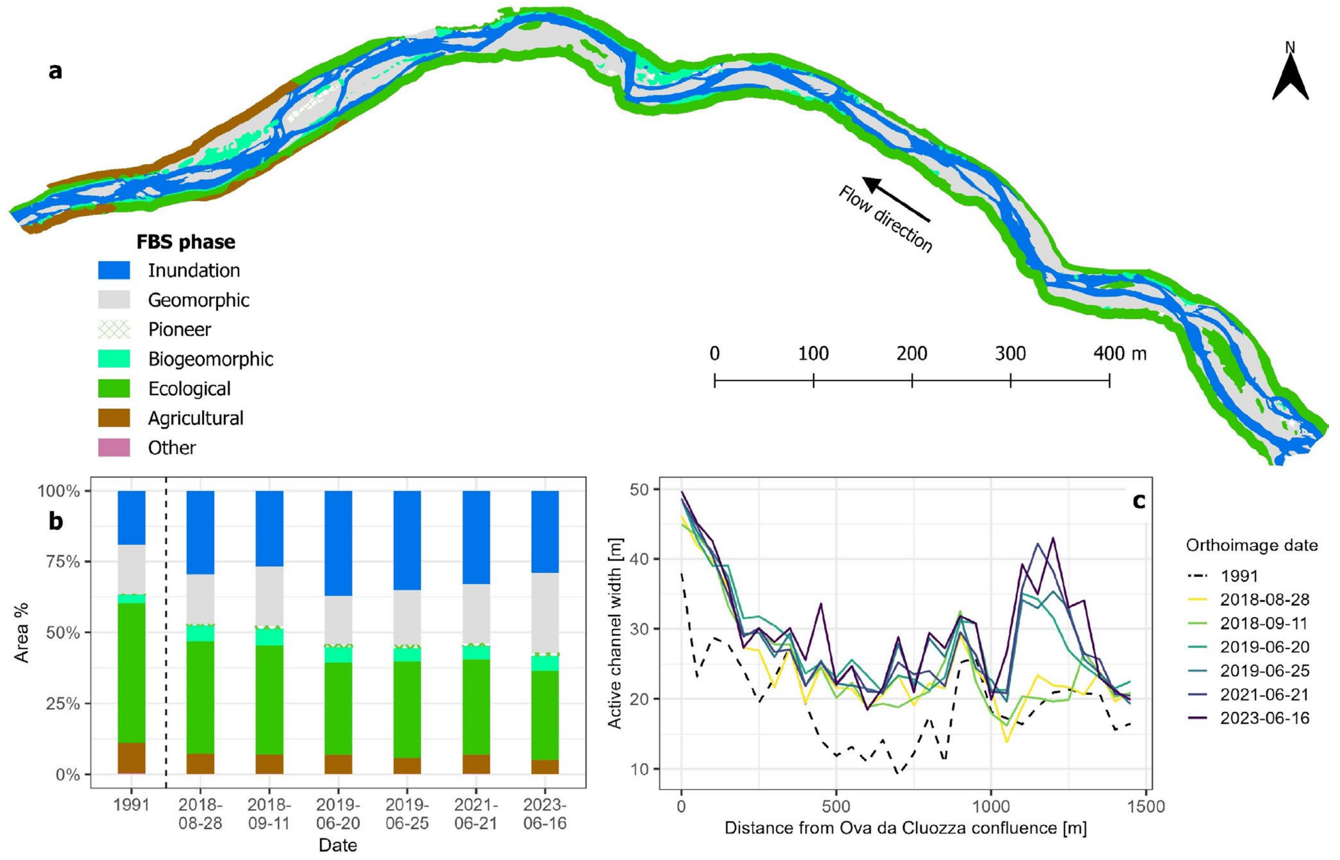

FIGURE 3 | (a) FBS phases in 2023, based on the 2023-06-16 SNP orthophoto. (b) Relative prevalence of each succession phase between 1991 and 2023 over the study reach. The dashed vertical line separates maps before and after the beginning of the experimental flood programme. (c) Width of the active channel along transects every 50 m between the confluence with the Ova da Cluozza and the wooden bridge. [Color figure can be viewed at wileyonlinelibrary.com]

widening of 21.1 m was observed (median 11.5 m). Total loss of agricultural land between 1991 and 2023 amounted to approx. 4000 m^2.

A Kruskal-Wallis rank sum test showed significant differences in median active channel width over time ($H(6, n = 210) = 44.1, p < .01$). A post hoc Dunn test showed that 1991 values were different from all channel widths from 2019 onwards ($z \in [4.56, 5.33], p < .01$), but did not differ significantly from 2018 values at $p < .05$.

Table 2 summarises the relative coverage of each trajectory of change and the respective overall proportions of progression, retrogression, and stability. Between 1991 and 2018, inundation constituted the largest portion of retrogression (9.14% of total area), and burial (defined as the transition from any vegetated area to the geomorphic phase) occurred over 3.57% of the study area. Gravel bar deposition in the active channel represented 6.80% of the area, and colonisation of pre-existing gravel bars (i.e., the transition from the geomorphic phase to any vegetated phase) covered 1.1%.

The active channel widening described above can be identified by the increased coverage of the active channel between 2018 and 2023 compared with 1991 to 2018, and the associated reduction in the ecological phase and agricultural land (cf. Table 2). Inundation occurred over 4.8% of the study area, and burial over 7.3%. Deposition in the active channel covered 11.89% of the area, and colonisation of pre-existing gravel bars represented 0.5%.

TABLE 2 | Percentual coverage of stable FBS phases and trajectories of change between 1991 and 2018 pre-flood, and between 2018 pre-flood and 2023 post-flood.

Trajectories of change/period	1991–2018	2018–2023
Stable/reworked active channel (%)	34.42	45.24
Stable pioneer (%)	0.03	0.03
Stable biogeomorphic (%)	1.30	2.10
Stable ecological (%)	34.07	30.19
Stable anthropic (%)	6.94	4.73
Progression (%)	2.59	2.27
Retrogression (%)	20.33	15.06
Anthropisation (%)	0.32	0.37
Progression: retrogression	0.13	0.15
(Progression + retrogression): stable	0.30	0.21

Note: Lower section shows the overall ratios of succession and stability.

In both periods, the reversal from the ecological to the biogeomorphic phase was a relatively substantial retrogressive process

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(3.28% of the study area in 1991–2018, 2.19% in 2018–2023). However, this was mainly not due to recolonization and will be further discussed in Section 4.2.

3.2 | Current State of Riparian Vegetation

We identified 20 species of trees or major shrubs within the 156 stands (Figure S1). The total canopy coverage of the inventoried stands was 17,557 m^2, as measured from the 2023-06-16 orthoimage. Hardwood species of the Betulaceae and Salicaceae were present across most of the study reach. Together, they were dominant in 104 stands. *Alnus incana* L. stands out as the most prevalent species overall, as it was dominant or codominant over 42.9% of the area covered by trees. Trees and large shrubs belonging to the *Salix* genus (presumably e.g., *S. appendiculata* Vill., *S. pentandra* L., *S. myrsinifolia* Salisb.) were the second-most prevalent group. Conifers also showed a strong presence in the study area, particularly *Picea abies* L. (dominant or codominant in 28.7% of the study area). *Larix decidua* Mill. was observed in 17 stands, but mostly as isolated individuals.

Between these three most prevalent tree assemblages (Conifer, Willow and Alder forest, cf. Table S2), a Kruskal-Wallis test found significant rank sum differences in mortality $H(2, n = 144) = 6.79, p = .03$. A post hoc Dunn's test showed significantly higher mortality in the Willow forest relative to the Conifer forest ($z = 2.47, p = .01$).

An ANOSIM conducted on species grouped by FBS phase (cf. Figure S3) returned significant results showing no difference between groups, with $R = 0.095, p < .01$. Excluding the permanent inundation and geomorphic phases (leaving a remainder of 96 stands), and grouping all deciduous species into a single class separate from conifers, showed a slight difference between groups ($R = 0.241, p < .01$).

3.3 | Dendrogeomorphology

3.3.1 | Tree-Ring Width Series

The cross-matched ring width series spanned from 1917 to 2022, with a maximum depth of 23 trees between 1990 and 2016. Two live trees produced their last ring before 2022 (2020 and 2021), and the earliest cessation of cambial activity in a snag was recorded in 2016 (cf. Figures S4 and S5b).

Figure 5 shows the mean annual ring width for each species. For better comparability, the values of each series were initially normalized to the species mean. The *Salix* spp. series included only two individuals, as most *Salix* trees were too small to be cored. It is presented nonetheless, as both individuals had been exposed to stem burial and subsequent bank erosion. The experimental flood *pilot project* period in Figure 5 includes 2003 under the assumption that the flooding of the previous season may have affected growth in 2003 as well.

A two-sample Student's *t*-test comparing annual mean tree ring widths across the entire dataset showed significantly lower values after 2003 compared with 1970–1999 ($t(48) = -14.08, p < .01$). When grouping the trees by species, all mean ring widths were significantly lower after the pilot project (2004–2022) compared with before (1970–1999) at $p \leq .02$, except one *Salix* sp. individual.

3.3.2 | Growth Disturbances

Across all individual trees, BSGC identified 22 negative pointer years, 10 of which after 2000. All of these were significant at $p \leq .02$. The three most prominent pointer years were 2019 (seven trees showed an abrupt growth decrease), 2009 (five trees), and 2005 (three trees). No individual tree showed significant positive pointer years at $p < .05$.

TRDs were observed in five conifers, with the largest number found in 2009. Overall, the greatest proportion of trees affected by GDs was reached in 2009 and 2019 (Figure 6).

A Mann–Whitney U test conducted on non-zero GDI values in years with and without experimental floods showed that GDI was significantly higher in years with experimental floods ($W = 1227, p < .01$).

A two-sample Student's *t*-test showed that mean temperature and precipitation during the growing season of years where abrupt growth decreases occurred (as identified by BSGC; see also Figure 5) did not differ significantly from the 1991–2020 mean at $p < .05$. Overall, however, growing season temperatures after 2003 were significantly higher than the 1991–2020 mean $t(48) = 1.906, p = .03$, whereas precipitation levels did not differ significantly at $p < .05$.

4 | Discussion

4.1 | Evolution of Biogeomorphic Activity

Experimental floods contributed to significant reworking of the active channel between 1991 and 2018 (cf. Figure 3b,c), and led to channel widening and the inclusion of bank vegetation, with varying degrees of impact on its fitness (Figure 1c).

One of the most striking changes in stream morphology is the increase in inundated area. This can be taken as an indicator of increased channel mobility through the reduction of incision (cf. Tonolla et al. 2021; Garófano-Gómez et al. 2013). Channel widening was associated with an important reduction in coverage of the ecological phase, which was predominant on the banks in 1991, and therefore showing these experimental floods to successfully reduce vegetation encroachment. The quasi-absence of recolonization by pioneer communities is presumably due to the permanent resetting of potential pioneer areas through the annual flooding and the burial it causes (cf. Figure 1h).

The 2018–2023 period was marked by a large channel widening event further downstream in 2019, due to remobilization of sediment provided by the Ova da Cluozza (cf. Consoli et al. 2022), which caused substantial land loss in agricultural areas of the floodplain. The lack of FBS progression due to permanent

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resetting is further demonstrated by the 10% increase in coverage of the geomorphic phase between 2018 and 2023.

4.2 | Application of the Fluvial Biogeomorphic Succession Model in the Spöl

Applying the FBS model proposed by Corenblit et al. (2007) to the lower Spöl shows a widespread regression to the geomorphic phase, with no significant development of a riparian habitat mosaic. The hydrogeomorphic variability of mountain rivers may truncate or disrupt biogeomorphic feedbacks even in unregulated rivers (Corenblit et al. 2020), but in the present case, the experimental flood regime appears to be a driving factor in the regressive FBS dynamic. The main reason for this is the aggradation of sediment provided by the Ova da Cluozza, redistributed by experimental floods (Consoli et al. 2022). The residual flows in place drastically reduce the Spöl's transport capacity, preventing it from mobilising the high sediment input from the tributary (see Figure 1f–h; also Mürle et al. 2003). Therefore, the sediment can only be mobilised once a year during experimental floods, which is insufficient to allow its full removal (Consoli et al. 2022).

Although aggradation, channel widening, and inclusion of bank vegetation all occur in unregulated rivers (cf. Ballesteros-Cánovas et al. 2015), the frequency and extent at which they occur in the lower Spöl give them a driving role in FBS dynamics. The inclusion of large vegetated "islands" in particular greatly modifies the riverscape. Accordingly, in this particular hydrogeomorphic context, we suggest dividing the biogeomorphic phase into two cases, namely:

1. The *spontaneous* biogeomorphic phase as described by Corenblit et al. (2007), which results from the development of pioneer vegetation to the point where it no longer suffers a drastic reduction in fitness from hydrogeomorphic stressors. In the Spöl, this can be observed sporadically in areas along the bank of the current active channel where channel widening is limited, that is in the upstream third. It remains very rare in the study reach, as physiological and mechanical stress is high due to aggradation and erosion;
2. The *induced* biogeomorphic phase, which results from the inclusion of previously disconnected vegetated areas (independently of vegetation development stage) into the active channel. This is best observed in the downstream third of the study reach, where extensive channel widening occurred (see Figure 3c). In the Spöl, the induced biogeomorphic phase consists of the vegetated banks prior to channel widening, now included in the channel. This is not biogeomorphic activity as intended by Corenblit et al. (2007) or Tabacchi et al. (2019), as the trees in question usually die within a few years (see Figures S5a and S6) without having contributed to the establishment of pioneers and did not develop from pioneers themselves. It should nonetheless be considered functionally "biogeomorphic" however, because this vegetation contributes to structural heterogeneities in the channel and to the establishment of preferential erosion/deposition and flow patterns. Indeed, large stands may deviate or slow the flow considerably or become vegetated islands disconnected from the channel. In the Spöl, Finch et al. (under review) showed that islands and vegetated gravel bars (largely corresponding to the induced biogeomorphic phase) stored proportionally more wood pieces relative to their spatial coverage than bare gravel bars. This seems to show that vegetated areas in the active channel, independently of their vitality and stand density, are efficient at trapping wood, further enhancing their biogeomorphic effect.

In terms of management, we suggest that a reduction of aggradation rates is necessary for the establishment of FBS dynamics, as pioneer communities are currently subjected to repeated burial and therefore unable to establish on gravel bars and progress to more mature stages. An increase in experimental flood frequency and/or magnitude may be an appropriate measure to remove sediment. The 1995 flushing flow, which eroded some 50,000 m^3 of sediment from the river bed, lowered the bed by approx. 1 m on certain transects (Molinari et al. 1996). This showcases the efficiency of larger flood events for sediment removal. In parallel to this management practice, the sediment regime in the Ova da Cluozza should be quantified, in order to better understand sediment delivery and availability. Finally, it must be stressed that concerns raised about aggradation are specific to the Spöl and the Ova da Cluozza, and not necessarily to be expected in other rivers. A comparative study in another catchment without such sediment input may allow more representative conclusions to be drawn regarding the effects of experimental floods on riparian vegetation in general.

4.3 | Vegetation Survey and Species Distributions

The tree stratum of the study reach has been shown to be dominated by an assemblage of *A. incana*, *Salix spp.*, and *P. padus* (see Figure 4). This assemblage is expected in a riparian zone (cf. Tabacchi et al. 2019; Gurnell et al. 2015; Delarze et al. 2015; Corenblit et al. 2010).

A clearly distinct assemblage is the one we term *Conifer forest*, as it is not composed of a priori riparian species. It makes up most of the surrounding forest, and it can therefore be assumed that it was part of the vegetation that encroached on the channel before experimental floods were implemented. The higher mortality of the Willow forest compared with the Conifer forest, and the lack of other significant differences in mortality between assemblages, seems to imply that burial and erosion have a stochastic effect on stands without affecting any species preferentially. This is consistent with the largely unidirectional control aggradation exerts on vegetation. The absence of preferential species compositions in FBS phases is in line with this, and is further explained by the largely retrogressive FBS dynamic due to aggradation. It is possible, however, that conifer stands were less exposed to channel widening, as this process was less pronounced in the upstream half of the study reach where most conifers are located (cf. Figures 4 and S6).

The fact that riparian pioneer patches containing tree saplings and large shrubs are 1. very rare and 2. display low mortality

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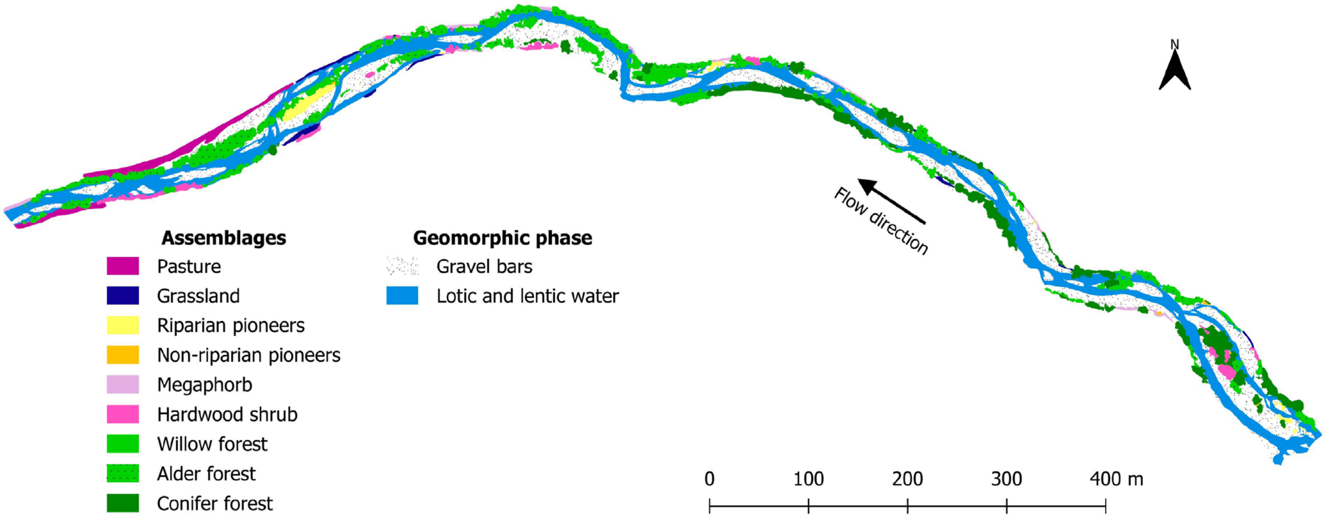

FIGURE 4 | Spatial distribution of vegetation assemblages as defined in Table S2, including tree stands and herbaceous and shrub strata. Only areas with a direct hydromorphological connection to the active channel were considered. [Color figure can be viewed at wileyonlinelibrary.com]

levels (Figure S2) supports the hypothesis that young pioneer communities are generally entirely destroyed by flooding and burial, while a very limited amount of durable vegetation development on disturbed surfaces does occur.

4.4 | Dendrogeomorphological Findings and Limitations

Mean annual ring width decreased significantly with the onset of the experimental flood programme (Figure 5). The year marked by the most intense growth disturbances, especially TRDs, was 2009, which is expected considering the exceptional magnitude and duration of the flushing flow (cf. Figure 2). The apparent GD decrease in the aftermath of this event may be hypothesised to be linked to a recovery period with comparatively low disturbance rates: no experimental flood occurred in 2010 or 2012, and the 2011 event was relatively small.

The second most intense growth disturbance occurred in 2019, during which two experimental floods were conducted within a few days of each other. Although neither was particularly large, this repeated stress over a short period of time did not allow trees to recover, nor perhaps root inundation to subside entirely. Additionally, 2019 was marked by a major channel widening episode, which is likely to have affected trees on the former banks of the Spöl, subjected to sudden burial. A large proportion of trees were affected by GDs, mostly mild eccentric growth, in 2006. This cannot be ascribed to a particularly large flood in the Spöl nor in the Ova da Cluozza, and may be hypothesized to be due to channel position at the time.

Conversely, no significant GD occurred in the aftermath of the 1995 flushing flow. It may be hypothesised that the water level did not reach as high, due to the fact that sediment redistribution had not yet started and that the stream bed was lower, and that inundation was therefore less severe. In 1995, the discharge was also lower than in 2009 (peak discharge 70 $m^3 s^{-1}$; Molinari et al. 1996).

GDI and growth patterns both indicate a quasi-unilateral control of flooding on trees, irrespective of their a priori tolerance to inundation, without difference between riparian and non-riparian species. This is explained by the fact that growth was mostly undisturbed before 2000, and experimental floods introduced a regular disturbance from which trees cannot recover fully between events (cf. Buras et al. 2022).

Comparing relatively short periods of time is difficult as the sample size is small, but the fact that several different species showed similar response patterns indicates a plausible trend. Collecting ring width data from additional trees may allow further investigation of the effect of experimental floods, and more particularly flushing flows, on ring width, and would allow the development of more robust estimates of growth trends over these short periods. Furthermore, the establishment of a reference chronology from undisturbed trees would provide a better understanding of growth patterns, notably in view of the rising temperatures since 2003 (Figure 5), and would allow the quantification of how growth rates differ in trees affected by experimental floods.

4.5 | Anthropic Interventions in the Riparian Corridor

The aggradation and channel widening discussed in the present study have been a cause for concern for local actors for several years already, particularly in view of the loss of agricultural land they already caused in 2019. This has prompted multiple interventions on the banks and in the river bed. These include building gravel dykes to prevent pasture flooding and stream bed excavations to avoid bridge clogging, sometimes with large temporary deposits atop bank vegetation (Figure 1e), but also instream tree felling to avoid bridge clogging during flood events. Discussing the relevance and effects of sediment management measures in the Spöl is outside the scope of the present study, but merits further investigation in light of the high sediment input from the Ova da Cluozza and the Spöl's limited transport capacity. The felling of instream standing trees, however,

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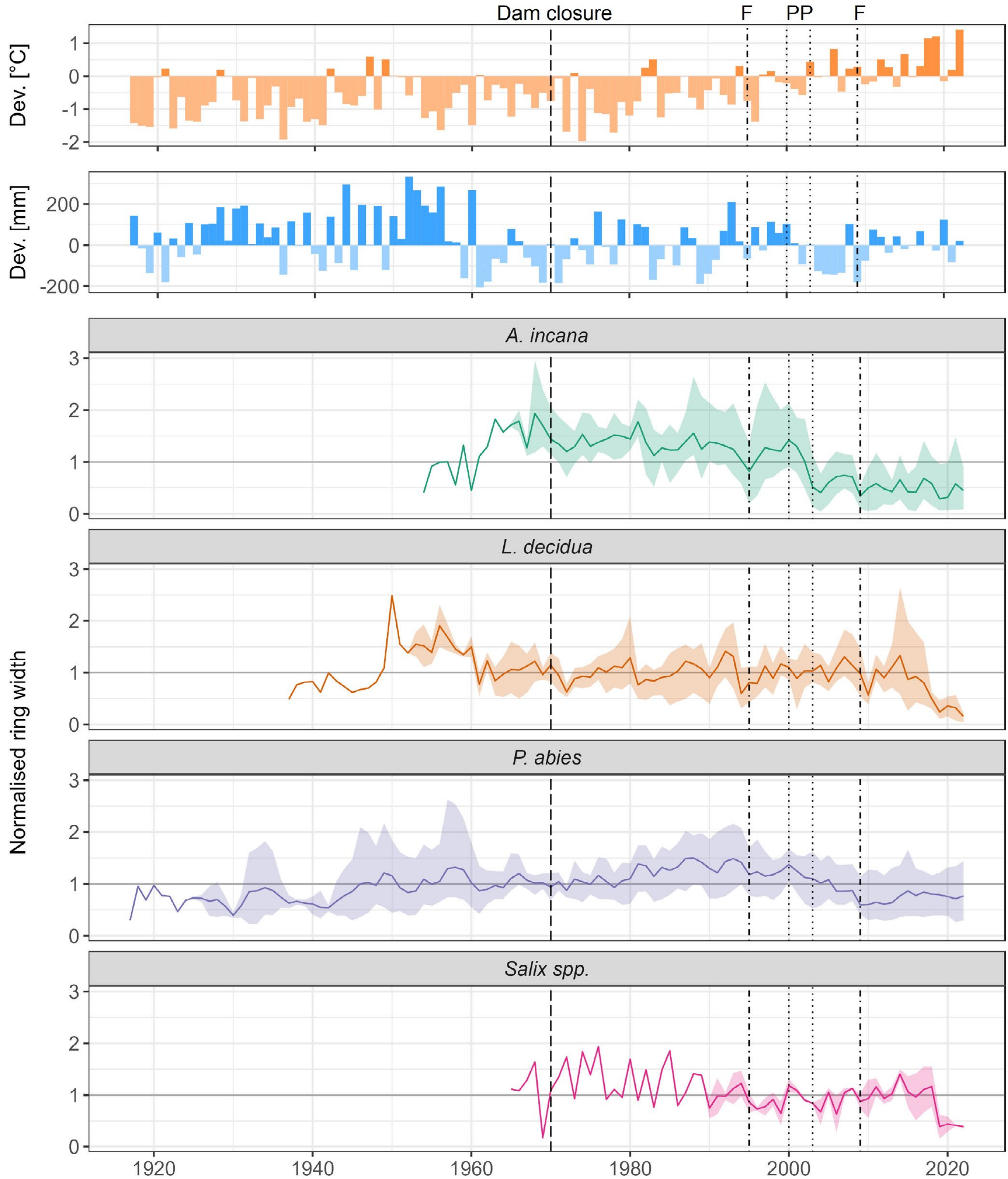

FIGURE 5 | *Top*: Deviations from the 1991–2020 mean of May–September temperature and precipitation at Buffalora (MeteoSwiss 2024). *Bottom*: Ring width values scaled to the mean of each species. Shaded areas show minimum and maximum values. The single *B. pendula* and *P. sylestris* samples were excluded. *F* markers represent years with a flushing flow, *PP* represents the experimental flood pilot project period. [Color figure can be viewed at wileyonlinelibrary.com]

hinders the dynamics of the proposed *induced biogeomorphic phase* by reducing flow heterogeneities due to the trees themselves and to potential wood jams they may trap. It also reduces the instream wood supply, as riparian tree mortality was shown to be the main recruitment process of wood in the Spöl (Finch et al. under review). The damage caused by temporary sediment deposits has not been investigated, but is likely to further impact the already weakened riparian vegetation.

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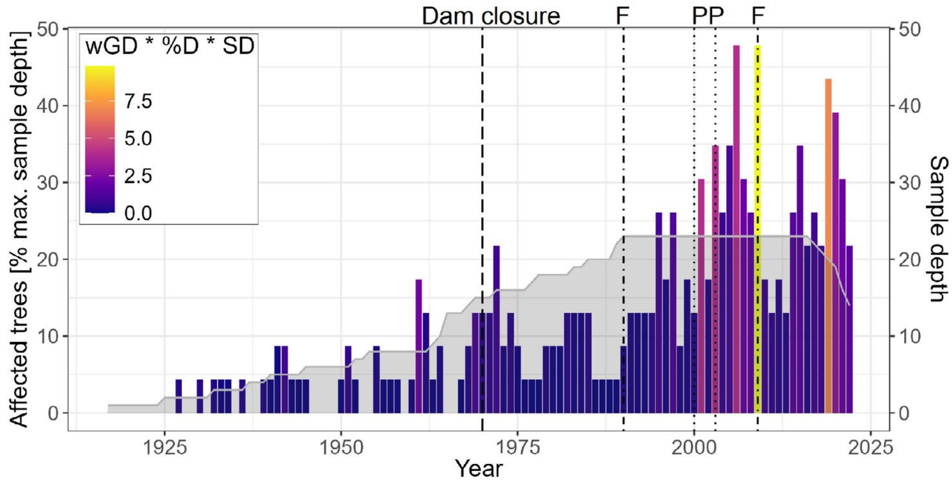

FIGURE 6 | Percentage of trees affected by GDs relative to the total sample depth, and weight associated with these GDs. *F* markers represent the 1995 and 2009 flushing flows, *PP* represents the experimental flood pilot project period. Note the scale of the y-axis (proportion of affected trees to maximum sample depth) is not equal to %D (proportion of affected trees relative to sample depth in that year), in order to avoid overrepresenting affected trees in years with low sample depth. [Color figure can be viewed at wileyonlinelibrary.com]

A flushing flow was planned for the spring of 2025 but was delayed due to insufficient water levels in the En/Inn River. Further interventions are to be expected in anticipation of the event, as well as heavy impacts on vegetation from the flood itself, similar to those observed in 2009.

5 | Conclusion

This study's findings show the experimental flood programme in the lower Spöl leads to an increase in hydrogeomorphic activity compared with the sole residual flow regime in place before 2000, particularly aggradation and channel widening from the redistribution of sediment delivered by the Ova da Cluozza. This has caused substantial land loss and a generalized reduction of fitness in riparian trees, and led to a dominance of retrogression in the FBS dynamic. However, as sediment input from the Ova da Cluozza is independent from the Spöl's flow regime, aggradation is likely to continue even in a sole residual flow regime. We therefore advocate that the experimental flood regime in the lower Spöl should not be discontinued, but designed in order to be able to effectively remove most of the accumulated sediment. Indeed, experimental floods have been shown to contribute favorably to aquatic ecosystem dynamics in the lower Spöl (cf. Mathers et al. 2021; Kevic et al. 2018) and we have confirmed they reduce vegetation encroachment. Designing the floods for better sediment removal, however, would require further investigations on sediment transport and budget in the Ova da Cluozza.

We have also provided a survey of trees in the riparian corridor documenting their species composition, distribution, and vitality as observed in late summer of 2023. This is likely to change considerably in the future with further vegetation dieback and removal. A flushing flow similar to that of 2009 was planned in spring of 2025, but was delayed due to insufficient water levels in the En/Inn River. When this flushing flow can be carried out, it is likely to affect heavily the already weakened riparian vegetation. Quantifying its effects on sediment would provide a better understanding of how higher magnitude floods can contribute to sediment removal.

Considering the pioneering nature of the experimental flood regime in the Spöl, further documenting the short- and long-term changes to the riverscape it causes appears to be an important step in understanding the effectiveness of such renaturation measures. Anthropic alterations to the riverscape for sediment management and flood risk mitigation should also be recorded to allow discrimination of them from changes due to the floods themselves.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.

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