# Unlocking vegetation age estimation and the identification of biogeomorphic floods in a braided river

## Estimation de l'âge de la végétation et identification des inondations biogéomorphiques dans une rivière en tresse

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## RÉSUMÉ
Cette étude explore l'intégration de la télédétection (RS) et du cloud computing (CC) pour estimer l'âge de la végétation et identifier les inondations biogéomorphiques dans les rivières en tresses, en se concentrant sur le fleuve Tagliamento, en Italie. Un algorithme innovant, mis en œuvre à l'aide des produits Landsat Surface Reflectance et Sentinel-2 sur Google Earth Engine, reconstruit la dynamique de l'âge de la végétation à l'échelle des pixels. La validation avec des données de terrain et des images haute résolution souligne des surestimations spatiales (15 %) et des sous-estimations temporelles (7 ans) dues aux limites de la télédétection. L'analyse des données historiques d'inondations révèle le rôle des crues à faible intervalle de récurrence dans le renouvellement et le recrutement de la végétation. Les résultats apportent des perspectives sur les dynamiques de la végétation riveraine et leurs interactions avec les processus hydro-géomorphologiques, mettant en avant l'utilité de la RS pour les études écosystémiques fluviales.

## ABSTRACT
This study investigates the integration of remote sensing (RS) and cloud computing (CC) to estimate vegetation age and to gain insights on biogeomorphic floods in braided rivers, using the Tagliamento River, Italy, as a case study. A novel algorithm, implemented using Landsat Surface Reflectance and Sentinel-2 products on Google Earth Engine, reconstructs vegetation age dynamics at the pixel scale. Validation with field data and high-resolution imagery highlights spatial overestimations (15%) and temporal underestimations (7 years) due to RS limitations. The analysis of historical flood data reveals the role of low-recurrence interval floods in vegetation turnover and recruitment. Results provide insights into riparian vegetation dynamics and their interactions with hydrogeomorphic processes, underscoring the utility of RS in advancing riverine ecosystem studies.

## KEYWORDS
Biogeomorphic flood, braided rivers, remote sensing, riparian vegetation, Tagliamento river
*Inondations biogéomorphiques, rivières en tresses, télédétection, végétation riveraine, fleuve Tagliamento*

## 1 INTRODUCTION

Despite recent advances in disentangling the hydro-morpho-ecological paradigm for riverscapes, quantifying riparian vegetation spatiotemporal dynamics still poses multiple challenges. The riparian zone exhibits significant spatial and temporal variability driven by flow and sediment regimes, bioclimatic conditions, morphodynamics, and land-use patterns. These factors change over time and are influenced by both natural and human dynamics. Monitoring and understanding these variations is crucial for effective river management and conservation. So far, observations on riparian vegetation age spatiotemporal dynamics have been limited to small areas with extensive fieldwork and historical datasets, restricting global applicability.

Fluvial Remote Sensing (RS) emerges as a powerful technical and methodological framework for monitoring processes and assessing fluvial trajectories in the Anthropocene at nested spatiotemporal scales (Piégay et al., 2020). This technology provides a comprehensive means of observing and analyzing the dynamic nature of riparian vegetation, offering valuable insights into ecosystem changes. Cloud computing (CC) has further transformed remote sensing applications in fluvial geomorphology by facilitating efficient computation and data management (Boothroyd et al., 2021). The integration of CC in RS enhances the scalability and accessibility of data, opening new avenues for more robust and comprehensive analysis.

This work explores the potential of remote sensing to investigate spatiotemporal dynamics of riparian vegetation. We reconstruct such dynamics and its linkages with flow and sediment regimes for the Tagliamento river (IT). Riparian vegetation age is estimated by integrating RS and CC with data from literature and collected through fieldwork , coupled with the analysis of flood and flow pulses.

## 2 MATERIALS AND METHODS

### 2.1 Study Area

The Tagliamento river is located in the Friuli Venezia Giulia Region, north-eastern Italy (Figure 1A,B ). The funnel-shaped catchment has an area of about $2580\ km^2$. Strong changes in flow energy, sediment size and distribution occur along the river's 170 km course. The climate is alpine in the headwaters and Mediterranean in the lower reaches, giving the river a flashy flow regime (*Bertoldi et al., 2009*). The study areas of this research are two near-natural river reaches nearby Pinzano al Tagliamento (Figure 1C). The upper reach presents an island-braided channel pattern, confined between Ragogna and Monte Prat, just upstream of Pinzano bridge. The selected lower sub-reach is located downstream of Pinzano village. Fieldwork was carried out in the lower sub-reach in September 2023 for the characterization of vegetation structure, composition, age, diameter, and height in targeted field plots. Fot the upper reach, previously collected field data and available historical images were considered. The Venzone hydrometric station was considered for the analysis of flood and flow pulses (Figures 1B,D).

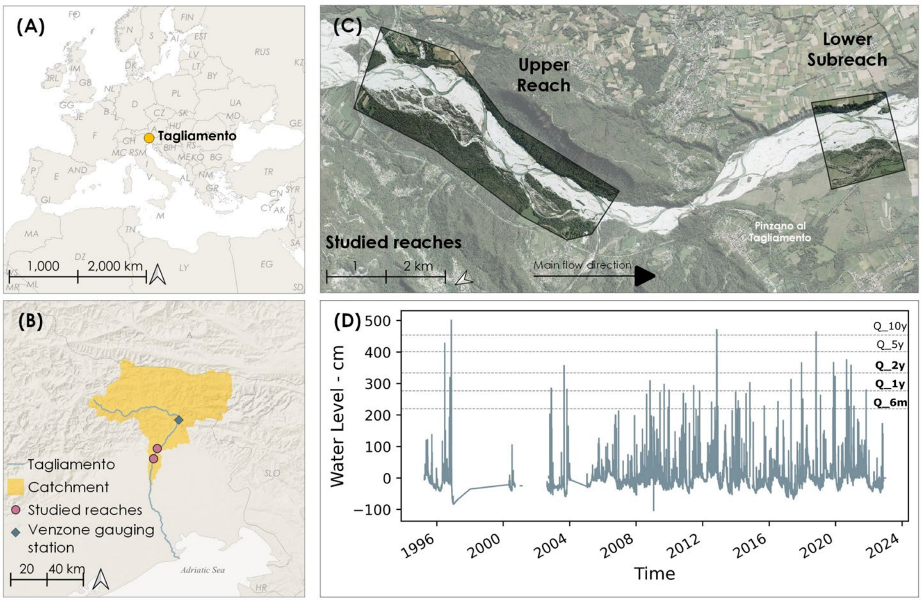


**Figure 1.** A: location of the Tagliamento river catchment in Europe (yellow dot). B: the Tagliamento river (blue line) flowing from the Alps to the Adriatic Sea and its contributing catchment ( yellow area); the pink dots denote the selected river reaches and the blue rhombus is the location of Venzone hydrometric station. C: overview of studied reaches for vegetation age estimation in the nearby of Pinzano al Tagliamento village. D: historical water level series at Venzone. Data are missing from 1997 to 2000 and in 2001 and 2002.

## 2.2 Methods

The proposed vegetation age algorithm combines the cloud computing Google Earth Engine (GEE) environment with Landsat Surface Reflectance and Sentinel-2 products. Vegetation age is estimated within the riverine active channel. The approach consists of three main steps: i) temporal setting and data filtering, ii) riverine macro-units classification and vegetation changes detection over space and time, and iii) the computation of vegetation age as a function of the time of the observation $t_{Obs}$, as detailed in Crivellaro (2024). The resulting vegetation age is computed at the pixel scale: for a given time of observation $t_{Obs}$, in each pixel classified as vegetation in $t_{Obs}$, the duration of such classification is computed in years, as the difference between $t_{Obs}$ and the most recent year in which vegetation was detected for such pixels.

Both spatial and temporal accuracy of the proposed algorithm are evaluated. Planet images with 3m resolution are considered per each year from 2017 to 2022 to assess the spatial accuracy of the algorithm. In each single Planet image, vegetation is mapped by computing the NDVI; all pixels with an NDVI value greater than 0.4 are classified as vegetated. The choice of a synthetic representative seasonal Landsat-derived NDVI and its thresholding is compared to Vegetation mapping derived from single Planet images in terms of false positive area, false negative area, and vegetation area % error. Landsat-derived NDVI vegetation threshold is set to 0.15 for the Tagliamento river, following Bertoldi et al. (2011). The temporal accuracy of Vegetation Age estimation is assessed through historical images, previous studies and fieldwork, to compare real vegetated field plots' ages with the ones estimated from Landsat and Sentinel-2 through the developed algorithm. In each field plot, vegetation core samples were taken and vegetation age was assessed by plant ring counting. Thus, the age of the older plant in each field plot is compared to the estimated vegetation age from Landsat and Sentinel-2 images. Once vegetation age is estimated, it is possible to reclassify age ranges in different ecological stages as proposed by Gurnell et al. (2016), namely three classes representing three major stages: the shrub phase, the young woody stage, and the mature woody stage. Furthermore, the historical water level dataset of the Venzone gauging station is analyzed in terms of cumulative annual and seasonal duration, magnitude, and frequency of events over potentially relevant thresholds for vegetation dynamics disturbances. Such thresholds are established as water levels with recurrence intervals of 6 months, 1 year and 2 years, estimated with a Gumbel extreme value distribution analysis on the water level time series.

# 3 RESULTS AND DISCUSSION

With the developed algorithm, vegetation age can be easily computed per multiples $t_{Obs}$ in a river reach. In the proposed case study, the procedure allows reconstruction of the temporal variation of vegetation age distribution at the reach scale, as visible in the clustered ecological classes in Figure 2A. For each year from 1987 to 2022, the three stages are classified and the total extent of each stage is computed.

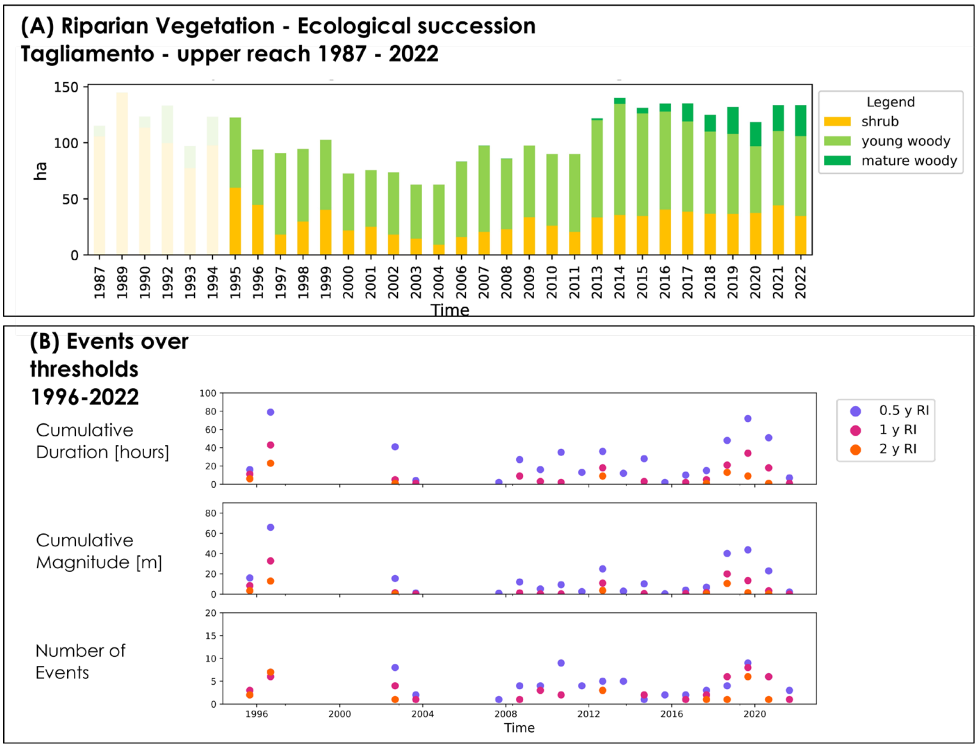

**Figure 2.** Panel A: Vegetation ecological stages and their extension over time in the upper reach of the Tagliamento river. Panel B: Analysis of events over thresholds of the Venzone water level time series in terms of annual cumulative duration, magnitude and number of events; purple dots are events with a recurrence interval (RI) of 6 months, while pink and orange dots represent events with 1 and 2 years RI, respectively.

The spatial accuracy assessment outlines a general overestimation of vegetation from Landsat images. Globally, error distribution has mean values of 15% and higher values are due to the presence of small lateral channels between densely vegetated patches, which are not detectable from Landsat Images. Furthermore, the temporal accuracy assessment showed an underestimation of vegetation age of about 7 years due to the spatial resolution of Landsat images.

The combined analysis of events over thresholds highlights the effect of biogeomorphic floods and flow pulses on vegetation age distribution and extent over time. Our findings are coherent with those of Surian et al. (2014), who showed the disturbance role of low RI events on vegetation (e.g. vegetation loss from 2019 to 2020) and related turnover in the Tagliamento river system, indicated by an increased presence of shrub and young woody stages Once vegetation is flooded, anoxia and flow drag can threaten the biomass and cause vegetation death or scouring. On the other hand, the dynamics of low RI events also facilitate the formation of suitable sites for recruitment, the dispersal of reproductive material, seedling recruitment, and survival (Vesipa et al., 2017).

The estimation of riparian vegetation age using medium-resolution multispectral remote sensing products such as Landsat and Sentinel-2 images opens a promising perspective to assess river ecomorphodynamics with stronger integration of remote sensing into river morphodynamics and ecological disciplines, as suggested by Brierley et al. (2023).

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