

UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingeniería de Montes, Forestal y del Medio
Natural



**Seguimiento ambiental de corredores
fluviales: tecnologías y marcos
metodológicos para cuantificar los
procesos de la vegetación de ribera**

TESIS DOCTORAL

Presentada para optar al título de Doctor por:

Daniel Díaz Alba

Ingeniero del Medio Natural y Máster en Restauración de Ecosistemas

Madrid, 2024



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Forestal y del Medio Natural

Doctorado en Investigación Forestal Avanzada

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Bajo la dirección de:

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Madrid, 2024

Título: Seguimiento ambiental de corredores fluviales: tecnologías y marcos metodológicos para cuantificar los procesos de la vegetación de ribera

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La desembocadura de un río es el final de su largo camino, pero desde que nace tiene muchos paisajes que recorrer, seres vivos que conocer y dificultades que afrontar. El final del camino es solo el principio de la inmensidad, y es por ello por lo que se acaba mi etapa dentro de la formación, pero todavía me queda mucho que descubrir en esa inmensidad. Todo empezó hace 31 años, era una gota de agua en un inmenso río, pero allí aparecieron mis padres, que, en esos primeros años desde mi nacimiento, me inculcaron el amor a la naturaleza y a los seres vivos como parte imprescindible de un todo. Con el tiempo el cauce continuo su curso, y después de unos kilómetros, me fui adentrando gracias a mi abuelo y a mi padre en el mundo de los ríos a través de la pesca, todavía eran tramos altos rectos y turbulentos, pero forjaron mi yo interior y mi amor a los peces y los ríos. Más tarde fuimos adentrándonos en paisajes más llanos, donde los mosaicos de cultivos aislados y los bosques caducifolios, se mezclaban con amplias riberas, y fui allí cuando apareció la Universidad, donde conocí muchos amigos que me ayudaron y apoyaron siempre, gracias, Daniel, Marcos, Arturo, Guillermo, Miguel, Carlos Correa, Carlos Fernández, Álvaro e Ignacio.

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ABREVIATURAS Y ACRONIMOS

LiDAR	Light Detection and Ranging
PNOA	Plan Nacional de Ortofotografía Ar
IGN	Instituto Geográfico Nacional
RGB	Red Green Blue
NIR	Near Infrared
CHM	Canopy Height Model
MDT	Modelo Digital del Terreno
MDS	Modelo Digital de la Superficie
MDC	Modelo Digital de Copas
DSM	Digital Surface Model
SIG	Sistemas de Información Geográfica
DEM	Digital Elevation Model
CMI	Channel Migration Index
ACC	Active Channel Change
ACW	Active Channel Width
BI	Braided Index
DAP	Diametro a la Altura del Pecho
LPI	Laser Penetration Index
NDVI	Índice de Vegetación de Diferencia Normalizada
IDW	Inverse Distance Weighting
REM	Relative Elevation Model
RMS	Root-Mean-Square (error)
VHR	Very High Resolution

ABSTRACT

Riparian corridors play a crucial role in the functioning of river ecosystems, acting as ecological corridors between aquatic and terrestrial ecosystems. These systems have been severely altered, largely due to human activity, which has modified their natural conditions. The study of riparian vegetation and the geomorphology that shapes river channels is essential for developing management plans and strategies that promote the conservation of these systems, or their restoration if they are in a state of degradation. In recent years, emerging technologies in the fields of remote sensing and GIS have enhanced processes and knowledge about the evolution of forest masses in remote areas.

This thesis first analyzes the factors and impacts affecting the regeneration of one of the most important genera in the Salicaceae family, a group of pioneer plant species found in rivers of the Northern Hemisphere: the genus *Salix*. The literature review shows that the proportion of *Salix* species studied is low. Additionally, a total of 19 abiotic factors influencing its regeneration were identified, with the most studied being related to soil and hydrology. Regarding pressures, the most studied were flow regulation and competition from invasive vegetation. There is a need for more research on aspects such as the effect of the impact of climate change on *Salix* regeneration in order to improve the conservation of these species, their environment or to improve restoration techniques.

Secondly, the study explored "in situ" the regeneration state of willows in a regulated channel in the middle-upper reaches of the Jarama River and analyzed the evolution of the active channel's mobility and the transformation of its forms over the past decades. The results indicate that the Jarama River has evolved from a wide, braided channel to a narrower, meandering one, with densely vegetated riparian corridors. Willow formations appear to be in decline, while more drought-tolerant species, such as *Fraxinus angustifolia*, have colonized the area due to reduced channel mobility and the absence of bare gravel bars. The dominant willow species, *Salix salviifolia*, has adapted to these changes and is widely distributed along the riparian stretch. The results predict a gradual disappearance of willows in the Jarama River due to a lack of significant recruitment, suggesting that the survival of these trees will depend on the old specimens that may still persist.

Finally, a methodological framework combining new LiDAR technologies and individual tree detection methodologies is proposed. These were applied in two case studies on two Mediterranean rivers, although in very different segments and conditions. First, changes in riparian vegetation and channel forms were analyzed following the demolition of a disused weir on a stretch of the Lozoya River. The riparian corridor has undergone changes due to natural vegetation growth, with an increase in the number of trees of medium height and diameter. However, the canopy cover fraction decreased significantly due to the creation of open spaces that have considerably widened the active channel area.

In the case of the Tiétar River, the analyzed area was much larger, and the methodology was extended to the study of several segments divided according to their geomorphological conditions. In unconfined segments, an increase in corridor density was observed in the lower areas near the shore. At lower elevations, there are more small-sized specimens and fewer large-sized ones. The methodology used in both chapters demonstrates the effectiveness of these technologies for monitoring forested riparian ecosystems and detecting changes in the corridor with high resolution and precision, thus improving the knowledge and management of these dynamic environments.

Keyword: recruitment, regeneration, willow, riparian vegetation, active channel, river mobility, encroachment, LiDAR, GIS, geomorphology, management.

RESUMEN

Los corredores riparios desempeñan un papel fundamental en el funcionamiento de los ecosistemas fluviales, actuando como corredores ecológicos entre el ecosistema acuático y el terrestre. Estos sistemas se han visto modificados gravemente, en gran medida por la acción humana, que ha modificado sus condiciones naturales. El estudio de la vegetación de ribera y la geomorfología que traza las formas de los cauces fluviales es fundamentales para el desarrollo de planes y estrategias de gestión que promuevan la conservación de estos sistemas, o la restauración de estos si se encuentran en estado de degradación. En los últimos años las nuevas tecnologías emergentes en el campo de la teledetección y los SIG ha permitido mejorar los procesos y el conocimiento sobre la evolución de las masas forestales en zonas remotas.

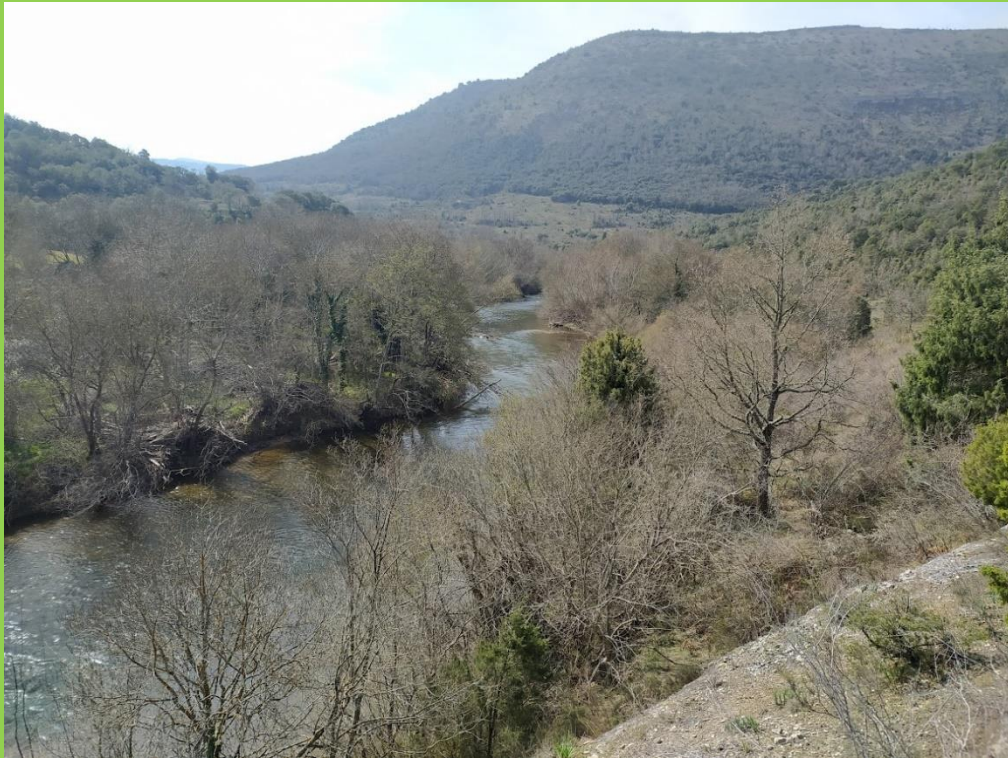
En esta tesis se analiza en un primer lugar los factores e impactos que intervienen en el regenerado de uno de los géneros de la familia Salicaceae más importante dentro de las especies vegetales pioneras de los ríos del hemisferio norte, el género *Salix*. La revisión bibliográfica realizada refleja que la proporción de especies estudiadas de *Salix* es baja. Además, se identificaron un total de 19 factores abióticos que influyen en su regenerado, siendo los más estudiados los relacionados con el suelo y la hidrología. En cuanto a las presiones, las más estudiadas fueron la regulación del caudal y la competencia de la vegetación invasora. Existe una necesidad de incrementar la investigación en aspectos como por ejemplo el efecto del impacto del cambio climático sobre este género para mejorar la conservación estas especies, su entorno o mejorar las técnicas de restauración.

En segundo lugar, se exploró “in situ” el estado del regenerado de los sauces en un cauce regulado en el tramo medio-alto del río Jarama, y analizó la evolución de la movilidad del cauce activo y la transformación de las formas del cauce. Los resultados indican una evolución del cauce ancho y trenzado, a uno más estrecho y meandriforme, con corredores riparios densamente vegetados. Las formaciones de sauces parecen estar en retroceso, mientras que especies más tolerantes a la sequía, como *Fraxinus angustifolia*, han colonizado la zona debido a la reducción de la movilidad del cauce y la ausencia de barras de grava desnudas. Los resultados predicen una desaparición gradual de los sauces en el río Jarama debido a la falta de un reclutamiento significativo, lo que sugiere que la supervivencia de estos árboles dependerá de los ejemplares viejos que aún puedan persistir.

Finalmente, se plantea un marco metodológico que aúna nuevas tecnologías LiDAR y metodologías de detección de árbol individual. Se aplicaron en dos casos de estudio en dos ríos de carácter mediterráneo, aunque en tramos y condiciones muy distintas. En primer lugar, se analizaron los cambios producidos en la vegetación de ribera y las formas del cauce tras la demolición de un azud en desuso en un tramo del río Lozoya. El corredor ripario ha experimentado cambios debido al crecimiento natural de la vegetación, con un aumento en el número de árboles de altura y diámetro medianos. Sin embargo, la fracción de cabida cubierta disminuyó notablemente debido a la creación de espacios abiertos que han ensanchado notablemente la zona del cauce activo. En el río Tietar, la superficie analizada fue mucho más extensa, y la metodología se amplió al estudio de varios tramos segmentados según sus condiciones geomorfológicas. En los segmentos no confinados, se observó un aumento en la densidad del corredor en las zonas más bajas cerca de la orilla. En las cotas bajas, hay más ejemplares de pequeño tamaño y menos de gran tamaño. La metodología utilizada en ambos capítulos demuestra la eficacia de estas tecnologías para monitorizar ecosistemas riparios forestales y detectar cambios en el corredor con resoluciones y precisiones elevadas, mejorando así el conocimiento y la gestión de estos entornos dinámicos.

Palabra clave: reclutamiento, regenerado, sauce, vegetación riparia, cauce activo, movilidad fluvial, “encroachment”, LiDAR, SIG, geomorfología, restauración, gestión.

1.INTRODUCCIÓN Y OBJETIVOS



1. INTRODUCCIÓN Y OBJETIVOS

La vegetación de ribera y el entorno donde se asienta dicha vegetación, desempeña un papel fundamental en el dinámica fluvial, actuando como corredores ecológicos entre el ecosistema acuático y el terrestre (Naiman & Decamps, 1997; Naiman et al., 2005), interaccionando con el funcionamiento hidrológico (Decamps et al., 2004; Dixon et al., 2016), proveyendo alimento y refugio a la fauna (Johnson et al., 1997; Allen et al., 2024), y aportando un gran valor cultural al entorno (Klein et al., 2015). El estado de las riberas y los cauces depende de su composición, atributos y estructura (Gregory et al., 1991; Naiman et al., 1993). Las perturbaciones naturales, principalmente las avenidas, son la base del mantenimiento de una zona riparia diversa, por lo que una reducción de su frecuencia e intensidad asociadas a un régimen hidrológico alterado produce cambios en la diversidad de hábitats, afectando a su correcto funcionamiento (Ward et al., 2002), siendo la regulación de caudales por presas y embalses la alteración más frecuente (Poff et al., 2007).

Dentro de estas zonas de ribera existen numerosas especies vegetales, destacando en los bosques ribereños del hemisferio norte los árboles y arbustos pertenecientes a dos géneros de la familia *Salicaceae*, *Populus* (es decir, álamos y chopos) y *Salix* (es decir, sauces) (Malanson, 1993). Ambos géneros desempeñan un papel crucial en los ecosistemas fluviales de zonas templadas, proporcionando refugio a la fauna, recursos nutritivos y sombra que regula la temperatura para la vida acuática (Cummins et al., 1989, Muhar et al., 2007). Además, la mayoría de las etapas, desde pequeños propágulos hasta grandes árboles, actúan como especies ingenieras del ecosistema favoreciendo la creación de formas en el cauce y condicionando la deriva fluvial.

En las últimas décadas se ha observado una pérdida considerable de dinamismo y de creación de estadios pioneros en los cauces. Las consecuencias generalizadas sobre la pérdida de dinamismo fluvial conducen a la estabilización y estrechamiento de los cauces fluviales, con la consiguiente falta de espacios despejados necesarios para el reclutamiento de esas especies pioneras (e.g., Lobera et al., 2015; Martínez-Fernández et al., 2017b; González et al., 2018; García de Jalón et al., 2020).

Por ello se hace necesario incrementar el conocimiento y optimizar las tecnologías para mejorar la gestión y el conocimiento de estos espacios. Conocer la distribución de la vegetación ribereña y sus cambios a lo largo del tiempo permite gestionar estos espacios de forma más eficiente. El uso de nuevas tecnologías, como la fotogrametría o la teledetección (por ejemplo, Huylenbroeck et al., 2021) podría aumentar la capacidad de análisis de superficies con gran precisión. La teledetección ofrece actualmente una amplia selección de productos, metodologías y técnicas aplicables a las mediciones de variables forestales (por ejemplo, Jochem et al., 2010; Moe et al., 2020), que complementan los inventarios tradicionales y amplían sus posibilidades (Ortiz-Reyes et al., 2015). Dada la complejidad de los corredores riparios en términos de diversidad, estructura y funcionalidad, el estudio de su evolución a partir de imágenes LiDAR y aéreas podría mejorar el seguimiento ambiental del corredor fluvial combinando el estudio de sus condiciones morfológicas y de la estructura de su vegetación. El objetivo de esta tesis es contribuir al seguimiento ambiental de las riberas mediante el uso de tecnologías que permitan mejorar la eficiencia y sean aplicables en su gestión y restauración.

Siguiendo estas líneas, se presenta brevemente el contexto específico en el que se ha desarrollado esta tesis, seguido de los planteamientos metodológicos generales necesarios para llevar a cabo los objetivos propuestos en esta investigación. A continuación, se describen los resultados en una serie de capítulos y, por último, se presentan la discusión y las conclusiones.

1.1. FACTORES BIÓTICOS, PRESIONES Y SU INFLUENCIA EN EL REGENERADO DE LOS SAUCES

Las especies del género *Salix* tienen características fisiológicas que les permiten colonizar barras frecuentemente inundadas, saturadas y expuestas al sol, lo que las convierte en especies ideales para habitar ecosistemas ribereños (Blom et al., 1990, Karrenberg et al., 2002) donde interactúan con la geomorfología para influir en la diversidad global de los ecosistemas fluviales (Tockner & Stanford, 2002; Gurnell, 2014). El conocimiento sobre las limitaciones que experimentan estas especies en las fases tempranas de regeneración y colonización contribuye sin duda a mejorar su seguimiento en el tiempo.

Se estima que el género *Salix* contiene entre 330-350 (Skvortsov y Tikhomirov, 1968) y 526 especies (sensu Zhen-Fu, 1987). Sin embargo, tradicionalmente se han estudiado agrupadas con las especies de *Populus* probablemente debido a su mayor valor comercial dentro de la industria maderera y del papel. Las especies de *Salix* están actualmente amenazadas por numerosas presiones antropogénicas (e.g., Stella et al., 2013; González del Tánago et al., 2016; Martínez Fernández et al., 2017), y su declive pasa relativamente desapercibido, por lo que una revisión global de los requisitos y limitaciones del reclutamiento es prioritaria para (1) incorporar lo que se conoce a las prácticas de gestión para restaurar y conservar la funcionalidad, el dinamismo y la diversidad de los ríos; y (2) identificar factores poco estudiados para guiar futuras investigaciones.

En base a todo lo expuesto, esta tesis comienza examinando la literatura científica con el objetivo de detectar tanto los factores abióticos que impulsan la regeneración de *Salix*, como otras presiones ambientales que pueden influir en el éxito del reclutamiento. Mientras que los factores abióticos pueden tener una serie de impactos en el reclutamiento de *Salix*, definimos las presiones ambientales como condiciones que dificultan el reclutamiento. Éstas pueden ser abióticas, como los incendios, o bióticas, como el pastoreo. Pueden ser de naturaleza antropogénica, como el cambio climático y la competencia de especies invasoras, o de origen natural, como la competencia interespecífica de especies autóctonas (Capítulo 3.1).

1.2. PÉRDIDA DE ZONAS PIONERAS PARA EL REGENERADO COMO PRINCIPAL CAUSA DEL DECLIVE DE LOS SAUCES

Los ríos mediterráneos están muy alterados debido en gran medida a la regulación del caudal, el regadío y los cambios en el uso del suelo, lo que altera el funcionamiento natural del ecosistema (Stefanidis et al., 2016; Lobera et al., 2017; Fazelpoor et al., 2021). Varios estudios en ríos mediterráneos ilustran un aumento de la densidad de la vegetación o un proceso de invasión asociado a la alteración del régimen de caudales (Friedman et al., 1998; Stella et al., 2003; García de Jalón et al., 2020). Este proceso ha influido en la dinámica fluvial de los ríos transformando ríos trenzados en ríos de un solo canal, disminuyendo las superficies disponibles para la regeneración de especies pioneras y cambiando las condiciones geomorfológicas fluviales (Gurnell et al., 2019). Además, las condiciones geomorfológicas naturales influyen en la evolución de las formaciones vegetales ribereñas a nivel de cuenca, contribuyendo a su vez a su dinamismo (Engelhardt et al., 2012). Esta pérdida de dinamismo ha conducido a que el estrechamiento de los cauces fluviales favorezca la presencia de otras especies menos pioneras, e impida el reclutamiento de especies pioneras como los sauces.

En este contexto, en esta tesis se exploran los principales factores que inducen el progresivo proceso de “vegetation encroachment” en el corredor ripario y el declive de formaciones de sauces observado, conociendo más sobre los factores que impiden la regeneración de los sauces y se aportan alternativas para su correcta recuperación, en este caso particularmente en el río

Jarama (Capítulo 3.2).

1.3. EFECTOS DE LA ELIMINACIÓN DE AZUDES EN LA APERTURA DE ESPACIOS FLUVIALES PARA MEJORAR EL DINAMISMO FLUVIAL

Los bosques de ribera se ven afectados globalmente por diversas actividades antrópicas como el cambio de usos en la llanura de inundación, la reforestación de la cuenca vertiente, la entrada de especies exóticas y más recientemente el cambio climático (Gordon, & Meentemeyer, 2006; Dufour et al., 2007; Stromberg et al., 2007; González et al., 2010; Dixon et al., 2012; Connolly et al., 2015; González del Tánago, Martínez-Fernández & García de Jalón, 2016). En las llanuras aluviales condicionadas por la actividad humana, los corredores riparios se ven limitados a ocupar espacios estrechos presentando una alta densidad de vegetación donde la regeneración es escasa (Cordes et al., 1997; Cooper & Andersen 2012) y se favorece el proceso de estabilización y maduración de la vegetación (“vegetation encroachment”) (García de Jalón et al., 2020; García de Jalón et al., 2024). En estas zonas la construcción de estructuras transversales al cauce, como azudes para derivar agua, están muy extendidas, generando una discontinuidad longitudinal en los cauces tanto para la componente biótica (i.e., peces y macroinvertebrados) como abiótica (i.e., caudales sólidos y líquidos). Aunque sean de pequeño tamaño (altura inferior a 2 m), la presencia de estas estructuras genera cambios en el funcionamiento geomorfológico e hidrológico transversal (Boix-Fayos et al., 2008) así como en la vegetación riparia (Göthe et al., 2015).

Una forma de restaurar el buen funcionamiento del ecosistema ripario es eliminando o permeabilizando estas barreras con el objetivo de promover los procesos geomorfológicos e hidrológicos naturales, además de favorecer el establecimiento de especies autóctonas pioneras en los espacios perturbados y recuperar los ciclos naturales de sucesión y rejuvenecimiento del corredor (Geerling et al., 2008). La eliminación de pequeños azudes se engloba dentro de las acciones de restauración fluvial, y diversos estudios demuestran una recuperación de la diversidad y heterogeneidad del corredor tras su eliminación (e.g., Martínez-Fernández et al., 2017; Kim & Choi, 2019; Díaz-Alba et al., 2021). La monitorización y seguimiento de la evolución del corredor fluvial tras este tipo de actuaciones de restauración es fundamental para analizar las consecuencias en todos los componentes del ecosistema de manera que sirva de base de conocimiento en otras actuaciones. Por lo tanto, es crucial el diseño de metodologías y protocolos que sirvan a este fin y orienten futuras intervenciones en caso de ser necesarias para alcanzar objetivos establecidos.

En este contexto, esta tesis contribuye con el análisis de los cambios experimentados por un tramo de río sometido a una restauración fluvial que consistió en la demolición de un azud considerando el contexto geomorfológico en el que tiene lugar y analizando su evolución (Capítulo 3.3).

1.4. NUEVAS TECNOLOGÍAS APLICADAS A LA GESTIÓN DE CORREDORES DE RIBERA.

Como ya se he expuesto previamente, las nuevas tecnologías (por ejemplo, LiDAR o “*structure from motion*”) suponen un gran avance de cara a la gestión de grandes superficies arboladas en los corredores fluviales. Estas herramientas permiten la obtención de datos tridimensionales de alta resolución, lo que facilita una comprensión más profunda de la estructura y composición de estos espacios. Además, en los últimos años se han producido interesantes avances en el análisis de datos procedentes de diferentes técnicas de teledetección para generar información precisa sobre los atributos de los corredores ribereños (Riedler et al.,

2015; Michez et al., 2016). Estas investigaciones resaltan la importancia de utilizar herramientas multidimensionales que integren diferentes tipos de datos para comprender mejor los ecosistemas ribereños y sus dinámicas.

En esta tesis, se contribuye a la mejora del seguimiento ambiental de las riberas mediante al uso de estas tecnologías valorando concretamente los datos LiDAR ya sea tras actuaciones como un proyecto de restauración (Capítulo 3.3) o en su evolución natural (Capítulo 3.4). Los datos LiDAR ofrecen una herramienta útil para desagregar los complejos efectos de las condiciones geomorfológicas y la ubicación de la vegetación ribereña en relación con el cauce principal. Su combinación con la clasificación de imágenes (RGB y NIR) es interesante para analizar su composición. Este enfoque no solo permite identificar las variaciones en la estructura del bosque a lo largo del cauce principal, sino que también proporciona a los gestores de recursos naturales una metodología rápida y eficaz para monitorear la evolución y el comportamiento de estos corredores ecológicos.

Además, al generar mapas detallados de la vegetación y sus atributos, se podrán establecer bases sólidas para la toma de decisiones en la conservación y restauración de estos ecosistemas, asegurando su resiliencia frente a las amenazas ambientales y antropogénicas.

2.METODOLOGÍA



2. METODOLOGÍA

2.1. LOCALIZACIÓN Y CONTEXTO

La investigación desarrollada en esta tesis se ha llevado a cabo en varios ríos de la mitad centro y norte peninsular, salvo la revisión inicial que analiza el regenerado de sauces en un contexto global. Las zonas analizadas fueron; el río Lozoya aguas arriba de la presa de Pinilla, el río Jarama agua abajo del embalse del Vado, y finalmente el río Tietar agua arriba del embalse de Rosarito, todos ellos pertenecen a la Cuenca del Tajo.

2.1.2. RÍO JARAMA

El río Jarama nace en el extremo occidental de la Sierra de Ayllón y fluye hacia el sur a lo largo de 190 km hasta su confluencia con el río Tago. Su cuenca, con una superficie de 11.600 km², se encuentra en el centro de España y constituye una red fluvial altamente regulada, principalmente debido a la cercanía de grandes desarrollos urbanos en torno a la ciudad de Madrid. La elevada demanda de agua se satisface mediante ocho grandes embalses construidos en la cabecera del río, desde donde el agua es conducida a la ciudad a través de tuberías y canales. Esta extracción de agua provoca una notable reducción del caudal en extensos tramos fluviales, como ocurre aguas abajo de los embalses de El Vado, construido en 1972 sobre el río Jarama, y del Atazar, construido en 1965 sobre el río Lozoya, su principal afluente. Además, el río Jarama, especialmente en sus tramos medio y bajo, recibe importantes cantidades de aguas residuales urbanas, que, aunque tratadas, aún contienen altos niveles de nutrientes.

El caudal medio diario ha disminuido prácticamente durante todo el año, siendo más notable entre los meses de abril y junio. Tanto el caudal medio anual como el caudal máximo anual disminuyeron a lo largo de los tres periodos analizados, registrando una reducción acumulada superior al 50 % en ambos casos (51,5 % y 58,6 %, respectivamente) en el último periodo en comparación con el primero (ver Tabla 1). En contraste, el caudal mínimo anual aumentó a lo largo del tiempo, con un incremento del 121,6 % en el primer periodo y un aumento del 235,0 % en el segundo periodo respecto al primero.

Tabla 1. Caudales característicos estimados para los periodos estudiados en el río Jarama. Se ha estimado el % de cambio acumulado en relación con el primer periodo y se indica entre paréntesis.

	Periodo		
	1943-1972	1973-1998	1999-2018
Caudal medio anual (m ³ /s) (% variación)	11,6	6,6 (-43,2)	5,6 (-51,5)
Caudal máximo anual (m ³ /s) (% variación)	138,7	101,6 (-26,8)	57,5 (-58,6)
Caudal mínimo anual (m ³ /s) (% variación)	0,2	0,4 (+121,6)	0,6 +235,1)

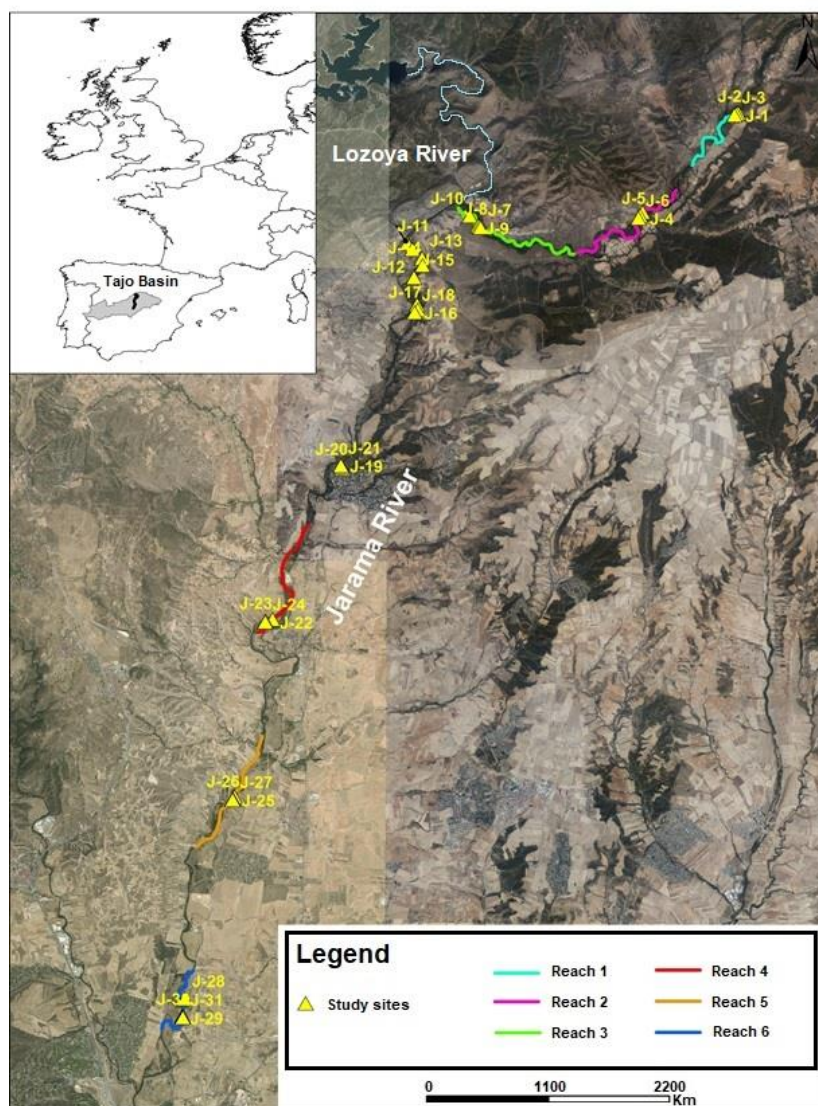


Figura 1. Localización de los tramos y puntos de estudio del río Jarama.

2.1.3. RÍO LOZOYA

El río Lozoya cuenta con una Cuenca hidrográfica de 1265 km², este río nace en el extremo occidental del Parque Nacional de la Sierra de Guadarrama a una altitud de 2.428 m, desembocando en el río Jarama a 692 m. La cuenca presenta una pendiente media del 24 % y gran parte de su superficie está cubierta por bosques (CORINE Land Cover, 2012). El clima de la cuenca es mediterráneo húmedo, con una temperatura media anual de 10,4 °C y una precipitación media anual de 520 mm.

El régimen de caudales del río está regulado en sus tramos medio y bajo por una serie de grandes presas. Antes de 1972, presentaba un régimen nival, pero en periodos más recientes ha mostrado una tendencia hacia un régimen pluvial, debido a la pérdida del máximo absoluto de caudal por deshielo. Según la estación de aforos de Paular (UTM30N; X: 425430, Y: 4522276), el caudal medio anual del río fue de 1,37 m³/s entre 1967 y 2015, mientras que en la estación de aforo de Pinilla (UTM30; X: 434830, Y: 4533015) alcanzó 4,84 m³/s. El embalse de Pinilla regula los caudales desde 1967 para el suministro de agua y la generación de energía hidroeléctrica.

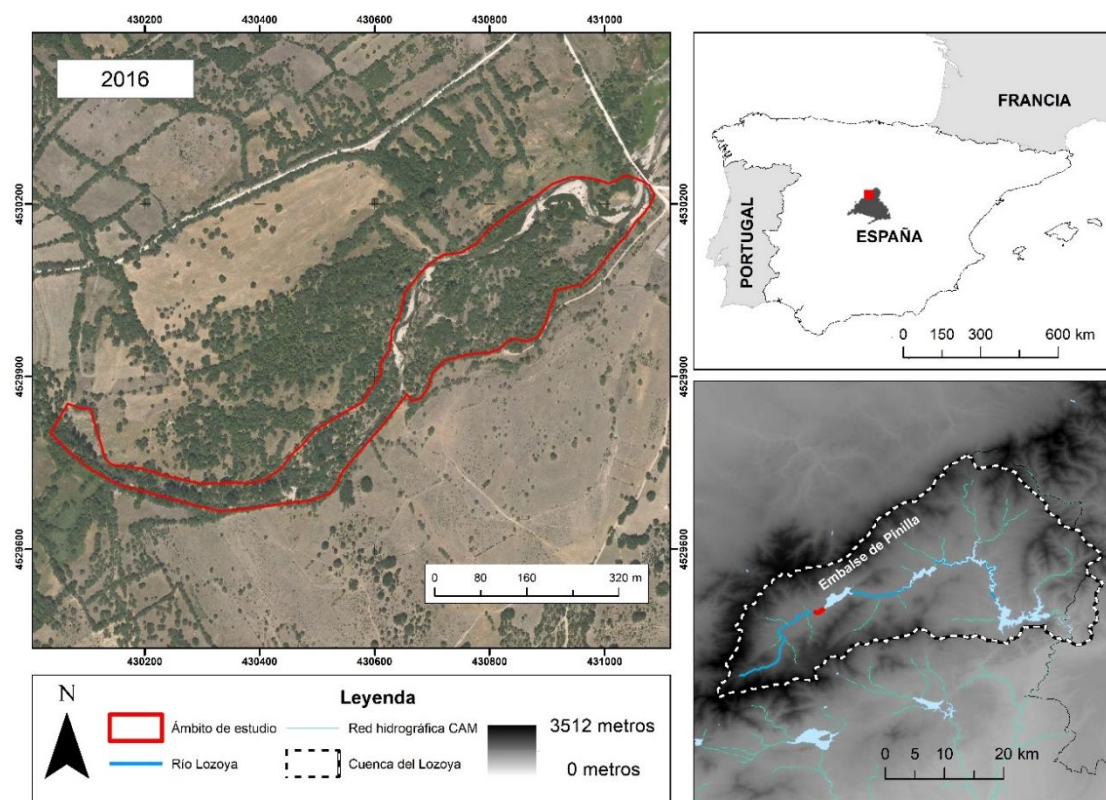


Figura 2. Localización del área de estudio en el río Lozoya. Ortofoto del PNOA correspondiente al año 2016.

2.1.4. RÍO TIÉTAR

El río Tiétar atraviesa la parte central de la Península Ibérica, fluyendo de este a oeste a lo largo de 170 km sobre una cuenca hidrográfica de 4.468 km². En casi toda la cuenca del Tiétar, así como en la zona de estudio, el río discurre por valles confinados y estrechos. Este cauce, de gran relevancia en la región, drena la vertiente sur de la Sierra de Gredos, donde varios arroyos temporales y barrancos escarpados desembocan en el río con caudales elevados y fuertes corrientes durante las épocas húmedas (Amor Morales et al., 1993), lo que favorece una alta conectividad de sedimentos y aporta dinamismo geomorfológico. El río está regulado por dos embalses: el embalse de Rosarito, construido en 1958, y el embalse de Torrejón-Tiétar, desde 1967, antes de desembocar en el río Tago.

El segmento fluvial estudiado comienza en un valle no confinado a lo largo de 18 km, que luego se convierte en un tramo confinado durante los siguientes 23 km, con altitudes que oscilan entre 389 y 314 metros y una pendiente media del 0,95%. El lecho y las márgenes del río están formados principalmente por sedimentos de tamaño medio. Para caracterizar los eventos de caudal en las últimas décadas, se utilizaron series históricas de caudales diarios desde 1968 hasta 2018 (estación de aforo 3161, disponible en <http://hercules.cedex.es/anuarioaforos>). Aguas arriba del embalse de Rosarito, el río Tiétar mantiene un régimen natural, con una descarga media anual de 6,8 m³/s durante los últimos 50 años, siendo 240,8 m³/s la media del caudal máximo anual y 0,1 m³/s la media del caudal mínimo anual.

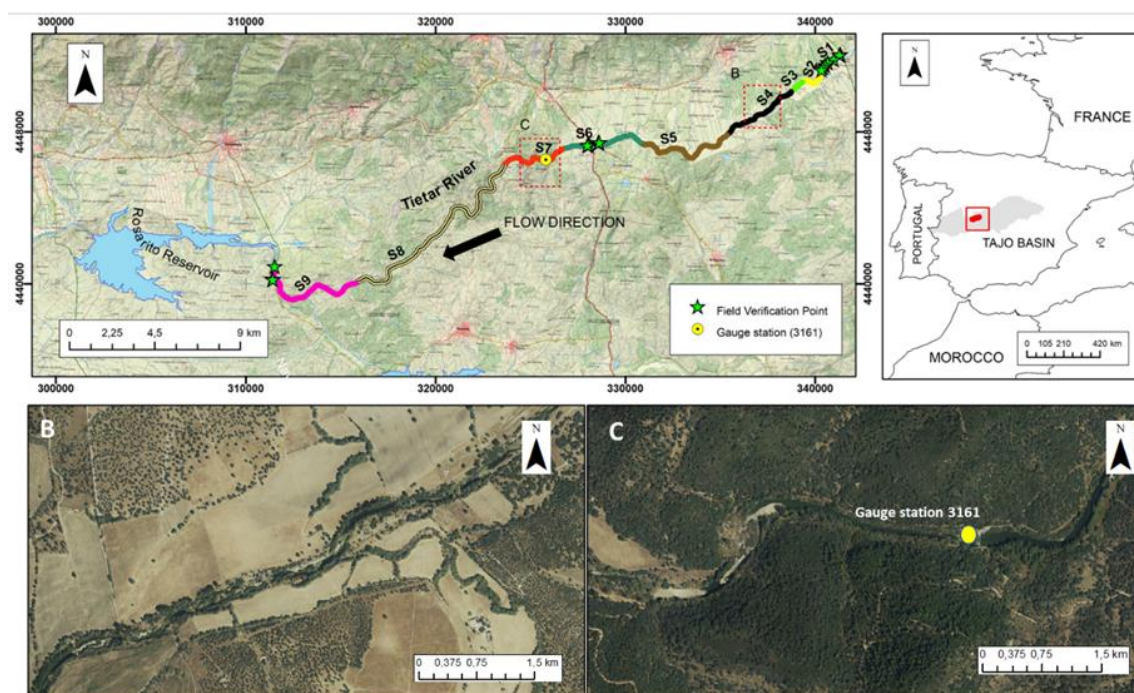


Figura 3. A. Localización geográfica del segmento de estudio dentro del río Tiétar en la cuenca del Tajo y localización de los segmentos fluviales y (B, C, D) imágenes aéreas del PNOA RGB 2019, incluyendo la estación de aforo (punto amarillo) y los puntos de verificación sobre el terreno (estrellas verdes).

2.2. MATERIALES Y MÉTODOS

En el proceso de realización de esta investigación se han utilizado diversos enfoques metodológicos, como el trabajo de campo combinado con el de gabinete, además de un gran trabajo en aplicaciones SIG, estadística y fotointerpretación. En la siguiente tabla (Tabla 2) se pueden observar las fuentes de datos utilizadas, así como los recursos de estas, que han servido de base para la consecución de muchos de los resultados obtenidos.

Tabla 2. Conjunto de datos utilizados durante los estudios realizados

Datos	Descripción	Web/enlace
Base de datos de Web Of Science (WOS)	Base de datos de publicaciones de la WOS	https://www.webofscience.com/wos/allldb/basic-search
1956 Vuelo Americano	Ortofoto en blanco/negro año 1956 (0,5-1 m)	www.ign.es
1998 Olisat ¹	Ortofoto en blanco y negro del año 1998, (1 m)	www.ign.es
PNOA ²	Ortofotos de máxima resolución (0.25 m) de los años 2009, 2014, 2017 y 2018.	www.ign.es
LiDAR-PNOA ³	LiDAR 1º cobertura, 0.5-1 puntos por m ² , y banda infrarroja cercana. LiDAR 2º cobertura, 1-2 puntos por m ² y banda infrarroja cercana. Años de los vuelos 2009 (Lozoya y Tietar), 2017 (Lozoya) y 2019 (Tietar)	www.ign.es

¹ mosaicos de ortofotos del vuelo OLISTAT Oleícola.

² PNOA: Plan Nacional de Ortofotografía aérea

³ proyecto PNOA-LiDAR.

2.2.1. RECOPIACIÓN DE DATOS

a. Obtención de la información bibliográfica

En el caso particular de la revisión bibliográfica cuyos resultados se presentan en el capítulo 3.1, se realizó una búsqueda sistemática en Web of Science. La información relevante de los estudios se recopiló de la bibliografía y se organizó en una base de datos. A continuación, se realizó un análisis cualitativo agrupando los estudios según factores abióticos que analizaban con relación al regenerado de los sauces, como por ejemplo factores edáficos e hidrológicos) y presiones, como por ejemplo la competencia entre especies, incendios o pastoreo. Cuando un estudio abordaba varios factores, se clasificó según el factor ambiental más destacado, y los factores que interaccionaban se discutieron en ese contexto.

b. Obtención de información geográfica

En esta tesis ha sido frecuente el análisis diacrónico de ortofotografías aéreas el cual se ha utilizado para describir y cuantificar los cambios geomorfológicos en los ríos estudiados. Concretamente, se han utilizado ortofotos de los años 1956, 1998 y 2018. Todas ellas están disponibles a través de bases de datos gubernamentales públicas (Tabla 2).

Junto con las ortofotos, los vuelos LiDAR fueron utilizados en diversos procesos para caracterizar la estructura de la vegetación de ribera. Por ejemplo, fueron utilizados para la obtención de árbol individual mediante la generación de cuenca individuales y realizar las mediciones forestales correspondientes.

En la siguiente tabla (Tabla 3) se muestra la Fuente SIG utilizada y la aplicación que se ha realizado en la presente tesis:

Tabla 3. Aplicación de los datos obtenidos

Datos	Aplicación
1956 Vuelo Americano	Fotointerpretación de formas del cauce
1998 Olisat	Fotointerpretación de formas del cauce
PNOA (con infrarrojo cercano del LiDAR)	Clasificación de imágenes mediante SCP (Semi-Automatic Classification Plugin) y Segmentación mediante MeanShift (MS) algoritmo. Fotointerpretación de formas del cauce.
LiDAR-PNOA	Generación de cuencas individuales. Cálculo de densidad de vegetación. Cálculo de otras variables dasométricas. Cálculo de modelo relativo de elevaciones.

Las fotografías aéreas se utilizaron para crear una base de datos espacial que permitieran caracterizar las distintas formas del cauce y conocer su evolución basándose en varios años con

información RGB disponible.

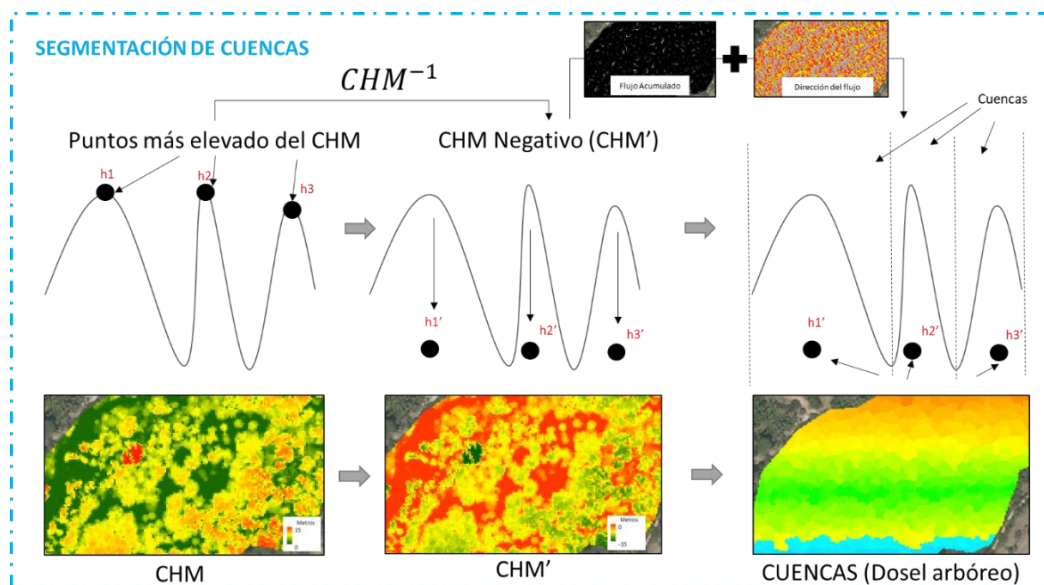


Figura 4. Ejemplo de segmentación de cuencas utilizado para el cálculo de las cuencas individuales que forma cada árbol formando parte del dosel arbóreo.

Por otro lado, y como fuente de información principal dentro de esta tesis, el LiDAR de la 1ª y 2ª cobertura fueron utilizados para estimar variables forestales dependientes del grado de evolución de masa arbolada presente en las riberas fluviales, como, por ejemplo, la densidad, la biomasa o la fracción de cabida cubierta, entre otros aspectos. Esta información LiDAR contiene la nube de puntos necesaria para construir el Modelo Digital del Terreno (MDT) utilizado para el cálculo del Modelo Digital del Terreno relativo al cauce principal, y para conocer el Modelo Digital de la Superficie (MDS) utilizado para obtener las cuencas individuales de los árboles o conjuntos de árboles que componen el corredor. La Figura 4 muestra como ejemplo el procesamiento de datos necesario para la obtención de las cuencas individuales que representa cada árbol. En el capítulo 3.4 este proceso se describe en detalle.

Todos estos recursos digitales se analizaron en un entorno SIG. El análisis SIG de la fotointerpretación se realizó con ArcMap de ESRI, la nube de puntos se trató con Global Mapper y LASTools, y finalmente algunos procesos y manejo de bases de datos con R (CITA de R).

c. Datos hidrológicos

En el caso particular del Río Tiétar, el régimen de caudales se analizó para el periodo 1968 a 2018. Para ello, se utilizaron los datos de la estación de aforos nº3161, situada aguas arriba del embalse de Rosarito (Figura 3), y disponible en <http://hercules.cedex.es/anuarioaforos/default>. El río Tiétar fluye con un régimen natural, y la descarga media anual de los últimos 50 años es de 6,8 m³/s, siendo 240,8 m³/s la media del caudal máximo anual y 0,1 m³/s la media del caudal mínimo anual.

En el río Jarama, se analizaron los datos de caudal medio diario de las estaciones de aforo (disponibles en <http://hercules.cedex.es/anuarioaforos/default>) más próximas a los tramos estudiados (Figura 1). En particular, se utilizaron los datos de la estación de aforo nº 3051 ubicada en el término municipal de Algete, Madrid para analizar los patrones de caudal

durante el periodo de estudio. Debido a que en esa estación de aforo la serie no estaba completa (faltaban datos del periodo 1949-1969), se estimaron a partir de la estación n° 3052 (Mejorada del Campo) situada varios kilómetros aguas abajo de la estación n° 3051.

d. Datos de campo

El trabajo de campo realizado en los capítulos 3.2, 3.3 y 3.4 sirvió para la toma de datos sobre vegetación de ribera y por otro lado para poder validar los modelos LiDAR estableciendo los errores medios cuadráticos de la medición predicha frente a la medición medida en campo

Entre otoño y primavera de los años 2019 a 2020 se realizaron varias salidas de campo para muestrear la vegetación de ribera siguiendo transectos perpendiculares al cauce donde se caracterizaba cada individuo con la distancia a la orilla, el diámetro a la altura del pecho y las zonas dinámicas de interacción vegetación-hidromorfología en la que se encuentran los individuos siguiendo a Gurnell et al. (2016). Esto es, cinco zonas laterales basadas en las limitaciones hidromorfológicas que suelen encontrarse en los ríos, donde la humedad del suelo, el régimen de perturbación del flujo y las interacciones de la vegetación ribereña son los elementos clave. Este muestreo se realizó dentro del Proyecto del Plan Nacional El declive de las saucedas arbustivas en ríos: causas, consecuencias e interacción con otras presiones (SAUCERES) en cuyo contexto se inició esta tesis.

Además, se localizaron hábitats adecuados para la colonización y establecimiento de plántulas, como barras de grava y arena. En los hábitats donde se encontraron plántulas, se establecieron parcelas experimentales (5-10 m²) en junio para evaluar la supervivencia de los brinzales hasta finales de septiembre. En cada parcela se contó el número de plántulas, se identificó cada planta a nivel de especie y se midió su altura (cm). Se indicó la presencia o ausencia de cubierta herbácea en el interior de la parcela, y el tamaño del sustrato.

En junio de 2021 se realizó una salida de campo al río Lozoya para muestrear 5 parcelas de vegetación arbórea que servirían para validar los resultados obtenidos en LiDAR. En estos muestreos se midió el n° de ejemplares, su diámetro a la altura del pecho y altura de los ejemplares dentro de la parcela circular de radio 15 metros con ayuda de un medidor Trupulse. Además, esta visita de campo también sirvió para observar los cambios generados tras la eliminación del azud, ya que se disponían de fotos antiguas con la presencia de esta infraestructura (Figura 5).





Figura 5. Imagen aguas arriba del Embalse de Pinilla del Valle, río Lozoya. Imagen inferior tras la demolición del azud.

Finalmente, en la primavera de 2022, se realizó una salida de campo al río Tiétar para validar los resultados obtenidos en LiDAR siguiendo el mismo procedimiento y mediciones que se hicieron en el año 2021 en el Lozoya (Figura 6).



Figura 6. Imagen de la ribera del río Tietar aguas arriba del embalse de Rosarito durante los trabajos de campo realizado en 2022.

2.2.2. ANÁLISIS DE LOS DATOS

a. Análisis hidrológico

En el caso del río Tiétar, se analizaron los caudales medios diarios para dos periodos temporales correspondientes a las décadas anteriores a las imágenes aéreas estudiadas y a un tercero intermedio. Es decir, se analizaron tres periodos en total, 1946–1956 (anterior a la primera foto aérea); 1962–1972; 2008–2018 (anterior a la última foto aérea). A partir de esta información se calcularon los caudales máximos, los caudales mínimos y los medios que servirían para discutir los resultados encontrados en el capítulo 3.4.

b. Digitalización y clasificación de las formas del cauce

-En esta tesis, se han empleado digitalizaciones manuales y clasificaciones automáticas de las distintas coberturas presentes en el interior del corredor ripario. En cada capítulo se detallan

las categorías diferenciadas y el método escogido, ya sea manual o automático.

En general se ha utilizado la superficie que ocupaba el cauce activo, es decir, la superficie cubierta por agua y sedimentos, en el año 1956 como superficie de referencia dentro de cuyos límites se procedió a analizar la evolución de las coberturas. Esta superficie ocupada por el cauce activo en 1956 se digitalizó manualmente. Las categorías o tipos de cobertura que se digitalizaron a continuación fueron en primer lugar el cauce activo como la superficie cubierta por la lámina de agua y las barras de gravas, en segundo lugar, distintos grados de cobertura de vegetación dependiendo del estudio concreto como por ejemplo “zonas parcialmente cubiertas por vegetación leñosa”, “pastizales”, o “zonas totalmente cubiertas por vegetación”. Y por último la categoría de zonas antropizadas donde se incluyen por ejemplo zonas urbanas o agrícolas. En cada capítulo se especifican y definen las categorías seleccionadas.

En el caso del río Jarama la digitalización de las distintas categorías fue manual. Sin embargo, en el caso del Río Lozoya se aplicó el complemento SCP (Semi- Automatic Classification Plugin) en el software QGIS 3.2.3. (Quantum GIS Development Team 2018). Esta clasificación semi-automática o supervisada clasifica las imágenes según su firma espectral mediante un entrenamiento automático utilizando regiones de interés (ROIs). Por último, en el caso del Río Tiétar,

se aplicó una clasificación automática, donde se extrajeron las características que definen cada objeto (Muñoz et al., 2019), concretamente se obtuvo la media y la desviación estándar para cada valor de característica y objeto. Posteriormente Se seleccionaron muestras de entrenamiento para cada una de las clases, cada conjunto compuesto por 100 objetos, lo que dio como resultado un total de 500 objetos en el conjunto de entrenamiento.

En resumen, las metodologías para el análisis diacrónico de ortofotos en esta tesis ha ido evolucionando desde la digitalización manual a la clasificación automática tecnificando el proceso, siendo más eficiente y capaz de considerar el error cometido.

c. Caracterización y evolución geomorfológica

Para conocer la situación geomorfológica actual y su evolución, se han aplicado diversos índices que permiten su cuantificación. Esta evolución geomorfológica temporal se ha realizado principalmente en el capítulo 3.2 sobre el río Jarama. En este caso, se calcularon la longitud del tramo (L), la pendiente (%), el área del cauce activo (AC), la anchura del cauce activo en m (ACW) y el índice de trenzado (BI) calculado como el número medio de canales medidos cada 25 metros por tramo, en cada año (Egozi y Ashmore 2008).

Además, se calcularon varios índices geomorfológicos que explican la tendencia y los cambios en las formas y dinámica del cauce (Figura 7). El cauce abandonado (Abandoned Channel) definido como la superficie ocupada por el cauce activo en una ortofoto anterior. El cauce común (Common Channel) definido como la superficie ocupada por el cauce en dos ortofotos consecutivas. El cauce nuevo (New Channel) definido como la superficie nueva ocupada por el cauce en una ortofoto no siendo cauce activo en la anterior.

Estas tres mediciones fueron utilizadas para extraer dos índices de movilidad fluvial el CMI (Channel Migration Index) (Sanchis-Ibor et al. 2019) y el ACC (Active Channel Change) (Richard et al. 2005). Ec. 1 y Ec.2 respectivamente.

$$CMI = \left(\frac{\text{New Channel} + \text{Abandoned Channel}}{\text{Common Channel}} \right) \quad (1)$$

$$ACC = \frac{\text{Active Channel (year2)} - \text{Active Channel (year1)}}{\text{year2} - \text{year1}} \quad (2)$$

ha/year

Las matrices de transición que tratan de analizar los cambios entre tipos de coberturas a lo largo del tiempo permiten conocer la evolución y cuantificar la intensidad de los procesos de sucesión, rejuvenecimiento, estabilización, antropización y naturalización. Esta metodología concreta fue utilizada en el capítulo 3.2. Para definir los tipos de cubierta se ha seguido a Corenblit et al. 2010.

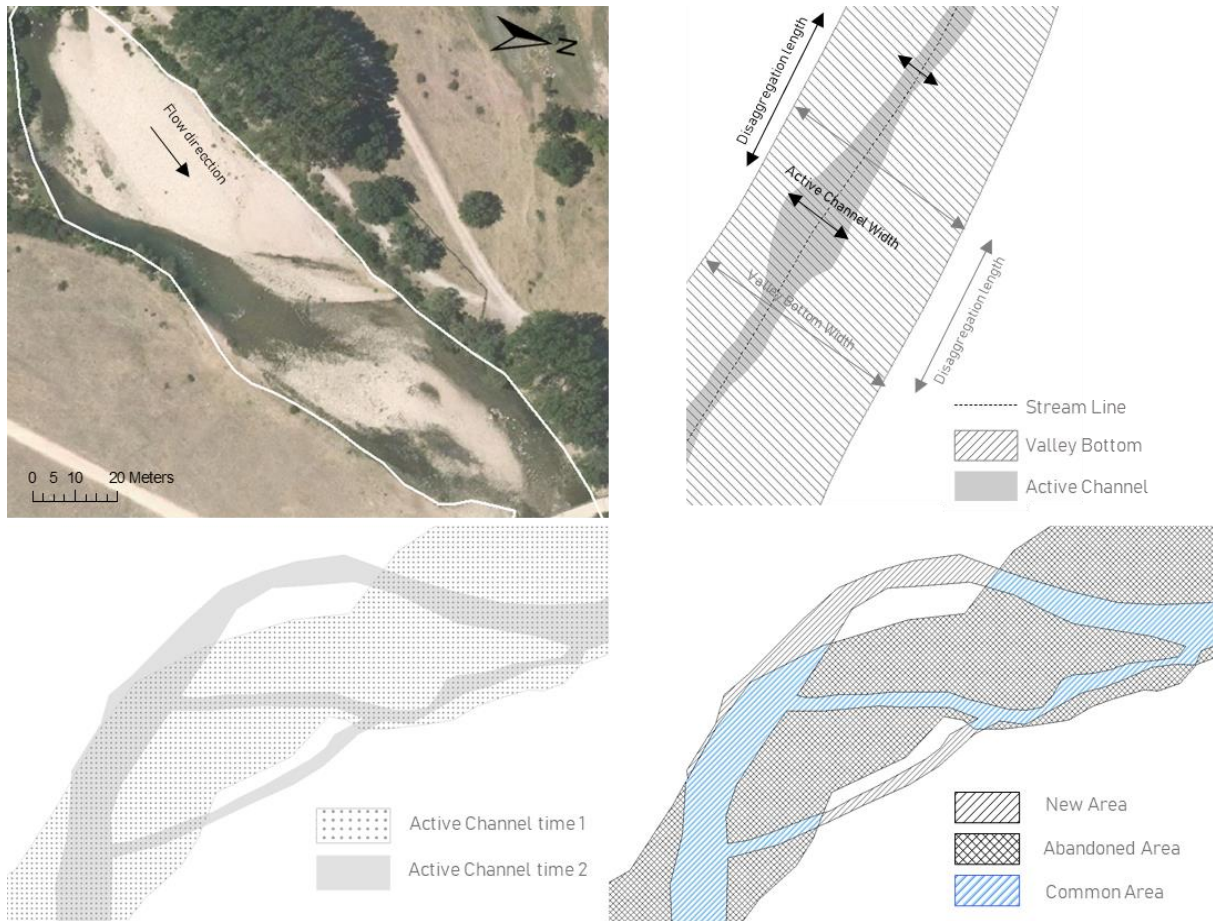


Figura 7. Variables geomorfológicas calculadas para la obtención de índices de movilidad fluvial.

d. Metodologías de tramificación de ríos

La búsqueda de tramos fluviales homogéneos mediante métodos estadísticos que permiten una discretización objetiva del sistema (e.g., Alber y Piégay, 2011; Martínez-Fernández et al., 2016) es una técnica que permite analizar la evolución de la vegetación de ribera considerando el tipo de tramo en el se encuentra. Este tipo de técnicas se aplicaron en el capítulo 3.4. Particularmente, se aplicaron procedimientos de permutación multirrespuesta (MRPP, Mielke, 1991; Orłowski et al., 1993) para segmentar el río utilizando el software R (R Core Team, 2019). La segmentación se basó en la anchura del fondo del valle y la pendiente del cauce, ya que estas variables proporcionan un contexto geomorfológico adecuado y son menos laboriosas que otras que requieren procedimientos manuales (Martínez-Fernández et al., 2019). El resultado permitió dividir los segmentos en tramos confinados y no confinados, que luego servirán de base para la diferenciación de la evolución geomorfológica y riparia.

e. Tratamiento de Modelos Digitales del Terreno

El cálculo de modelos de elevaciones relativas puede ser una técnica útil para el análisis de la configuración de las zonas ribereñas y pueden generarse utilizando distintos métodos. Concretamente, en el capítulo 3.4. el modelo de elevación relativa a la línea central del río se creó utilizando el método de distancia inversa ponderada (IDW), que se basa en la construcción de puntos, la extracción de valores múltiples a esos puntos, IDW y la resta según Coe (2016).

Posteriormente, el modelo de elevación relativa se reclasificó en rangos de altura como condición geomorfológica de gran importancia para la vegetación de ribera. Tras un análisis exploratorio de más de 50 tramos a lo largo de los segmentos fluviales, se identificaron tres rangos (0-1 metros, 1-2 metros y >2 metros), en los que se detectaron tendencias significativas (Figura 8).

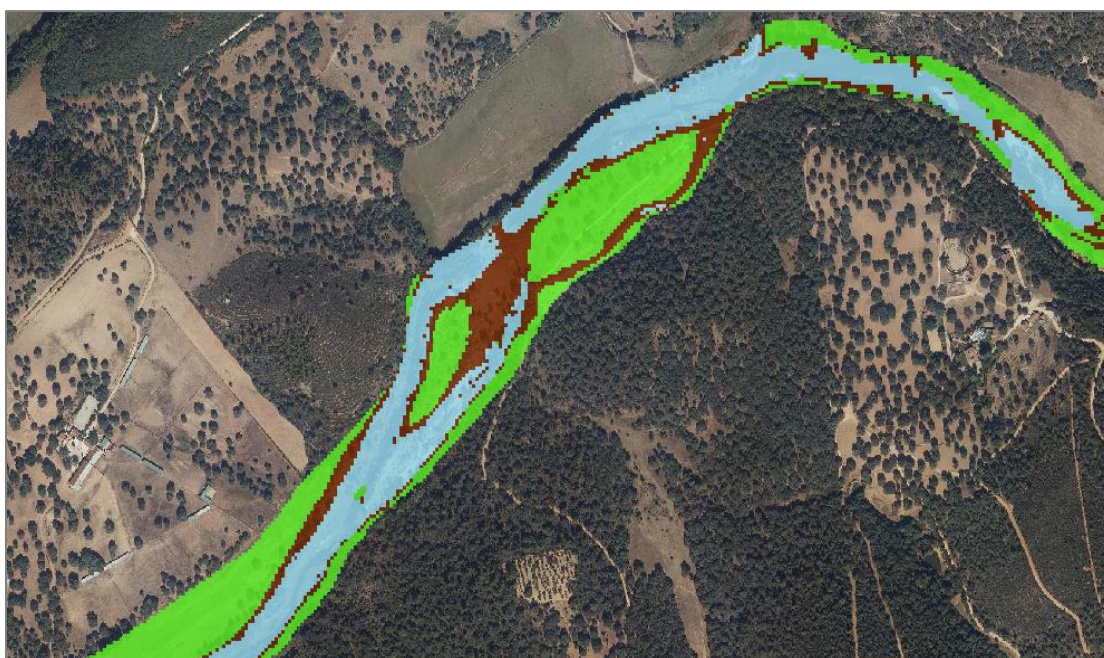


Figura 8. Ejemplo de modelo Digital Relativo de Elevaciones clasificado en 3 clases.

f. Metodologías para el análisis de la evolución de la vegetación

En el caso del capítulo 3.2, de los datos tomados en las parcelas experimentales se calculó la densidad total (número de individuos/m²), la altura media por especie dentro de cada parcela, la tasa de supervivencia (densidad septiembre/densidad junio) y particularmente cuando la tasa de supervivencia es superior a 1 el exceso correspondería al reclutamiento en verano. Además, se evaluó la capacidad edáfica de la parcela mediante el índice Freddle que cuantifica el tamaño de los espacios entre las partículas del sustrato.

Con base en los transectos de inventario de vegetación descritos en el apartado 2.2.1 (capítulo 3.2), en cada parcela se registró el número de plántulas, se identificaron las plantas a nivel de especie y se midió su altura en centímetros. Además, se anotó la presencia o ausencia de cobertura herbácea en el interior de la parcela y se registró el tamaño del sustrato. Tras la recopilación de los datos de campo, se calcularon la densidad total (número de individuos/m²) y la altura promedio por especie en cada parcela.

En cuanto al capítulo 3.3. la evolución de la cobertura de vegetación entre los años 2010 y 2016 fue medida a través del cálculo de cuatro variables: biomasa (tn/m²), altura (m), diámetro

(cm) y Fracción de Cobertura (FCC en %). El método de cálculo fue mediante obtención de alturas a partir de CHM (“Canopy Height Model” o Modelo Digital de Copas) y la aplicación de ecuaciones alométricas.

Finalmente, en el capítulo 3.4. la evolución de la estructura y cobertura de la vegetación entre los años 2009 y 2019 (vuelos LiDAR) se analizó aplicando metodologías de detección de árbol individual en una gran superficie (Tramo aproximado de 40 km) y además se introdujeron otras variables de gran utilidad para el conocimiento de la evolución de la vegetación riparia como el “Laser Penetration Index” (LPI) (Barilotti et al., 2006) como indicador indirecto de la densidad arbórea y la exposición a la luz, útil para evaluar la estructura del bosque de ribera. Los valores de este índice a lo largo del tiempo se analizaron en tres rangos de elevación relativa al cauce que incluye la componente transversal y proporciona información valiosa para el seguimiento del estado del corredor. Modelo Digital de Copas, cuya obtención se explica en el apartado siguiente, se puede estimar la altura del dosel de la vegetación (Pascual et al., 2010), pero también permite estimar la biomasa o el diámetro (Tesfamichael et al., 2010). Para calcular la altura dominante a resolución de píxel y la altura y densidad individual de los árboles, se generó el Modelo de Altura del Dosel (MCA) a partir de la sustracción del MDS menos el MDT en ArcGIS v 10.1 con un tamaño de píxel de 0,33x0,33 m. La altura dominante definida como el árbol más alto en una superficie determinada, en nuestro caso fue definida para el mismo tamaño de píxel que otras variables, 25 m².

2.2.3. METODOLOGÍA APLICADA A LA DETECCIÓN ÁRBOL INDIVIDUAL

Las nuevas tecnologías aplicadas al estudio de la vegetación en consonancia con las técnicas de inventarios tradicionales han hecho que el mundo de la teledetección y los SIG avance de manera rápida y precisa.

En la presente tesis se ha aplicado uno de estos métodos novedosos en dos de los estudios realizados (capítulos 3.3 y 3.4), aunque es el último el que incorpora mejoras y nuevas aplicaciones. Esta metodología está basada en el método de creación de cuencas a partir de máximos locales obtenidos del Modelo Digital de Copas (CHM a partir de aquí). Para poder calcular el CHM es necesario realizar un pretratamiento de la nube de puntos LiDAR que en este caso ha sido realizado en el software Global Mapper y LAStools, donde se extrae el Modelo Digital de Elevaciones (DEM) y el Modelo Digital de la Superficie (DSM), de los cuales se extrae el CHM (Figura 9). Para calcular el árbol individual se detectó mediante la segmentación de cuencas por morfología matemática (Beucher & Meyer, 2018) y se mejoró la precisión mediante con el algoritmo focal statistics (type = maximum as local maxima), que analiza cada celda contigua (es decir, dentro de un radio determinado, 3 metros de circunferencia y dependiendo también del tamaño del píxel, Niemann et al., 1999) en el ráster y calcula el máximo específico con la vecindad identificada. La capa resultante fue CHMmax. La cuenca de cada árbol se obtuvo calculando la inversa del CHMmax generando la capa CHMmax'. A partir del CHMmax', se calcularon la dirección del flujo y el flujo acumulado como pasos previos a la obtención de las cuencas del dosel arbóreo. En la figura 10 se puede observar el resultado de la obtención de las cuencas individuales, así como el CHM completo.

Finalmente, una vez obtenidas las cuencas de los árboles obtenemos la altura que servirá para obtener otras variables de interés como la altura dominante de la masa.

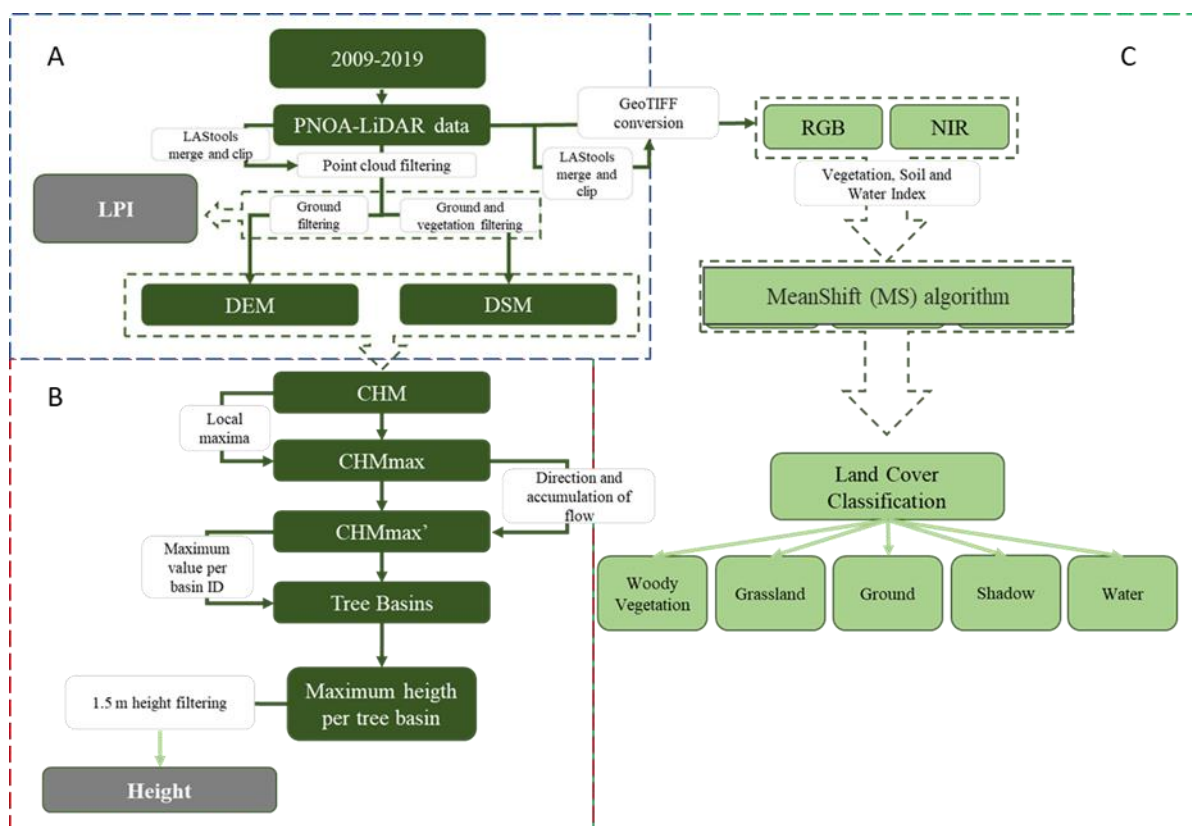


Figura 9. Metodología para analizar la estructura de la vegetación basada en la detección de árboles individuales (verde oscuro) y la clasificación de imágenes (verde suave).

A partir del RGB y el NIR de los vuelos LiDAR obtenemos los distintos índices que sirven de entrenamiento para clasificar la cobertura vegetal y realizar la segmentación (verde claro Figura 9).





Figura 10. Imagen superior corresponde a las cuencas individuales de los árboles, imagen inferior CHM en un tramo del río Tietar.

3.RESULTADOS

3.1. EL REGENERADO DE LOS SAUCES: HALLAZGOS EMPÍRICOS BASADOS EN UNA REVISIÓN SISTEMÁTICA.



3.1.1. SALIX REGENERATION IN FLUVIAL LANDSCAPES: EMPIRICAL FINDINGS BASED ON A SYSTEMATIC REVIEW

1. INTRODUCTION

The successful regeneration of many native riparian species is threatened in fluvial landscapes around the world. In the northern hemisphere, riparian forests are often composed of trees and shrubs belonging to two genera of the Salicaceae family, *Populus* (i.e., cottonwoods) and *Salix* (i.e., willows) (Malanson, 1993). Both genera play a crucial role in fluvial ecosystems of temperate zones, providing refuge to wildlife, nutrient resources, and shade that regulates the temperature for aquatic life (Cummins et al., 1989, Muhar et al., 2007). Moreover, most life stages of Salicaceae, from seedlings and saplings to fully established adults, act as ecosystem engineers creating landforms and mediating their trajectories (Gurnell, 2014) with the great advantage that members of this Salicaceae family reproduce easily vegetatively (Karrenberg, et al., 2002). While the genus *Populus* has been widely studied, in part due to its greater geographic range, *Salix* remains understudied. The lack of synthesised knowledge relating to the complex and specific requirements for *Salix* regeneration is a barrier to the effective management of riparian forests. Management practices to encourage *Salix* regeneration require an understanding of the breadth of factors influencing all phases of regeneration.

The genus *Salix* is diverse with an estimated 330 (Skvortsov & Tikhomirov, 1968) to 526 species (sensu Zhen-Fu, 1987). Species within *Salix* have physiological characteristics allowing them to colonise frequently flooded, saturated, and sun-exposed bars, making them well suited to riparian ecosystems (Blom et al., 1990, Karrenberg et al., 2002) where they interact with geomorphology to influence global diversity of fluvial ecosystems (Naiman et al., 1988; Tockner and Stanford, 2002; Gurnell, 2014). *Salix* species are currently threatened by pressures such as flow regulation, the reduction of annual mean flows, channel incision, and drought (e.g., Stella et al., 2013; González del Tánago et al., 2016; Martínez Fernández et al., 2017). A comprehensive understanding of the drivers of *Salix* recruitment is crucial to effectively restore and conserve *Salix* biodiversity and river functionality. A global review of *Salix* regeneration will also identify understudied factors to guide future research.

In this review, we examine both the abiotic factors driving regeneration of riparian *Salix* species, as well as pressures that may influence recruitment success. While abiotic factors may have a range of impacts on *Salix* recruitment and survival, we define pressures as conditions that make recruitment more difficult. These can be abiotic, such as fire disturbances or biotic, such as grazing or competition with invasive species. These might be anthropogenic in nature, such as climate change and invasive species competition, or naturally occurring, such as interspecific competition from native species.

The factors influencing *Salix* reproduction are of primary importance in predicting the effects of environmental pressures because they determine an individual's ability to colonize, establish and survive in a plant community. *Salix* regeneration occurs in the most dynamic places within the riparian ecosystem (Mahoney and Rood, 1998; Friedman and Lee, 2002) under such specific fluvial geomorphic conditions that years may pass without large-scale regeneration (Mahoney and Rood, 1998, Stromberg, 1998; González et al., 2018). Consequently, riparian forests are commonly composed of mosaics of relatively even-aged cohorts that established in favourable years (Johnson et al., 1976). Within this dynamic context, other abiotic and biotic factors influence *Salix* recruitment and survival, to the extent that they may alter the succession of riparian vegetation. For example, summer dry conditions cause high mortality rates of seedlings, while flood disturbances create bare areas that are the optimum areas for the regeneration of these species.

Current anthropogenic threats to fluvial systems, such as flow regulation (e.g. Williams and Wolman, 1984; Nilsson and Berggren, 2000; Petts and Gurnell, 2005), land use and land cover changes in river basins (e.g., Kondolf et al., 2002; Liébault et al., 2002), invasive plant introductions (e.g., González et al., 2017; Bruno et al., 2019), and more recently climate change (e.g., Seavy et al., 2009; Capon et al., 2013; Martínez-Fernández et al., 2018) directly alter the vegetation inhabiting fluvial systems. *Salix* regeneration is particularly sensitive to these changes, resulting in declining populations (Coble and Kolb, 2013). Given the specificity of regeneration requirements along with these anthropogenic threats, riparian plant communities will likely give way to terrestrial or later successional communities resulting in a loss of biodiversity and riparian habitat (e.g., Bejarano et al., 2011, Martínez-Fernández et al., 2017).

In this review, we provide a global synthesis of *Salix* recruitment requirements from the scientific literature and identify current gaps in the body of knowledge. We focus on abiotic factors and pressures (both anthropogenic and naturally occurring) that influence the regeneration phases of this genus because of the fundamental role *Salix* spp. play in the functioning of river ecosystems.

2. METHODOLOGY

2.1. Selection of articles

An exhaustive systematic literature search was done in ISI Web of Science on March 1st, 2020, using the following chain of keywords “(salix OR willow) AND (recruit* OR regener* OR mortality) AND (river OR riparian OR floodplain OR stream) NOT (coast* OR estuar* OR mangrove OR tidal)”. The search was done for the period 1990-2019 and yielded 303 articles, which were evaluated for inclusion using the following criteria. To be included the study had to: i) deal with riparian ecosystems and the regeneration of at least one *Salix* species, ii) analyse *Salix* regeneration either in its natural context, experimentally in the field, or ex situ (i.e., laboratory or greenhouse) under controlled conditions, iii) consider the germination and establishment of either seed or cuttings, and iv) have been written in English and published in SCI indexed journals. We limited our search to the scientific literature as we considered screening technical reports globally unfeasible. Thus, a total of 61 articles were ultimately included in the review (Appendix S1).

2.2. Information extraction

Relevant information regarding study details was extracted from the literature and entered into a database (Table 1). We then conducted a qualitative analysis of the studies, grouped by the abiotic factors (i.e., soil factors, hydrologic factors, etc.) and pressures (i.e., species competition, fire disturbance, grazing, etc.) that emerged from the literature as the most relevant to *Salix* regeneration.

When multiple factors were dealt with in a single study, all factors are considered but the study appears in relation to the most prominent factor. For example, some authors study the influence of flow regime, which ultimately affects soil moisture on *Salix* recruitment. In such cases flow regime is considered a hydrological factor because the main focus is hydrological. Similarly, water table level and the elevation where seedlings germinate are related and often studied together. For that reason, papers may be discussed in sections other than the one that they were categorised in.

Table 1. Categories and descriptions of information extracted from the papers.

Category	Description
World region	The world region where the study was carried out, i.e., continent and country.
Motivation	The main motivation or purpose of the publication. -<u>Basic science</u>: the primary aim was to contribute to the knowledge of the topic from its own sake without an applied objective. -<u>Applied science</u>: practical benefits of the acquired knowledge were obtained. - Subcategories: conservation, restoration and climate change adaptation.
Species	The name of the <i>Salix</i> species analysed (if species was not differentiated in the paper <i>Salix</i> sp. was entered).
Type of study	-<u>Field study</u>: data collected from the field without intervention. -<u>Field experiment</u>: data collected from the field with intervention (e.g., seeding or planting). -<u>Lab experiment</u>: data collected from laboratory experiments (e.g., viability tests carried out on seeds). -<u>Greenhouse experiment</u>: data collected from seedling germination or establishment and sapling growth in the greenhouse.
Regeneration step	The regeneration step that was studied: seed availability, seed dispersal, seed entrapment, seed germination and establishment, seedling growth, survival and mortality, sapling growth and mortality, and cutting establishment and growth.
Factor	The abiotic and biotic factors related to regeneration that were included in the study (e.g., soil moisture, light, altitude, etc.).
Pressure	The environmental pressures that are studied relating to regeneration, when applicable (e.g., dam construction and flow regulation, invasive plants competition, etc.).

3. GLOBAL OVERVIEW OF SALIX RECRUITMENT STUDIES

3.1. Geographical distribution of studies

The majority of *Salix* regeneration studies came from North America (57 %), followed by Europe (28 %) and Asia (9 %), with South America and Oceania making up the remaining 6 % (Figure 1). By country, the United States was the largest contributor of *Salix* regeneration papers with 53 % of the total number, followed distantly by Spain (7 %), Germany (5 %), France (5 %), and Japan (5 %).

The high number of publications in the United States and European countries aligns with the broader increase in riparian research (Figure 2) and the increased recognition by the scientific community of the services riparian willows provide and their vulnerability to global change. This trend may be a result of the environmental policies on the rise in these countries. In the case of European countries, the Water Framework Directive (WFD; 2000/60/EC 23 October

2000) has provided an incentive for environment and water research (Teodosiu et al., 2003, Voulvoulis et al., 2017). In the case of the United States, some specific programs encourage the study of riparian zones, such as AREMP (USFS Aquatic and Riparian Effectiveness Monitoring Program), the Regional Interagency Monitoring for the Northwest Forest Plan, and others included in their Environmental Plans (Ohmann and Gregory 2002, Reeves et al., 2003).

3.2. Main purpose of studies

Basic science was the main purpose of the majority of studies worldwide (56 %) (Figure 1 and 2). Studies about the regeneration of willows with restoration motivations was the second most frequent type (22.5 %), which denotes the growing desire to recover fluvial ecosystems that have been degraded or damaged by human action. Studies with conservation objectives represented 17.1 % of studies. The studies that dealt with the regeneration of willows under future scenarios of climate change were scarce (4.3 %) and concentrated in North America.

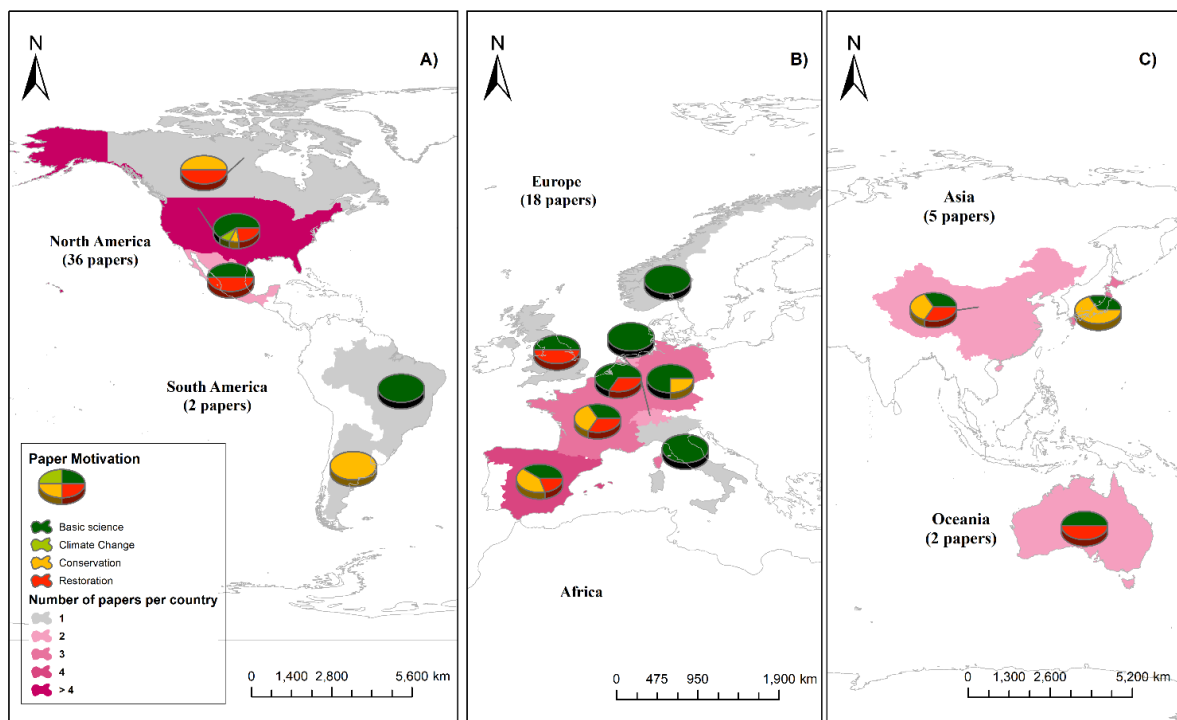


Figure 1. Spatial distribution of papers about *Salix* regeneration by world regions and countries and proportion of types of studies in each country and region. Panel A refers to the Americas, B refers to Europe, and C refers to Asia and Oceania.

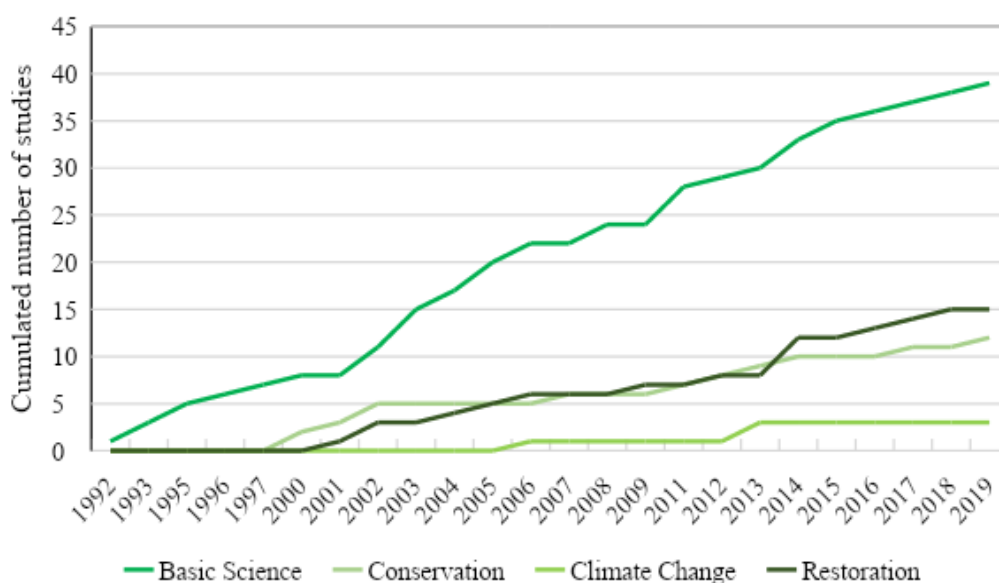


Figure 2. Temporal evolution of the number of papers dealing with *Salix* recruitment by the main motivation of the studies.

3.2. Global distribution of *Salix* species studied

Studies were conducted in five continents: South America, North America, Europe, Asia, and Oceania. In all of the continents where research has been carried out, *Salix* is a native genus except in Oceania, specifically Australia, where it is considered an invasive species. Studies covered 35 *Salix* species (the complete species list is shown in Appendix S2). Sixteen percent of papers did not identify *Salix* to species (Figure 3). The most frequently studied species was *S. alba*, which is native to Europe, Asia, and North of Africa (GBIF.org, 2021). The second most studied species were *S. exigua*, *S. gooddingii*, and *S. nigra* (native to North America; GBIF.org, 2021), and *S. viminalis* (native to Europe and Asia, and considered invasive in America, UK and Australia; GBIF.org, 2021). Of the 35 *Salix* species studied, 24 were studied in only one or two papers, revealing a lack of replication of studies for these species (Figure 3).

North American studies included the highest number of different *Salix* species (17). *S. exigua*, *S. nigra*, *S. atrocinerea*, and *S. monticola* were the most frequently studied species in this region (Appendix S2; note that two of the studies dealing with *S. exigua* have been recently described as *S. interior*). With 91 species present in North America (Zhen-Fu 1987), the studied species represent only approximately 19 % of the total species. In Europe there are 65 native *Salix* species (Tutin et al., 1980) but only nine species (~14 %) have been studied (*S. fragilis*, *S. purpurea*, *S. alba*, *S. criminalis*, *S. atrocinerea*, *S. salviifolia*, *S. triandra*, and *S. eleagnos*). In Asia the regeneration phase of five *Salix* species have been studied (*S. integra*, *S. pet-sus*, *S. gigliana*, *S. sachalinensis* and *S. variegata*) which represents a negligible proportion (~1 %) of the total number of *Salix* species present on this continent (375 *sensu* Zhen-Fu, 1987). Four out of the 5 species have been studied exclusively in Asia. *S. variegata* has been studied in North America as well as Asia.

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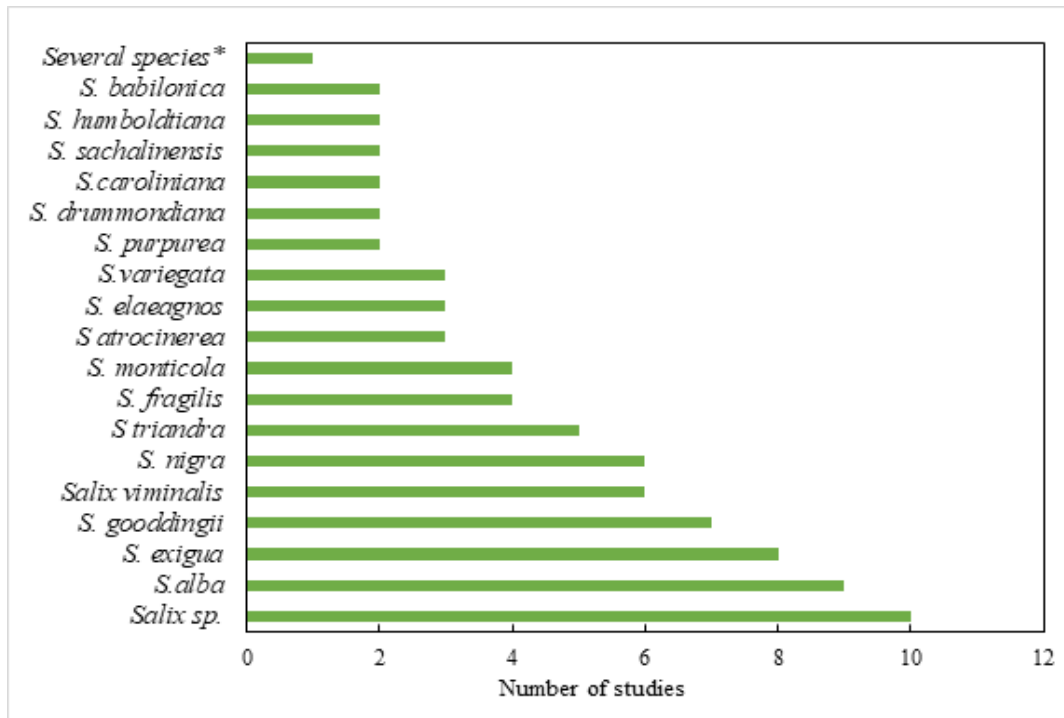


Figure 3. Number of studies carried out for each *Salix* species. *Salix sp.* means that the species is not mentioned in the paper and the genus is analysed as a group. *Species occurring in only one study and not shown individually in the figure.

3.4. Distribution of study type

Globally, most studies were field studies (46 %), followed by greenhouse experiments (24 %). Lab and field experiments account for 14 % and 16 % of studies respectively (Figure 4). Most of the field studies were carried out in the U.S. (61 %), followed by Spain (12 %). Japan and Australia had 2 field studies each. Greenhouse experiments were more prevalent in the U.S., followed by the Netherlands.

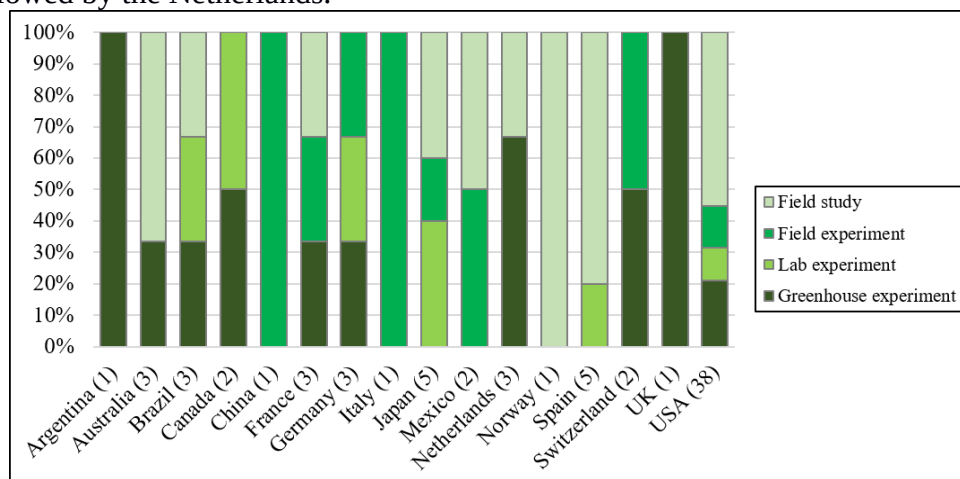


Figure 4. Percentage of the different types of study by country. Number in parentheses after each country represents the total number of studies conducted in that country. Note that there could be more than one type of study in a single article.

4. Influence of abiotic factors on *Salix* regeneration

Across all the studies included in this literature review, we found a total of 19 abiotic factors. We grouped these factors into 4 categories for simplicity of interpretation: soil factors (e.g., soil moisture, nutrient content; 72 % of studies), hydrological factors (e.g., flow regime, shear stress; 56 % of studies), atmospheric factors (e.g., aerial temperature, light exposure; 27 % of studies) and lastly, surface factors, a set of varied factors such as spatial distribution and geomorphologic dynamism (53 % of studies) (Figure 5). Soil moisture and flow regime were the most frequently explored categories, with 22 and 21 studies respectively. These are followed by water table level (13 studies), elevation above the stream channel (13 studies), and the consideration of the spatial distribution within the gravel bar (12 studies). Less frequently studied factors were interstitial temperature (in the soil category); precipitation, relative humidity, wind and CO² atmospheric (in the atmospheric category); shear stress (in the hydrological category); and geomorphologic dynamism (in the category of surface factors).

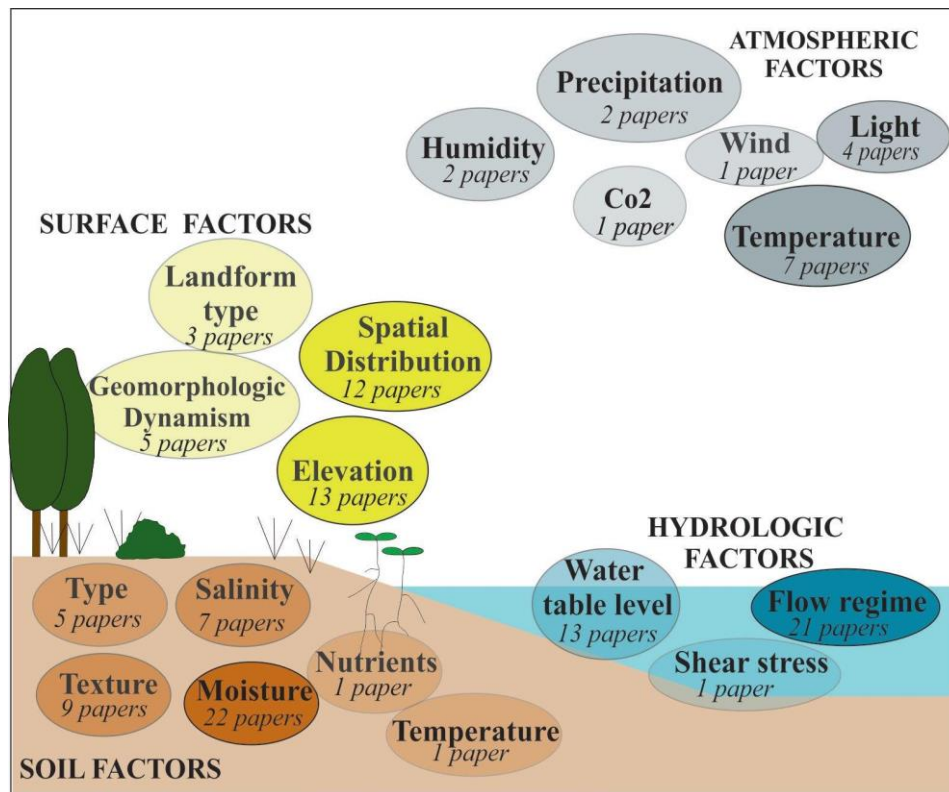


Figure 5. The frequency of abiotic factors empirically studied in relation to *Salix* regeneration, coloured by category: soil factors, hydrologic factors, atmospheric factors and surface factors. The darkness of the background colour represents the frequency of study, with darker backgrounds representing more studies and lighter backgrounds representing fewer.

4.1. Soil factors

Within the soil factors category, soil moisture, nutrient content, texture, salinity and interstitial temperature were most commonly considered important in the early stages of *Salix* regeneration (e.g., Merrit and Shafroth, 2012, Chen et al., 2013, Asaeda et al., 2015, Castro-Morales et al., 2014, Gorla et al., 2015; Figure 5).

Soil Moisture

While soil moisture was most frequently studied in the field, either under natural or experimental conditions, we also found instances of laboratory or greenhouse experiments that sought to control some additional abiotic factors at the same time as soil moisture. The relationship between *Salix* regeneration and soil moisture was often studied in the context of decreasing moisture following a flood, either real or simulated.

Overall, the findings were of a positive relationship between soil moisture and regeneration at all stages. For example, in the Kurobe River (Japan), flooding with a high degree of sediment runoff led to a decrease in sediment particle size and a corresponding increase in soil moisture (Asaeda et al., 2015). One year after sediment release, a large number of seedlings of *S. gilgiana* were recruited on the bar, with a high relative abundance (87 %). In another example looking specifically at *Salix* recruitment, Chen et al. (2013) showed experimentally that germination rates of *S. variegata* improved with increasing soil moisture content, reaching the highest value with moisture-saturated, sandy soils while no germination occurred below 5 % of water content. A combination of experimental and observational methods in Arizona demonstrated that a lack of soil moisture was the main cause of mortality for seedlings of *S. lasiolepis* during the first two years after germination (Sacchi and Price, 1992).

One study demonstrates that species differ in their response to varied levels of moisture. Through a combination of field and laboratory experiments, Van Splunder et al. (1995) showed that soil moisture levels had a varied effect on three *Salix* species (*S. triandra*, *S. alba* and *S. viminalis*). After germination trials developed on sand with different moistures, *S. viminalis* was found to be the most drought-tolerant species, followed by *S. triandra* and *S. alba*.

Castro-Morales et al. (2014) showed that while higher moisture levels encourage *Salix* regeneration overall, timing also matters. Growth chamber experiments allowed the authors to test varied watering regimes in addition to conducting a gradient. They found that a delay in watering (8 days) significantly reduced the germination of seeds of *S. caroliniana* that otherwise would quickly germinate after being sown in saturated soils.

Vegetative reproduction in *Salix* spp. is also influenced by soil moisture. Using a field experiment, Gorla et al. (2015) showed that mature cuttings of *S. viminalis* (1-year-old) were not affected by water table dynamics, while juveniles (around 3-months old) were strongly impacted by the minimum water level with an important reduction in biomass (~60 %). In this case, the water level was used as a proxy for soil moisture. An experimental field study carried out in the Río Negro (Argentina), examined the effects of both soil moisture and vegetative reproduction of two invasive willow hybrids on the regeneration of the only native species in the area, *S. humboldtiana* (Thomas et al., 2012). The results of this study showed that increased moisture led to an increase in survival, growth and biomass of cuttings in all three *Salix* species with the invasive species performing better than the native one.

Other Soil Factors

In addition to soil moisture, several other soil factors have been studied in terms of their effect on *Salix* regeneration, such as nutrient content, salinity, texture and interstitial temperature. There are often interacting effects among these soil factors. For example, Day et al. (2006) measured growth rates of *S. nigra* seedlings under the interactive effects of substrate (peat vs. sand), nutrients (fertilised vs. unfertilized), and hydroperiod (permanent vs. periodic flooding). They found that growth was higher in peat substrates and in fertilised soil that was

also well drained. In a field experiment in Cedar River Iowa, USA, seedling density of *S. interior* and *S. nigra* was shown to be moderately associated with the fine sediment texture. This study also found that seedlings established mainly in a very narrow band of sediment produced as a result of water dispersal (Craig and Malanson, 1993). Similarly, along the Snake River (Oregon, Idaho and Washington, USA), Rood et al. (2011) showed that *S. exigua* establishment primarily occurs in association with alluvial sand deposits where seedlings emerged from interstitial sands between cobbles and gravels.

The soil salinity content can also be a limiting factor for the regeneration of *Salix*. This is of particular importance in areas of the southwestern United States where an invasive tree (*Tamarix* spp.) increases soil salinity (Merrit and Shafroth 2012). By measuring changes in soil salinity and nutrient content over time in riparian plant communities dominated by *Tamarix*, Merrit and Shafroth (2012) showed that *Tamarix* can in fact reduce and inhibit the germination of *S. gooddingii* and *S. exigua* seeds by changing soil salinity.

Based on our literature review, we can draw several conclusions regarding the influence of soil properties on *Salix* regeneration that could be considered before any management initiative. First, water-saturated soils and abundant water in general stimulates germination and establishment for the seeds of *Salix* species (Van Splunder et al., 1995; Chen et al., 2013; Asaeda et al., 2015; Castro-Morales et al., 2014). Second, well fertilised, sandy soils including soil types with interstitial sands between cobbles and gravels increase germination and growth rates (sensu Craig and Malanson, 1993; Day et al., 2006; Rood et al., 2011; Chen et al., 2013; Asaeda et al., 2015). Conversely, water scarcity (i.e., low flows conditions) and high salinity conditions dramatically reduce seedling growth and germination (Merrit and Shafroth, 2012; Gorla et al., 2015).

4.2. Hydrological factors

Flow regime and water table levels are the most studied hydrologic factors in the literature. It is worth mentioning that all water conditions ultimately affect soil moisture and texture, but as previously explained, the factors described in this section are considered hydrologic because the main variables that authors measured are of this type.

Flow Regime

Because *Salix* spp. are specially adapted to hydrological disturbances, the flow regimes of rivers and the subsequent alterations of river morphology are arguably the most important factors in the recruitment of these riparian pioneer species (Karrenberg et al., 2002). Maximum discharge periods scour riverbanks and deposit sediments creating colonisation sites for seedlings. Minimum discharge periods allow for growth and establishment of seedlings and saplings. In this way, all aspects of the flow regime, both extreme events and moderate flows are important in *Salix* recruitment, particularly in terms of seedling growth and mortality. This presents a particular challenge for management of riparian forests given the ubiquity of anthropogenic flow alterations world-wide. However, our findings can be used to guide water releases from dams and alterations to river morphology that may be a part of a management plan.

The results of several field studies showed that *Salix* spp. produce a large number of seedlings, particularly after a large flood event, but have a very high seedling mortality (90 % or higher at the end of the first year; *Salix* spp. - Johnson, 2000; *S. nigra* and *S. exigua* - Dixon, 2003; *S. gooddingii* - Stromberg 1993). The high seedling mortality is a result of three main

environmental factors: high streamflow in early summer, river bed transformation by ice in winter and desiccation during summer dry periods. In the southwestern U.S. on the Hassayampa river, Stromberg et al. (1993) showed that seedling mortality has a threshold-type response, with a sharp increase where water is higher than 1.5 m deep. Stromberg et al. (1993) also examined survivorship as a function of shear stress during a 10-year return flood event and found no significant relationship.

The required flood regime may vary depending on the species of *Salix* under study as well as the type of reproduction. For example, Miao et al. (2016) found that *S. variegata* was particularly tolerant to several periods of winter submersion, making it a useful species for revegetation along a tributary of the Yangtze River (China). Additionally, in four rivers distributed in the southeast of Australia, Stokes and Cunningham (2006) found that the occurrence of peak flow disturbances favoured vegetative reproduction of willows.

Location within the floodplain was identified as an important factor in several studies because of how it mitigates the impact of flooding. Galuszka and Kolb (2002) showed that in a free-flowing perennial stream, germination and establishment of *Salix* spp. were promoted by high winter and spring flows and that the active channel was the preferred location for *Salix* recruitment. Few seedlings occurred in areas that were not as hydro-geomorphically active, such as abandoned channels, gravel-boulder bars, and bench locations. However, seedling mortality tended to be higher at lower elevations which experience a greater inundation depth and duration (Pasquale et al., 2014; Stokes, 2008). This trend was found in areas where *Salix* is native (Pasquale et al., 2014) as well as along the shorelines of the Blowering Dam in Australia, where *S. nigra* is considered an invasive species (Stokes 2008).

The influence of other abiotic factors on *Salix* recruitment may be altered by flow regime. In Day et al. (2006) hydroperiod (i.e., permanent flow versus periodic flooding) interacted with nutrient levels to influence *Salix* seedling growth. Specifically, under well drained conditions, fertilised seedlings of *S. nigra* grew better than unfertilized seedlings. Under flood conditions, however, there was no effect of fertilisation on biomass. Given that this was the only study we found looking specifically at interacting abiotic factors, there is a large gap of knowledge in how flow regime changes the impact of other abiotic factors on recruitment.

An additional way that *Salix* is adapted to flow regime is through seed morphology. Seiwa et al. (2008) found a positive effect of cottony hairs of *Salix* seeds in their dispersion by water. Seeds with cottony hairs, particularly from *S. sachalinensis* and *S. integra*, floated for more than six days on the water surface substantially increasing successful establishment, whereas all seeds without cottony hairs sank rapidly in the water. Their results showed that cottony hairs promote seed dispersal over water surfaces over longer distances.

Drought periods

In addition to high flow frequency, drought periods also affect *Salix* recruitment and growth patterns. For example, Sacchi and Price (1992) observed that *S. lasiolepis* seedlings in Schultz Creek (Arizona, USA) were vulnerable to drought periods and that 9-days without precipitation was enough to cause drought on the soil surface and plant death. The physiological response to drought conditions varies by species. In a greenhouse experiment, Van Splunder et al. (1996) showed inter-species variation in root depth in response to drought conditions. Drought caused *S. triandra*, *S. alba* and *S. viminalis* to develop a deeper rooting system, with *S. viminalis* and *S. triandra* developing the deepest root system. They concluded that *S. alba* would be the most drought resistant species among the *Salix* species here studied, due to a 40 % lower rate of transpiration, followed by *S. triandra* and *S. viminalis*. This type of study and finding can be

used to select *Salix* species most appropriate for revegetation under specific environmental conditions or to identify particularly vulnerable species under changing conditions for conservation.

Water Table Rate of Decline

The rate of water table decline following a high flow period is important in determining seedling growth and survival and was the specific focus of several studies. Seedling growth and survival of *S. gooddingii*, was studied by Horton and Clark (2000) in a greenhouse experiment using seeds collected from natural populations along the Hassayampa and Bill Williams rivers (U.S.A.). The experiment simulated water table declines at different rates to explain how this affected growth and survival of seedlings. Willow seedlings performed best in the 0 cm/day rate (i.e., no water table decrease), in which the soil was saturated and showed decreasing survival and growth with increasing rates of water table decline. A comparative experiment between tolerance of willows (*S. exigua* and *S. drummondiana*) and poplars to water table decline was carried out by Amlin and Rood (2002). This experiment concluded that abrupt water table decline reduces the recruitment of willows. For this reason, authors recommend a gradual stream stage recession along regulated rivers to promote shoot and root growth. Field experiment carried out by Rodríguez-González et al., 2017 suggest similar results than other previous authors, in which an abrupt change in phreatic level are related with an increase of *Salix atrocinerea* mortality.

While many of the studies we found revealed *Salix* spp. to have very specific requirements for the timing of high flows, the rates of water table decline and drought tolerances, this was not the case for all species. In a greenhouse experiment using rhizopods to simulate water table declines and flood conditions, Francis et al. (2005) showed that cuttings of *S. eleagnos* are adapted to a wide range of rates of water table decline and could tolerate a wide range of drought and flood conditions. Such a finding has important implications for the success of revegetation projects. As more species are tested for their range of tolerances, managers will have a better sense of species likely to survive after planting in uncertain conditions.

In general, the author's findings suggest that there is a negative effect of high floods during the establishment period on *Salix* recruitment (Johnson, 2000; Dixon, 2003; Pasquale et al., 2014). Additionally, low summer stream flows which lead to drought periods dramatically increase seedling mortality (Sachii and Price, 1996; Van Splunder et al., 1996; Johnson, 2000; Schaff et al., 2002). However, some species are more resistant to drought than others such as *S. alba* (Van Splunder et al., 1996) and *S. eleagnos* (Francis et al., 2005). On the other hand, high floods before the dispersal period favour seedling recruitment by the formation of bare areas where *Salix* seeds can easily germinate and cuttings can easily establish (Galuszka and Kolb, 2002; Miao et al 2016). Although seedlings are sensitive to drought, cuttings appear to have a greater tolerance than seedlings to these conditions (Francis et al., 2005). Finally, seedling growth rate tends to be slower in flood zones (e.g., *S. nigra* in Day et al., 2006; Stokes, 2008). This information can be used to select species for revegetation, as well as to incorporate strategies to compensate for unfavourable environmental conditions into management planning.

4.3. Surface-related factors

Elevation, spatial distribution, and landform typology are the most frequently studied surface-related factors in relation to *Salix* recruitment. The elevation above the stream channel may determine the availability of soil moisture and soil saturation, which are strong drivers of willow establishment as described above. The spatial distribution (e.g., location on gravel bars

or sand bars) and landform preference of seedlings, saplings, and cuttings also determines recruitment success. For example, drought tolerant species could survive at higher elevations than drought intolerant species. The combination of both spatial distribution and elevation above the stream creates a multidimensional spatial reference that is frequently studied in the scientific literature and provides a valuable guide for restoration and management.

Elevation above water channel studies

A consistent trend in the literature was that seedling and cutting establishment was most successful at low to moderate elevations above the water channel. Along the Drome River (France), Barsoum (2002) showed that *S. alba* seedlings occurred most frequently at an elevation above the channel between 0.2 and 1.4 metres, reaching their maximum between 0.5 and 0.8 metres. Barsoum (2002) provides further support for the idea that cuttings have a wider range of abiotic tolerances. In this study, cuttings established between 0.2 and 2 metres with maximum abundances reached between 0.8 and 1.1 metres. This study also showed that at low elevation microsites *S. alba* seedlings primarily colonise sediment-filled depressions and to a lesser degree side-channel edges while at higher elevations colonisation is confined to sediment-filled depressions (Barsoum 2002). Parolin et al. (2002) showed that in the Amazonian floodplains, *S. humboldtiana* primarily colonised low elevation sites characterised by long periods of inundation and large sedimentation rates. Magdaleno et al. (2014) showed that in three Mediterranean rivers, *S. salviifolia* preferentially colonised lower areas of the topographic gradient, particularly for the range between 0.5 and 1.5 metres above water level. Asaeda et al. (2015) showed that *S. gilgiana* also prefers the lowest areas of sand bars (average elevation $0.8 \pm 0.5\text{m}$). Studies comparing elevational preferences of several species are scarce. For example, Craig and Malanson (1993) found that more than 95 % of seedlings from four species (among them *S. nigra* and *S. interior*) colonised the lowest part of the bars. Van Splunder et al. (1995) showed that, along an elevation gradient, seedlings of *S. viminalis* were found at a higher elevation (20 cm higher) than *S. alba*.

Several field experiments also support the observational findings of greater recruitment success at lower elevations relative to the river channel. In a field experiment carried out in Colorado (USA), Roelle et al. (2001) examined the importance of the location of a disturbed and wetted edge to the successful establishment of three pioneer species, including *S. amygdaloides* and *S. exigua*. The authors divide the potential surface for the establishment of *Salix* species into 3 zones: zone 1 was located above the highest water level, zone 2 was completely inundated with the highest flood, and zone 3 was made up of all the plots located below zone 2. They found that seedling density was higher in zone 2, where a wetted edge was present during the period of seed fall but was not permanently inundated, supporting the idea that intermediate elevations above the water channel facilitates seedling germination. Similarly, a field experiment using artificial islands in the Blue Cypress Water Management Area (Florida, USA) evaluated the tolerance of *S. caroliniana* cuttings and seedlings to flooding events based on their elevation (Quintana-Ascencio et al., 2013). They showed that survival was constant over time with the highest mortality associated with flooding, except for seedlings at the highest elevation (0.5 metres), which had higher initial mortality due to the pre-flood dry period.

Elevation above the water channel interacts with soil factors to influence *Salix* recruitment. In the Snake and Salmon Rivers in the states of Colorado and Idaho (USA), Rood et al. (2011) showed a wider range of elevation for seedling recruitment, but a similar pattern of seedlings favouring lower elevations. In this study seedlings established 0.2–5.5 m above stream channel, with greater density at 0.4–2.2 m seedlings. However, they also found that presence of alluvial sands enhanced *S. exigua* recruitment, potentially accounting for the wider elevation range for

seedling presence. A field experiment in headwaters of the Fall River (Colorado State, USA) showed that the combination of fine textured soils and intermediate elevation fine (50 cm above the stream level) had the highest density of seedlings of *S. monticola* (Gage and Cooper, 2004).

While many studies show high densities of seedling recruitment at low elevations, they do not necessarily show high survivorship at these low, frequently inundated and disturbed locations. To understand the nuances of survivorship, some studies have examined life stages in relation to elevation above water or location within the floodplain. In the Wisconsin River (USA) Dixon et al. (2002) demonstrated that *Salix* seedlings occupied lower sandbars (median elevation < 0.37 m), while sapling presence was higher on high sandbars (median elevation > 0.37 m). In a study carried out in the Platte river Nebraska (USA) Johnson (2000) showed that *Salix* sp. seedlings in the youngest cohort (around 0.3 m tall) grow on sand-bars of medium elevation (i.e., 12 to 48 cm), but the oldest cohort was composed of plants (around 1±3 m tall) growing in dense thickets on moderate to high sand-bars (i.e., 12 to 72 cm). Both of these studies allude to the higher risk of mortality due to flooding associated with germinating in the lowest sites. However, Johnson (2000) also showed that there was higher summer mortality at higher elevations above the water channel due to drought stress.

Landform and substrate focused studies

Fluvial landforms have distinct willow recruitment patterns due to hydrologic regimes and disturbance dynamics. The interaction between both components generates suitable habitat patches for the recruitment of these pioneer species. In a montane ecosystem located in Rocky Mountain National Park in Colorado (USA), Cooper et al. (2006) showed that the establishment of willows on abandoned channels and point bars was driven by flow events of 2- to 5-year return intervals. Conversely, in abandoned beaver ponds the recruitment was related to flow events higher than the 5-year return interval. Therefore, the mean elevation of germination sites changed depending on flood regime and fluvial landform type: around 0.51 m above low-flow channel height for beaver ponds, 0.26 metres for point bars, and 0.17 metres for abandoned channels. In glacial regions, Douglas et al. (1995) analysed processes of seed germination, establishment and growth in relation to landform type. Growth, measured by leaf area, and establishment of seedlings, were affected by location, likely due to micro-environmental differences on gravel bars related to higher moisture levels. Most seedlings were located on gravel bars with greater plant cover, probably to the higher soil moisture contents according to these authors. Nakamura et al. (2007) examined the colonisation places of *S. sachalinensis* and *S. pet susu* in Rekifune River (Japan) in different landforms; i.e., gravel bar, lower floodplain, upper floodplain, secondary channel and terrace. Their results showed that seedlings only colonise gravel bars, lower floodplain and secondary channels, with gravel bars having the largest presence of seedlings. Woods and Cooper (2005) also demonstrated the importance of landform type in mitigating the influence of elevation on recruitment in a subalpine reach in the Colorado River. They showed that seedling density in the lowest elevation plots was significantly different between landform types, with more density on sandbars (72 %) than on gravel bars (44.3 %). Seedling density was also higher overall in the lowest elevation plots compared to both the medium (15 cm higher than low plots) and high (30 cm higher than low plots) elevation plots. While the elevation treatments chosen by these authors are low compared to other studies, this is because these treatments encompassed the range of elevations of exposed bar surface in early summer in their study area. Elevation treatments are determined by river and landform types and they should be adapted to the particular site prior to any methodological design.

According to the surface-related factors analysed in the scientific literature, *in situ* studies (i.e., field experiments and observational field studies) are the most frequent due to the difficulty of recreating elevation gradients in a laboratory or greenhouse experiment. Also noteworthy is the high frequency of studies examining both elevation and surface type (e.g. gravel bar, terrace, abandoned channel). The literature revealed a trend of seedlings and cuttings occupying low areas (Craig and Malanson, 1993; Woods and Cooper, 2005; Nakamura et al., 2007). These lower areas are subjected to frequent floods which make bare spaces available for establishment. According to several studies, maximum regeneration occurs between 0.17-2.2 metres (Barsoum 2002; Cooper et al., 2006; Rood et al., 2011; Asaeda et al., 2015; Magdaleno et al., 2014). The centre of that range is the most suitable for the growth, establishment and survival of cuttings, saplings, and seedlings (see Table 1). In addition, older individuals tend to occur in denser populations higher above the channel, while young individuals are more abundant in the lower parts of the channel (Johnson, 2000; Dixon et al., 2002). Although it may be harder for seedlings to establish at higher elevations, if they are able to establish, the higher elevations experience less frequent flood scouring and submersion, allowing for a population to age. Other studies focus on the position of seedlings, cuttings, and saplings within different landform types (gravel and sand bars or secondary channels). These studies generally agree with the elevation focused studies, showing a clear relationship between the greater presence of willows in low elevation areas (Craig and Malanson, 1993; Parolin et al., 2002; Woods and Cooper 2005; Nakamura et al., 2007) and medium elevation areas (Roelle et al., 2001; Gage and Cooper, 2004), in addition to an increase in the mortality of seedlings in high elevation areas due to summer drought (Johnson 2000; Quintana-Ascencio et al., 2013).

Table 1. Elevation preferences for the regeneration of *Salix* species based on the systematic review carried out in this study. The studied species, the phase, the type of landform area, the elevation conditions, and the reference is cited for each case. This table provides guidelines of where species may be planted within a floodplain to have a higher likelihood of survival.

Species	Phases	Type of landform	Elevation above stream channel (in m when possible)	References
<i>S. nigra</i>	Seedlings	Gravel bars	Lowest part	Craig and Malanson (1993)
<i>Salix</i> sp.	Seedlings	Gravel and Sand bars	Lowest part	Woods and Cooper (2005)
<i>Salix</i> sp.	Saplings and seedlings	Bars and Beaver complexes	0.17-0.51	Cooper et al. (2006)
<i>S. gilginiana</i>	Seedlings	Bars	0.3-1.3	Asaeda et al. (2015)
<i>S. exigua</i> , <i>S. nigra</i> and <i>S. eriocephala</i>	Saplings and seedlings	Sand bars	> 0.37	Dixon et al. (2002)
<i>S. alba</i>	Seedlings	Gravel bars	0.5-0.8	Barsoum (2002)
	Cuttings		0.8-1.1	

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<i>S. exigua</i>	Seedlings	Sand bars	0.4–2.2	Rood et al. (2011)
<i>S. caroliniana</i>	Seedlings	Marsh	0.5	Quintana-Ascencio et al. (2013)
<i>S. salviifolia</i>	Saplings	River banks	0.51 -1.5	Magdaleno et al. (2014)
<i>Salix</i> sp.	Seedlings	Gravel bars	0.6	Johnson (2000)
<i>S. monticola</i>	Seedlings	Field experiment	Intermediate elevation and fine texture	Gage and Cooper (2004)
<i>S. atrocinerea</i>	Seedlings	Gravel (pit)	Inundated by the highest water level	Roelle et al. (2001)

4.4. Atmospheric factors

Aerial temperature, light exposure, wind and relative humidity were the most studied atmospheric factors affecting *Salix* regeneration found in our literature review. Most commonly studied was aerial temperature, specifically relating to concerns of the increasing temperature trend (Table 2). Field and greenhouse experiments examining the impact of varied temperature on germination and growth have been conducted in several ecosystems with varying results. Several studies showed a clear relationship between temperature and growth. Using seeds from *S. variegata* from the Three Gorges Region (China), Chen et al. (2013) conducted germination trials testing temperature from 12 to 33 °C. Their results showed maximum germination rates at 21 to 24°C (around 60.6 %) that significantly declined with higher temperature (>27 °C). On the other hand, in a field experiment in Rocky Mountain National Park (USA), Kaczynski and Cooper (2013), found a 30 % increase in below ground biomass of *S. monticola* cuttings in a warming treatment compared to an ambient temperature control, although the ratio of aboveground biomass was similar under both treatments.

Aerial temperature can also affect seed dispersal, as demonstrated by Bourgeois and González (2019). These authors found peaks of seed release of *S. alba*, concurring with high aerial temperature along the Middle Ebro River (Spain), although the capacity to germinate was reduced after 4 days (González et al., 2016). Moreover, dispersal of willows is maximum in the proximities of seed trees (Tiebel et al. (2018). This finding can be very useful in the case of a restoration plan as releasing water during the hottest days within the dispersal period may lead to better results. This may suggest that temperature has different effects on different life stages, but with only two studies there is not yet enough information to draw strong conclusions.

We found only one study examining the extreme conditions typical of desert riparian ecosystems. In a laboratory experiment, *S. lutea* and *S. exigua* seeds were collected from Walker River in Nevada (USA), to study the relationship between the germination of their seeds and temperature regimes. They found that the optimum range of temperature to support germination were combinations ranging from 15 to 30°C (Young and Clements, 2003).

Other studies found no relationship between temperature and *Salix* regeneration. Castro-Morales et al. (2014) examined the influence of two aerial temperature regimes (i.e., spring temperature of the northern and southern Florida region) on survival and establishment of *S. caroliniana*. They found no significant differences between these two temperature regimes. Similarly, in a greenhouse experiment, Van Splunder et al. (1995) found no response of

temperature on seed germination for *S. triandra*, *S. alba* and *S. viminalis* (temperature treatments 5, 10, 15, 20 and 25°C).

In summary, there is some evidence for life-stage specific temperature preferences. Several authors provided optimal germination temperatures based on laboratory trials or greenhouse experiments, generally with the higher germination rates from 15 °C to 30 °C. On the other hand, some did not find significant impacts of warmer treatments, in germination (Castro-Morales et al., 2014) or in above ground biomass (Kaczynski and Cooper 2013). Finally, seed release peaks may be favoured by high temperatures (Bourgeois and Gonzalez 2019).

Table 2. Optimal temperature conditions for the regeneration of *Salix* species based on our literature review. The studied species, the phase, the optimal temperature range, and the reference are cited for each case.

Species	Phases	Optimal temperature for study phases (°C)	References
<i>S. triandra</i> , <i>S. Alba</i> and <i>S. viminalis</i>	Germination	5 - 25	Van Splunder et al. (1995)
<i>S. lutea</i> and <i>S. exigua</i>	Germination	15 - 30	Young and Clements (2003)
<i>S. variegata</i>	Germination	12 - 24	Chen et al. (2013)
<i>S. monticola</i>	Cuttings growth	Significant results for belowground biomass No significant results for aboveground biomass	Kaczynski and Cooper (2013)
<i>S. caroliniana</i>	Germination and establishment	No significant results	Castro-Morales et al. (2014)
<i>S. alba</i>	Seed release	High temperature	Bourgeois and González (2019)

Other atmospheric variables such as wind, precipitation, CO² concentration, and light exposure have also been studied as factors that influence the different phases of willow regeneration. For example, on the Colorado River (USA; Woods and Cooper, 2005) demonstrated that summer rainfall might increase seedling survival in the first year reducing the hydric stress. This finding is in agreement with other authors (e.g., Castro-Morales et al., 2014; Stromberg et al., 1993). In the Rekifune River, an incised-meandering river in Japan, Nakamura et al. (2015) found that seedlings of *S. sachalinensis* and *S. pet-susu* established in gravel bars are exposed to high light intensities and dry conditions and suffer the most intensive flood disturbance. In a greenhouse experiment Perry et al. (2013) showed that elevated CO² concentrations are likely to favour the recruitment of drought-tolerant exotic species (*Tamarix*, *Elaeagnus*) over native species such as *S. exigua* or *Populus* spp.

Because there were so few studies examining each of these atmospheric factors, these results remain anecdotal. Regarding precipitation, summer rainfall may increase seedling survival according to Woods and Cooper (2005) by reducing dry conditions. Elevated CO² may favour exotic species over native *Salix* species. However, further studies must be conducted to identify larger trends in the impact of precipitation, light and CO₂ concentration on *Salix* regeneration.

5. INFLUENCE OF PRESSURES ON SALIX REGENERATION

We identified seven different pressures affecting *Salix* regeneration from the 62 papers included in the systematic literature search. The most frequently studied pressures were flow regulation and hydropeaking (a specific type of flow regulation), followed by competition with other species.

5.1. Flow regulation effects on *Salix* recruitment

Flow regulation by large dams is the most frequently studied anthropogenic pressure in relation to willow recruitment. It is widely known that the reduction of the peak discharges is one of the main causes of degradation of willow formations in many parts of the world (e.g., Petts and Gurnell, 2005; González et al., 2018). This is because peak discharges remove established riparian vegetation and create open spaces for the regeneration of new individuals of riparian species. Moreover, if water is stored in the reservoir and released mainly in summer for irrigation purposes, this summer water availability favours vegetative encroachment, including by the encroachment by willows, and further reduces the availability of open spaces needed for *Salix* regeneration.

In the context of flow regulation, Rood et al. (2011) investigated the interactions of flowing water, sediments and vegetation in the Snake River on *S. exigua*. They found that *S. exigua* was abundant in the lowest bank position of reaches located upstream of the dam, similar to previous studies carried out by Amlin and Rood (2002), but sparse in downstream reaches. The colonisation and vegetative (clonal) spread of willows creates slow-water areas where sand is trapped, sustaining sand bars along river systems and creating more suitable habitat for further colonisation. The study found that downstream from the dam, sandbars were eroded, making these types of colonisation sites scarce. Instead, willows were restricted to incised sand surfaces. This example demonstrates how flow regulation by large dams can trap sediments and accelerate the process of willow degradation. The reciprocal relationship between sandy substrates and willows also demonstrates the importance of willow species in maintaining ecosystem function acting as ecosystem engineers.

Increasing soil salinity is another consequence of flow regulation that affects *Salix* recruitment. Merritt and Shafroth (2012) studied the effects of a heavily regulated river (Colorado River) on germination and establishment of *S. gooddingii* and *S. exigua*. Although the results demonstrated that the presence of *Tamarix* (saltcedar), an invasive riparian tree, increases soil salinity via salt exudation, the alteration of natural fluvial processes by flow regulation and channelization also contributed to severe soil salinization in areas where *Tamarix* is absent. Similar conclusions were drawn by Lovell et al. (2009) in a study of the influence of flooding and damming on riparian communities. Their study demonstrated that drought and salinity stress from flow regulation, and aggravated by the presence of *Tamarix*, negatively affected the recruitment and survival of *Salix*. They found that willow populations were younger above dams than below dams, suggesting that *Salix* recruitment was scarce below dams.

Environmental flows, in the sense of Acreman and Dunbar (2004), have been proposed as a measure to restore willow formations. When possible, water releases from the dam at the appropriate time could greatly contribute to the establishment of new individuals as long as viable seeds were present in the area (Karrenberg and Suter, 2003a). In the same sense, recruitment box model have been usually applied to *Populus* genus, and this model could be well suited to *Salix* as well favouring its regeneration implementing adequate environmental flows (Amlin and Rood, 2002). Also Stella et al. (2006) Along these lines, Schlatter et al. (2017)

analysed the effects of an important flow release from the Morelos Dam on the Colorado River (U.S. – Mexico binational agreement, Minute 319) on Salicaceae recruitment. In this study, there was no germination of willows in control or inundated treatments, except where there was previous removal of vegetation or active seeding. Their predictive models showed that inundation was the most significant predictor of willow germination, followed by bare ground, seed availability and low soil salinity. During the same flow release, Shafroth et al. (2017) found that the bare surface available for new seedlings was similar before and after the high flow, suggesting that the flow was not high enough to create colonisation sites. The combined lack of available seed and bare wet surfaces resulted in germination failure in 16 out of the 19 transects observed in the study. This points directly to the need for managers to create germination sites prior to water releases if the releases will not be large enough to scour germination sites.

Hydropeaking is a specific type of flow regulation that occurs with dams built for hydroelectric production. Hydropeaking refers to a sudden change in river discharges, which can have a large impact on the recruitment and growth of willow species. To investigate the response of *S. viminalis* cuttings to the effect of rapid changes in water level, Gorla et al. (2015) experimentally recreated hydropeaking conditions, *ex situ*. Their results suggest that *S. viminalis* can recover from inundation stress by concentrating their roots closer to the mean water table. However, cuttings of young plants with shallow root systems were more sensitive to water level fluctuations than older cuttings. Similarly, survival and growth of *S. alba* seedlings were examined under different abrupt drops in water table levels along the Garonne River (France; Guillois et al., 2011). They found nearly 100% seedling mortality in the treatments where the water level dropped more than 60 cm, demonstrating the sensitivity of *Salix* seedlings to hydropeaking during the first months of establishment. In the case of *S. elaeagnos*, its uprooting resistance was the highest compared to other riparian species (*Populus nigra* and *Alnus incana*) due to its high root anchorage in a study carried out in the Tagliamento river by Karrenberg et al. (2003b). Experiments to recreate hydropeaking conditions greatly contribute to our knowledge of the impact on riparian vegetation. Further, they can be used as a guide in planning water releases to minimise the negative effects on riparian plant communities.

5.2. Effects of grazing and browsing on *Salix* recruitment

Grazing by livestock and wild animals can impact riparian corridors in ways other than the biomass removal that is readily apparent. This includes the redistribution of nitrogen and seeds, the trampling of riparian vegetation and the compaction of soils (Belsky and Blumenthal, 1997). Depending on the intensity, timing and duration, livestock grazing can lead to irreversible ecosystem impairment with the destruction of natural bank structures and the loss of riparian vegetation (Beschta et al., 2012). As such, the reduction of grazing in fluvial corridors has frequently been proposed as a passive restoration measure to recover some riparian vegetation, including the recruitment of willow species (Beever et al., 2003, Magilligan and McDowel, 2007).

Several studies have used exclosures to keep herbivores out of an area, finding that overall, a reduction of grazing pressure does increase *Salix* growth and survival (Kaczynski et al. 2018; Breton et al. 2014). Similar results were found in Norway, where in summer, reindeer decrease *Salix* survival and size, and in winter, rodents increase *Salix* mortality compared to exclosures (Ravolainen et al., 2014). In addition to the effect of wild herbivores on the regeneration of willows, other domestic small ruminants also affect the growth and survival of willows. Aboling et al. (2011) found that grazing by small ruminants (i.e., sheep and goats) led to willow

mortality after willow bark had been removed. They also found that early season grazing was less damaging to willow growth and that consecutive periods of grazing increased willow mortality. However, excluding grazers alone may not be enough to facilitate recovery of *Salix* species. Kaczynski et al. (2018) found that even after 5 years of grazer exclusion, the seed rain had not yet recovered in heavily grazed areas. Therefore, active revegetation may be necessary to encourage *Salix* regeneration in heavily impacted areas.

Grazing can also interact with other pressures in its influence on *Salix* regeneration. In a stream tributary of the Snake River (Wyoming, USA), Dwire et al., (2006) found that native ungulates and livestock herbivory influenced the post-fire growth of riparian shrubs (including *S. wolfii*, *S. drummondiana* and *S. boothii*). Specifically, they found that the growth of riparian shrubs was limited by high levels of browsing in the first years following the fire, when resprouting shrubs are more exposed to disturbance.

While several grazing species cause a clear negative impact on *Salix* seedlings, beavers have a strong influence that is not completely negative. When beavers bring willow cuttings to their dams, the cuttings are often transported downstream by the river and may accumulate in channels and stream margins, facilitating *Salix* recruitment in new areas and constraining the water table level (Bilyeu et al., 2008). In the Missouri River system (Montana, USA), Levine and Meyer (2019) demonstrated that beavers contribute to willow recruitment by supplying fine woody debris and willow cuttings that were trapped by beaver dams. This promotes vegetative propagation on suitable substrates. Tallent et al. (2011) also found a significant positive relationship between *S. gooddingii* individuals and the presence of beavers. While the beavers were likely attracted to the area by the presence of *S. gooddingii*, beaver activity increased the vegetative reproduction of this species. This resulted in an increase of total cover of *S. gooddingii*.

In summary, grazing herbivores have an important but varied impact on willow regeneration, depending on species, timing, and spatial extent of grazing. Generally, longer grazing periods lead to higher *Salix* mortality. Exclosure areas, although a very common measure, may not be sufficient in isolation to recover *Salix* populations. It may be necessary to combine active planting with exclosures to successfully recover *Salix* populations. Grazing is particularly detrimental to the survival and growth of willows during the first years of development. While many herbivores have a negative impact on willows, beavers seem to play an important role in encouraging the vegetative regeneration of willows.

5.3. Effects of competition on *Salix* recruitment

The regeneration of *Salix* species requires open surfaces with adequate moisture during the seed dispersal window. Sometimes species other than *Salicaceae* occupy the space, hindering *Salix* colonisation and creating competition for space and light. For example, Radtke et al. (2012) found negative effects of above ground competition from *Poa trivialis* on growth and secondary resprouting capacity in cuttings of three willow species (*S. fragilis*, *S. viminalis* and *S. triandra*) were studied in a greenhouse experiment.

Allelopathic effects of competitive species can also hinder the establishment of new individuals of *Salix*. For example, *Impatiens glandulifera* has an allelopathic effect by producing 2-MNG (2-methoxy-1,4-naphthoquinone). Germination trials showed that this molecule led to a reduction in growth rates of native riparian vegetation, including *Salix fragilis* (Bieberich et al., 2018).

Invasive species in riparian environments may also have a negative impact on *Salix* regeneration, as is the case with non-native, invasive *Tamarix* in the United States Southwest.

In this case, the combination of intense flow regulation by dams as well as the presence of *Tamarix*, which is well adapted to the conditions of flow regulation and alters soil conditions by salt exudation from the roots favours the presence of *Tamarix* instead of *Salix* (Merritt and Shafroth, 2012). While *Salix* has lower recruitment below dams (e.g., Rood et al., 2011), *Tamarix* has been found in greater abundance below dams than above dams, showing that flow regulation favours this invasive species (Lovell et al., 2009). The same effect has been detected in reservoirs such as in Lake Mohave where the only regeneration of *Salix gooddingii* was vegetative and restricted to the frequently inundated zones while *Tamarix ramosissima* seedlings were present in all zones (Tallent et al. 2011). Some authors argue that the restoration of a flood pulse regime will encourage regeneration in native riparian vegetation (Nagler et al., 2005). Other authors suggest the combined actions of invasive species removal and seed augmentation to encourage native vegetation (Sher et al., 2002; Schlatter et al., 2017). More research is needed to determine potential areas for the establishment of riparian native species when reinstating historical flow patterns.

In summary, competition and allelopathic effects can have negative consequences for *Salix* regeneration and so should be considered in plans for conservation or restoration of riparian communities. The dominance of invasive species also presents a challenge for *Salix* recruitment in some regions by reducing the space needed for the regeneration of native pioneer species. Because of this, vegetation removal and active revegetation of *Salix* species may be needed to facilitate regeneration.

5.4. Climate change effects on *Salix* recruitment.

Climate change alters the natural hydrological conditions of rivers that drive composition and structure of vegetation in riparian corridors (Capon et al., 2013; Garssen et al., 2014; Perry et al., 2020). Changes in snowmelt timing (Dudley et al., 2017; Vicuna et al., 2011; Blöschl et al., 2017), long dry periods (Ceballos et al., 2004), and lack of soil moisture (Okkonen et al., 2010) are the main ways that climate change affects willow regeneration (Singer et al., 1998; Jones et al., 1999; Cooper et al., 2006).

After defining the conditions for willow establishment, Cooper et al. (2006) used future climate scenarios to predict changes in willow recruitment in montane ecosystems. They predicted that seedling establishment will decrease due to a reduction of peak flows and significant changes in landforms and that mortality will increase due to drier conditions caused by early snowmelt and less soil moisture. Increasing temperatures may also lead to changes in growth, as discussed in the aerial temperatures section. However, changing temperatures and water levels were shown to have no influence on the susceptibility of one *Salix* species (*S. monticola*) to fungal infection (Kaczynski and Cooper 2013). Higher atmospheric concentrations of CO₂ may interact with water availability with varying effects on *Salix* species. Perry et al. (2013) found that increased aridity, simulated by a faster water table decline, reduced seedling growth more intensely for *S. exigua* than for drought-tolerant exotic species. In this case however, there were no significant interactions of CO₂ with water availability. Given that this is the only study examining possible interacting effects of water availability and CO₂ concentrations on *Salix* regeneration, more replication is necessary to understand this relationship.

In summary, *Salix* regeneration could be negatively affected by climate change effects such as the reduction of flows, earlier snowmelt, the decrease of soil moisture under longer dry periods, and indirectly, the increase of CO₂. Such changes may lead to increased mortality and reduced establishment and growth. Management of *Salix* in riparian forests will need to

compensate for the effects of climate change by encouraging recruitment of species that are likely to tolerate anticipated changes.

5.6. Fire effects on *Salix* recruitment

Fire is a natural disturbance that strongly influences biotic communities, providing irregularity and diversity in aquatic and terrestrial habitats (Foster et al., 1998). However, studies about the impact of forest fires on riparian ecosystems and *Salix* seedlings are scarce (Bisson et al., 2003). Along a free-flowing river in the southwestern United States, Stromberg and Rychener (2010) found that *Salix goodingii* had the highest rates of resprouting compared to *Populus* and *Tamarix* following fire. Two studies examined the combined disturbances of fire and grazing on *Salix* seedling establishment. In Wyoming (USA), Dwire et al. (2006) observed that grazing by native ungulates and livestock following a fire reduced the growth of riparian seedlings, including three willow species (*S. boothii*, *S. drummondiana* and *S. wolfii*). In Rocky Mountain National Park (Colorado, USA), Kaczynski et al. (2018) found greater seedling biomass following fire disturbance in plots protected by exclosures. However, in this case exclosures also reduced seed rain by 90 %. Kaczynski et al. (2018) also found a reduction in seed rain following a fire, caused by the mortality of mature, seed producing individuals. Given that wildland fire reduces available seed and grazing after fire reduces the growth of the new seedlings, it is advisable to limit grazing in fire affected riparian areas in order to facilitate *Salix* regeneration.

6. Gaps in *Salix* recruitment research and future challenges.

Based on this scientific literature analysis, the recruitment phase of 35 *Salix* species has been studied globally, mostly in North America and Europe. With around 526 species of *Salix* in the world (*sensu* Zhen-Fu, 1987) the proportion of species studied is limited overall and extremely limited in Asia. Only 1 % of *Salix* species that occur in Asia have been studied. Notably there is also a particular lack of studies in arid and semi-arid environments.

One possible reason for the paucity of studies may be the complicated and particular requirements for *Salix* recruitment, including the adaptation to very specific disturbance regimes. Some factors can be controlled in *ex situ* experiments (i.e., laboratory or greenhouse), making it possible to isolate factors of interest. For example, controlling atmospheric CO₂ concentration (Perry et al., 2013) or air temperature (e.g., Van Splunder et al., 1995; Young and Clements 2003; Chen et al., 2013) can only be done *ex situ*. On the other hand, factors such as flood regime or geomorphic dynamism can only be done in the field. Field studies with such complex factors may be unattractive to take on due to the likelihood of not reaching a conclusive result if the conditions are not adequate. For example, the loss of monitoring devices due to extraordinary events like a flood or the occurrence of an extreme drought episode after planting can jeopardise even the most well thought out project. Replication of field experiments is another obstacle, not only for the study of *Salix* species but for all ecological studies (Fraser et al., 2020). The selection of optimal field sites for comparison is a crucial, yet difficult task that can determine the success or failure of the experiment and the conclusions that can be obtained. Despite these difficulties, further research describing the adaptations and requirements of different *Salix* species would reinforce the important role that these species play in fluvial ecosystems and improve their conservation status. As it stands, much of our knowledge remains anecdotal, with only one or two studies on a given topic.

The ecological niche that willows occupy is traditionally considered similar for the whole genus since they are grouped as pioneer (with some exceptions), disturbance-dependent species (Karrenberg et al., 2002; González et al., 2018). Based on this grouping, some general conclusions have been extracted from the studies found in this literature review that need to be incorporated into management practices. We have identified elevation associations of *Salix* seedlings (Table 2), optimal temperature ranges for seed germination (Table 3), and the need for improved flow regime patterns in impounded rivers. However, subtle differences may be found when several species are analysed in the same experiment or survey. For example, studies by Van Splunder et al. (1995) regarding the optimal temperature range and for germination and moisture tolerance of three different willow species found differences among the species. Comparative studies and experiments provide valuable knowledge that could mean the difference between the success or failure of a management plan. *Salix* species are widely used for restoration and rehabilitation in fluvial zones. Both sowing and planting are frequently applied using different techniques in restoration projects with varying degrees of success (González et al., 2018). Learning more about *Salix* ecology and requirements would greatly increase the success of restoration initiatives around the world.

In our literature review, we found that soil and hydrologic factors together with some surface-related factors such as the spatial distribution and the elevation above the channel have been the most frequently studied environmental factors in relation to *Salix* regeneration. Atmospheric factors such as light exposure, air temperature, or the concentration in the air of certain gases are less studied. Studying these kinds of factors requires controlled laboratory or greenhouse conditions that may not be readily available. However, given the current context of climate change, with increasing temperatures and the alteration of gas emissions into the atmosphere (Jiménez-Cisneros et al., 2014), there is much to be gained from experiments that can manipulate these types of variables. For instance, will a hypothetical increase in temperature affect the germination of willow seeds or the seedling growth? Will the alteration of CO₂ concentration or other greenhouse emissions modify water use-efficiency of willows? Will the effect vary among *Salix* species? How will changes in climate related variables interact with other abiotic factors, such as the spatial distribution, surface type or soil moisture in their impact on *Salix* regeneration? These are a few of the many possible questions that need answers in order to improve our response capacity in the face of global change.

Given the specific habitat requirements of *Salix* species, several human pressures have detrimentally affected *Salix* regeneration. We found flow regime alteration by dams and invasive species competition to be the most studied pressures in relation to *Salix* regeneration. Both pressures have been frequently studied independently. However, several authors found a relationship between flow regime alteration and invasive species competition on *Salix* regeneration. This is particularly apparent in the case of *Tamarix* spp. in the U.S., where the lack of discharge due to flow regulation and the presence of *Tamarix* both increase soil salinity, which then further promotes *Tamarix* and hinders *Salix* regeneration (Merritt and Shafroth, 2012). A more holistic approach considering several anthropogenic pressures and their interaction could provide new evidence into the role that different factors play in regeneration phases. For example, is there a relationship between the cooler temperatures of water released in summer from deep parts of reservoirs (Martínez-Fernández and García de Jalón, *in press*) and the scarcity of *Salix* recruitment? What are the effects of cooler water temperatures on *Salix* growth and mortality? Is the impoverishment of the water quality linked to agricultural and urban areas an influential factor in *Salix* recruitment and development? The answers to these kinds of scientific questions will improve our ability to design more adequate management measures and mitigate the impact of anthropic pressures.

Based on the results of this review, the following topics should be highlighted for future research: (1) expanding our knowledge to the numerous *Salix* species unexplored to this day, (2) comparative studies looking at variations in gradient effects among species, (3) effects of extreme climatic events in fluvial ecosystems with special attention to increasing temperatures and greenhouse gas concentrations, and (4) consideration of multiple interacting pressures. Further research of these aspects, among others, could greatly contribute to the management and conservation of fluvial landscapes.

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SUPPLEMENTARY MATERIAL

APPENDIX S1.

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APPENDIX S2.

	<i>Salix. sp.</i>	<i>S. fragilis</i>	<i>S. purpurea</i>	<i>S. alba</i>	<i>S atrocineria</i>	<i>S triandra</i>	<i>S gilgiana</i>	<i>S. daphnoides</i>	<i>S. elaeagnos</i>	<i>S. salviifolia</i>	<i>S. monticola</i>	<i>S. planifolia</i>	<i>S. drummondiana</i>	<i>S. geyeriana</i>	<i>S. bebbiana</i>	<i>S. lucida subsp.caudata</i>	<i>S. viminalis</i>	<i>S. caroliniana</i>	<i>S. goodingii</i>	<i>S. variegata</i>	<i>S. exigua</i>	<i>S. sachalinensis</i>	<i>S. pet-susu</i>	<i>S. humboldtiana</i>	<i>S. babilonica</i>	<i>S. nigra</i>	<i>S. eriocephala</i>	<i>S. interior</i>	<i>S. setchelliana</i>	<i>S. boothii</i>	<i>S. lasiopelis</i>	<i>S. wolfii</i>	<i>S. integra</i>	<i>S.amygdaloides</i>	<i>S. x rubens</i>	<i>S. lutea</i>
Aboling et al., 2011	x																																			
Amlin & Rood, 2002	x																																			
Asaeda et al., 2014							x																													
Barsoum, 2000				x																																
Bieberich et al., 2018		x																																		
Bourgeois & Gonzalez, 2019				x																																
Breton et al., 2014		x	x	x	x	x											x																			
Castro-Morales et al., 2014																		x																		
Chen et al., 2013																				x																
Cooper et al., 2006	x																																			
Craig & Malanson, 1993																										x		x								
Day et al., 2006																										x										
Dixon et al., 2002																					x					x	x									
Dixon, 2003																					x					x										
Douglas, 1995																														x						
Dwire et al., 2006													x																		x		x			
Francis et al., 2004									x																											
Gage & Cooper, 2004											x																									
Gage & Cooper, 2005											x	x	x	x	x	x																				
Galuszka & Kolb, 2002	x																																			
Gonzalez et al., 2015				x																																
Gorla et al., 2015																	x																			
Guilloy et al., 2011				x																																
Horton & Clark, 2000																			x	x																
Johnson, 2000	x																																			
Kaczynski & Cooper, 2013											x																									
Kaczynski et al., 2018											x																									
Karrenberg & Sutter, 2003			x	x		x		x	x																											
Karrenberg et al., 2003									x																											
Lovell et al., 2009																					x															
Magdaleno et al., 2014										x																										
Merrit & Shafroth, 2012																			x		x															

3.2. EL DECLIVE DE LOS SAUCES EN CORREDORES RIPARIOS SOBRE VEGETADOS



3.2.1. EXPLORING WILLOW DECLINE IN AN OVER-GREENING RIPARIAN CORRIDOR (RIVER JARAMA, SPAIN)

1. INTRODUCTION

Present anthropised rivers are part of the global consequences of human behaviour. The construction of dams along rivers, river channelisation, the conversion of floodplain areas into artificial surfaces (e.g. urban, agricultural and industrial uses) or the practice of gravel mining in channels are among the most relevant direct pressures on fluvial ecosystems with many examples all over the world (e.g. Gordon and Meentemeyer 2006; Graf 2006; González del Tánago et al. 2016; Calle et al. 2017).

Moreover, other human actions indirectly cause relevant alteration of rivers at watershed scale such as interbasin water transfers (Chen et al. 2001; Fazelpoor et al. 2022), the abandonment of rural areas, (e.g. García-Ruiz and Lana-Renault 2011; Scorpio and Piégay 2021); the use of pesticides and nutrients added in agriculture (e.g. Zhang et al. 2016; Parveen et al. 2017). All of these pressures, in summary, reduce the magnitude and frequency of floods, increase summer flows in the case of regulated rivers, decrease sediment supply in afforested catchments, laterally stabilize the rivers and increase the availability of the nutrients for vegetation (e.g. Shafroth et al. 2002; Nilsson et al. 2005; Merritt and Poff 2010; Lorenzo-Lacruz et al. 2012; Morán-Tejeda et al. 2012; Martínez-Fernández, González del Tánago, et al. 2017). The generalised consequences of river dynamism lead to the stabilisation and narrowing of river channels, favouring the establishment and growth of riparian vegetation with the consequent lack of bare spaces necessary for the recruitment of pioneer species as willows and pop-lars (e.g. Kondolf et al. 2002; Lobera et al. 2015; Martínez-Fernández, González del Tánago, et al. 2017; González et al. 2018; García de Jalón et al. 2020). Moreover, in these stabilised landforms, pioneer species adapted to disturbance regimes as Salicaceae, compete at a disadvantage with other species with also includes those with an invasive character such as the remarkable cases of expansion of non-native *Tamarix* and *Elaeagnus angustifolia* in regulated rivers of the western US (e.g. Shafroth et al. 2002; Merritt and Poff 2010). Alpine rivers that have been straightened channelised have developed alternate gravel bars to dissipate the kinetic energy. In the River Isere, these gravel bars were inexorably colonised by vegetation (Salicaceae species) since 1955 on the upper reaches affected by a major flow diversion, and sediment mining, and since 1975 on the lower ones where bars migrate intensively (Serlet et al. 2018). A similar bar pattern was found on River Rhine (Caponiet al. 2019) where in the upper reaches with more stable bars vegetation has constantly increased since 2005, while in downstream reaches bars with larger migration rates remain bare.

Riparian vegetation encroachment has often recently occurred in Spanish rivers, changing from bare sand/gravel bars to green lands covered with woody vegetation (García de Jalón et al. 2020). Although the succession of recruitment to mature vegetation is a natural phenomenon, the rate of change has been affected by human activities caused by alteration of the flow and sediment regimes, but also by a generalised eutrophication and the climate change background. This anthropogenic process with intensive vegetation encroachment is what we call 'riparian over-greening'. In this context, this paper aims to explore the main drivers inducing the progressive over-greening process in the riparian corridor and the observed willow forest decline. The results could be useful to guide managers and practitioners to resolve what factors prevent the regeneration of willows, and provide solutions for their correct recovery, particularly in the Jarama River. Antecedents on the riparian species recruitment are rare. Only

Mora-Navarro (2004) studied the recruitment in a site located at the medium River Jarama founding seedlings and saplings of Salicacea (*Populus nigra*, *Populus alba*, *Salix alba*, *Salix pur-purea* and *Salix salviifolia*) at densities up to 65.1 stems/m².

2. METHODOLOGY

2.1. Study area

The Jarama River has its source in the western extreme of Ayllón Mountains (Central Spain) and runs south through 190 km long to its confluence with Tajo River. Jarama River basin has an area of 11,600 km² being a fluvial network highly regulated mainly due to the proximity of large urban developments around the city of Madrid. The high demand of water supply is satisfied by eight large reservoirs that were constructed at the headstreams, from where water is derived through pipes and canals to the city. This water abstraction causes long river reaches to have their flow greatly reduced, as occurs downstream of the lower reservoirs El Vado reservoir (constructed in 1972) located in the Jarama River and the Atazar reservoir (constructed in 1965) in the Lozoya River, which is its main affluent. These reaches below dams were even completely dry during some years at the end of last century (Sotelo and Sotelo 2013). In addition, the Jarama river, especially in its middle and lower reaches, receives relevant amounts of urban waste-water after being treated, although containing a large amount of nutrients.

The study area is located in the middle reaches of the Jarama River below the large reservoirs, where it runs along open valleys (Figure 1.1). The study segment comprises a section upstream of the confluence with Lozoya River (reaches 1–3 in Figure 1.1) and another downstream of this confluence (reaches 4–6 in Figure 1.1).

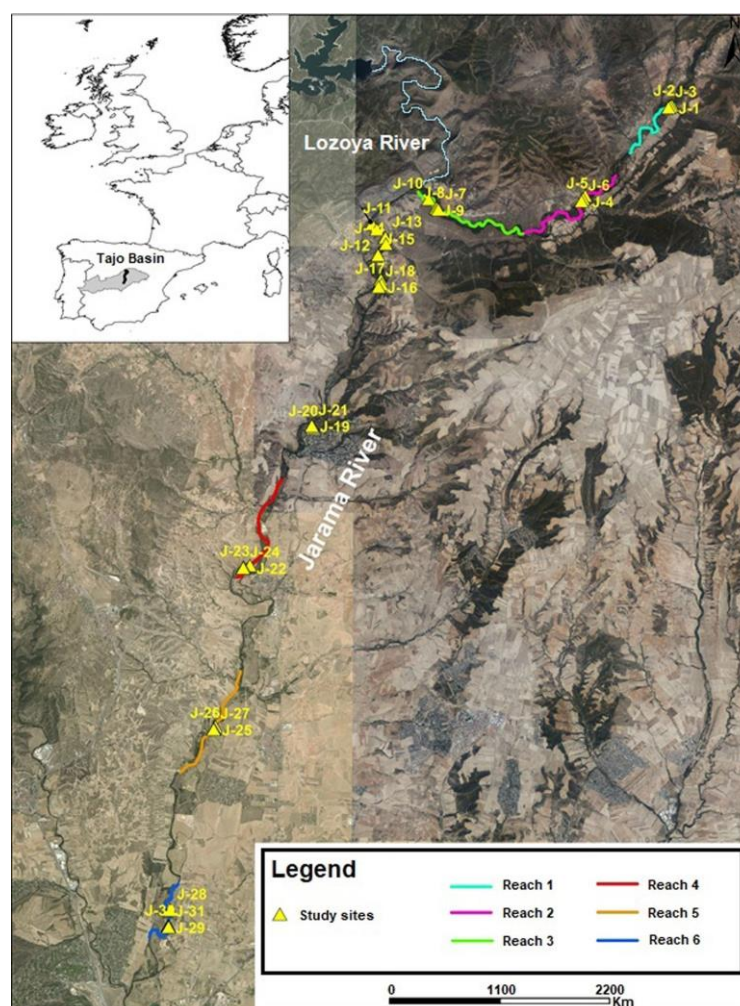


Figure 1. 1. Por qAerial photo showing the Jarama River study area in the Iberian Peninsula. Reaches for the morphological study and cross-sections were riparian vegetation and *Salix* recruitment was studied are shown.

Channel forms digitisation

Channel forms were manually digitised (scale 1: 2000) in the orthophotographs of years 1956, 1998 and 2018 in a GIS environment (pixel size of 0.5–1 m, 1 m and 0.25 m, respectively) with the help of a digital elevation model and the slope raster created from LIDAR point cloud (0.5 points/m²), all these data are available at www.ign.es. The study river segment was divided into six reaches based on their geomorphological characteristics. First, the zone occupied by the active channel in 1956 was digitised and considered as the reference for the subsequent analysis. Then, 5 cover types were digitised in 1956, 1998 and 2018 images:

(i) the active channel as the area covered by water and bare gravel bars, patches with (ii) grasslands, (iii) shrubs, (iv) medium and tall vegetation and finally, and (v) anthropic areas including agricultural lands. This analysis has been carried out using ArcGIS 10.1., the toolbox Fluvial Corridor (Roux et al. 2015), and Global Mapper V.20 to extract the digital elevation model and slope from LiDAR point cloud.

Morphological parameters and indexes

Reaches were selected from those not confined running through open valley (Figure 1.1). For each river reach, reach length (L), slope (%), active channel area (AC), active channel

width in m (ACW), and braided index (BI) calculated as the mean number of channels measured every 25 meters per reach, has been calculated in each year (Egozi and Ashmore 2008). Then, two temporal sub-periods were differentiated, the sub-period from 1956 to 1998, and the sub-period from 1998 to 2018 to calculate several indexes. First, the area of 'New Channel', the 'Abandoned Channel' and the 'Common channel' were calculated in each year respectively as the new, abandoned and the coincident area of the active channel between two consecutive aerial images. Then, Channel Migration Index (CMI) (Sanchis-Ibor et al. 2019) was calculated following Eq. (1) with higher values indicating high mobility.

$$CMI = \left(\frac{\text{New Channel} + \text{Abandoned Channel}}{\text{Common Channel}} \right) \quad (1)$$

Moreover, active channel change (ACC) was calculated following Eq. (2) (Richard et al. 2005) with negative values indicating a reduction of the active channel in that period of time, while positive values indicate an expansion of the active channel.

$$ACC = \frac{\text{Active Channel (year2)} - \text{Active Channel (year1)}}{\text{year2} - \text{year1}} \quad (2)$$

ha/year

Hydrological data and analysis

Mean daily discharge data from gauges close to the studied reaches (<http://hercules.cedex.es/anuarioa-foros/default.asp>) were analysed (Figure 1). Particularly data from gauge station #3051 (Algete) were used to analyse flow patterns during the study period. Unfortunately, the series was incomplete for the period 1949–1969. These data were estimated from station #3052 (Mejorada) located several kilometers downstream station #3051 (see Figure 1.1) and from #3062 (Espinillos) at Henares River (affluent in between).

According to the date of analysed aerial images, three ten year periods were considered: 1946–1956 (before first photo), 1962–1972 and 2008–2018 (before last photo). Characteristics of mean, maximum and minimum annual flows were analyzed for the three periods.

Evolution of landforms and vegetation cover

Five transition classes were defined in order to analyse the temporal evolution of cover types in the fluvial zone (based on Corenblit et al. 2010): *Maturation* process is the transition to a more mature stage as any change that leads to the natural succession in the evolutionary sense of a natural vegetation mass, for example, the natural growth of a mature forest or the change from active channel to shrub patches; *Rejuvenation* which is the inverse change, that is, the regression to pioneer stages of the community; *No change* category represents an unalterable transition in vegetation cover or landforms, particularly we defined *permanent active channel* as those areas remaining as Active Channel areas; *Anthropisation* is defined as the change from natural cover, either bare gravel bar or riparian vegetation cover to anthropic cover such as crops or urban areas; and *Naturalisation* as the transition from anthropic areas to natural covers, either bare gravel areas or vegetated areas.

Riparian vegetation inventory and analysis

Riparian vegetation was inventoried along 31 transects (6 m wide) perpendicular to the main channel, along the middle reaches of Jarama River. Each individual was characterised by the distance from the shore, the diameter at breast height, and the dynamic zones of vegetation-hydromorphology interactions in which they were found following Gurnell et al. (2016). A total of five lateral zones were defined by these authors based on the hydro-morphological constraints that are typically found in rivers where soil moisture, flow disturbance regime and riparian vegetation interactions are the key elements. Zone 1 is the perennially inundated zone where the main interaction processes take place between aquatic plant growth, water flow velocity, and erosion or sedimentation of the river bed. Zone 2 and Zone 3 are frequently inundated and both are fluvial disturbance dominated, with coarse sediment and erosion processes being frequent in the former while finer sediment deposition domain in the latter. Zone 4 is occasionally inundated without significant sediment dynamics, then riparian plants used to vary according to the inundation tolerance. Finally, Zone 5 presents a soil moisture regime dominated where the inundation is absent and plants depend on local soil moisture conditions.

Each transect was geolocated by GPS and later at the desk, the altitudinal profile was inferred from the digital elevation model already described, then the position of each individual plant was determined along with its altitude.

Vegetation recruitment analysis

The analysis of riparian species considering both seedlings and saplings was done in two ways: One based on the vegetation inventory transects described before, in which specimens of detected saplings (height < 1.5 m) were located on the cross section and the elevation of plant relative to the water level in the river was measured. The second method consisted on traveling along the riverbed in the study segment searching for suitable habitats for the colonisation and establishment of seedlings, such as gravel and sand bars. In the habitats where seedlings were found, experimental plots (5–10 m²) were established in June to evaluate saplings survival until the end of September. Plots were marked with metal pegs, delimited with rope and located at different distances between 0 and 2.50 m from the shore. In each plot the number of seedlings and saplings was counted, each plant was identified at species level and its height (cm) was measured. In addition, the presence or absence of herbaceous cover inside the plot was indicated, and the substrate size was characterised by the 50th percentile of the average diameter of at least 100 gravels (D₅₀). Once field data were taken, the total density (number of individuals/m²) and the mean height per species within each plot were calculated. By comparison between June and September data, the rate of survival (September density/June density) was calculated and particularly when the survival rate is greater than 1 the excess would correspond to recruitment in summer. We evaluate the edaphic capacity of the plot by means of the Fredde index that quantifies the size of the spaces between the substrate particles. This index is calculated as the ratio of the median diameter of gravels between the dispersion coefficients of the diameter distribution.

3. Results

Morphological conditions and evolution

Results from the morphological characterisation of Jarama River (Table 1.1) show that upstream reaches (i.e. R1, R2 and R3) are more confined and present the highest slopes of the river (>0.4%), while the reaches located downstream the confluence with Lozoya River (i.e. R4, R5 and R6) present lower slope values (<0.3%). All reaches presented braiding index higher than 1.20 in 1956 reaching maximum values of 1.98 in the case of R5. Results

show a steady decrease of active channel width and braiding index along the studied period for all reaches, with the first sub-period presenting a higher width reduction.

Table 1. 1. Morphological parameters of the studied reaches in Jarama River: active channel width (ACW) and braided index (BI).

ACW (m)			BI					
Reach Length (km)		Slope (%)	1956	1998	2018	1956	1998	2018
R1	3.21	0.47	94.9	38.0	13.1	1.31	1.23	1.15
R2	5.02	0.44	142.9	12.7	11.5	1.44	1.05	1.00
R3	5.11	0.41	104.1	18.2	9.3	1.26	1.16	1.11
R4	4.59	0.24	148.1	17.0	14.9	1.42	1.05	1.05
R5	4.49	0.27	269.1	29.1	18.3	1.98	1.26	1.16
R6	3.10	0.23	137.4	19.5	15.7	1.62	1.14	1.00

Regarding indexes of channel mobility (Figure 1.2B), CMI in the first sub period was considerably higher ranging from 1.72 in R1 to 11.52 in R5, while in the second period the mobility has been considerably reduced ranging from 0.20 in R2 to 2.46 R1. The process of channel narrowing can be seen in the negative values of ACC for all reaches with maximum loss for the initially widest reach (i.e. R5) (Figure 2A).

Flow regime trends in the study area along the three analysed periods

Figure 3 shows daily average flows for two analysed periods, corresponding to the decades before studied aerial images and a third one intermediate. Table 1.2 presents average values of mean, maximum and minimum annual flows for each period. Average daily discharge has decreased practically throughout the entire year. Mean annual flow decreased during the last two periods, with a cumulative decrease in both cases (8.7% and 55.3%, respectively) regarding the first one (Table 1.2). Maximum flows for the last period show a clear reduction not only in magnitude (54%) but also in the duration of the year period when they occur (it used to be from November–June, and nowadays is from February–May). On the other hand, the average annual minimum flow increased along periods, with an increase of 14.2% in the second period, and specially an increase of 419% in the last period compared to the first one.

Evolution of landform and vegetation cover

An example of the distribution of different landform and vegetation cover types along a Jarama R. reach (R3) is shown in Figure 4. Dealing with its evolution along time, it is observed that in the years 1956 and 1998 maturation processes of the corridor are very predominant, with more than 50% of the surface showing this process in R1, R2, R3 and R5 (Figure 1.5). In the rest of the reaches, this process exceeds 40% of the surface. The anthropisation process is quite evident in downstream sections, being around 30% of the surface in R5 and R6. On the other hand, a certain percentage of rejuvenated channel is found (any change that leads to a natural regression towards earlier stages of the successional stage, for example, transformation from grassland to active channel) in the lower reaches characterised by a wide valley and more active channel platform. Finally, the maintenance

of unchanged forms also represents a high percentage in this time interval, although it is much more evident between 1998 and 2018.

In the second stage analysed, from 1998 to 2018, after the dominance of the maturation processes in the first subperiod, a stage without changes (around 60%) of channel forms occurs, maintaining the landforms present in 1998. The maturation process decreases as well than anthropisation, although they account for a large percentage of the total. It should be noted that in this period naturalization increases due to the renaturalisation of certain previously anthropised spaces. Finally, in the lower sections, an increase in rejuvenation can be seen (around 10% of the surface in sections R5 and R6).

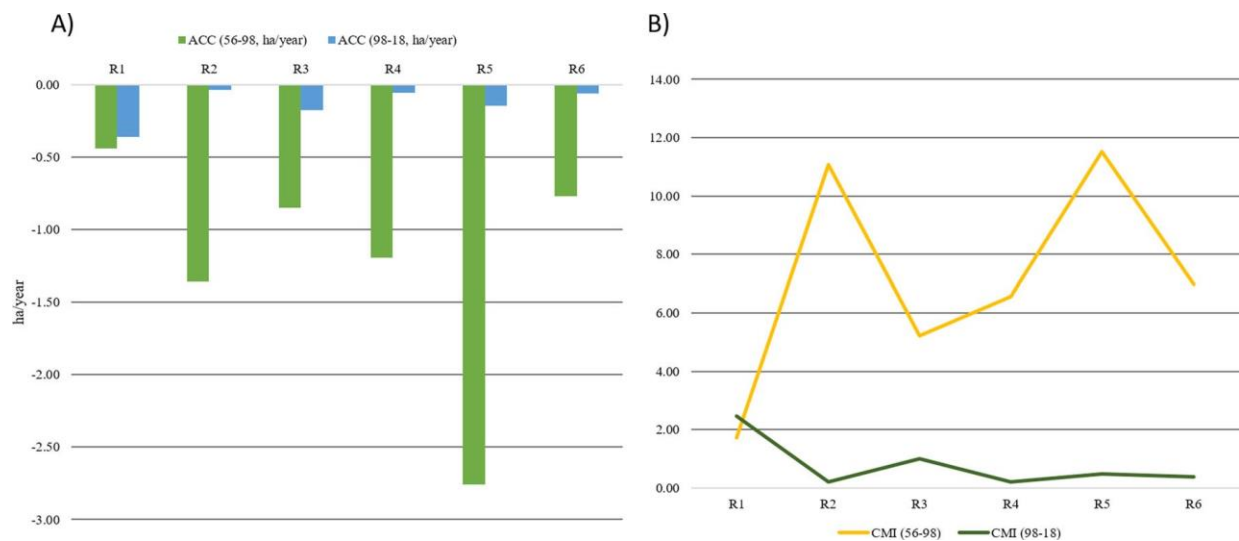


Figure 1. 2. Active channel change (ACC) (left diagram) and Channel Migration Index (CMI) (right diagram) values for the sub periods analysed, from 1956 to 1998 and from 1998 to 2018.

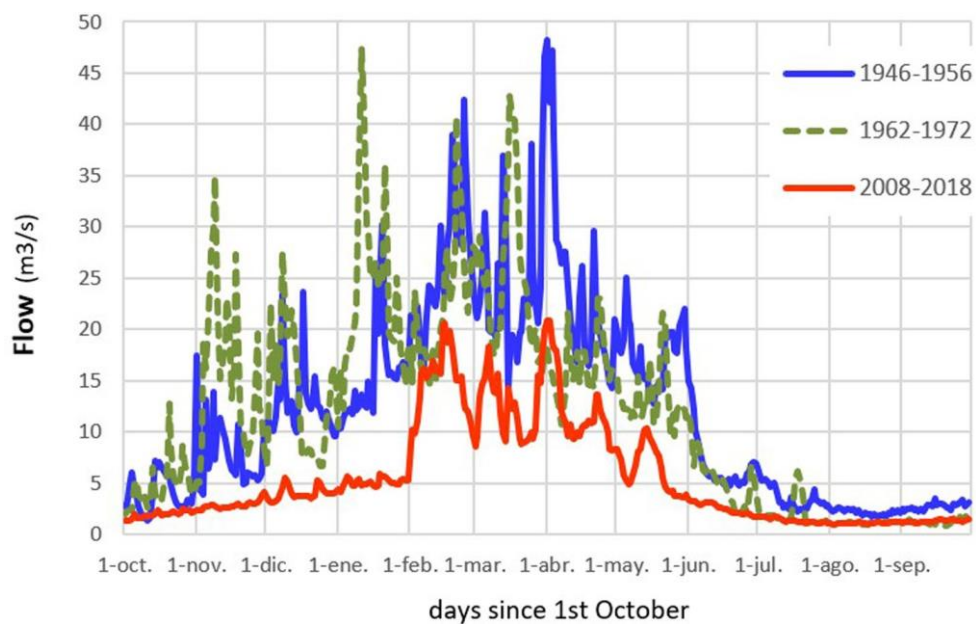


Figure 1. 3. Average daily flow (m³/s) data along the studied period considering three different subperiods: 1946–1956 (before first aerial photo); 1962–1972; 2008–2018 (before last aerial photo).

Table 1. 2. Characteristic discharges estimated for the studied periods. % of cumulative change has been estimated in relation to the first period.

	Period		
	1946–1956	1969–1979	2008–2018
Average annual flow (m ³ /s) (% change)	12.2	11.2 (–8.7)	5.5 (–55.3)
Maximum annual flow (m ³ /s) (% change)	138	177 (+28.1)	64 (–54.0)
Minimum annual flow (m ³ /s) (% change)	0.17	0.20 (+14.2)	0.6 (+419)

Riparian vegetation

Results of woody species inventory included 1120 individuals that were identified and whose location in the transects was determined. The woody vegetation composition of the Jarama riparian system includes 25 species and it is clearly dominated by ash (*Fraxinus angustifolia*) with the 25% of the individuals (Figure 1.6). Willow brushes are dominated by

S. salviifolia, an endemic species adapted to drought (14%), but also pioneer engineering willows are present as *S. eleagnos* (2.2%) and *S. purpurea* (0.7%). The only willow tree present is *Salix fragilis*, although rare (2.3%). Poplars are represented by *P. nigra* (11.2%) and *P. alba* (10.1%). Other drought tolerant species are *Tamarix* spp. (11%) that also may behave as a pioneer engineering species; *Crataegus monogyna* (6.6%) a zoochorian species, and *Ulmus minor* (6.5%).

Most of the species lack of a tendency on their longitudinal distribution, but *Alnus glutinosa*, *Salix eleagnos* and *S. purpurea* are more frequent and abundant upstream of Lozoya River confluence (i.e. sections from J-1 to J-10 in Figure 1) than downstream. On the contrary, *S. fragilis* and *U. minor* are more frequent on the lower sections.

Density of woody vegetation resulted greater on the upstream sections (i.e. J-1 to J-18) than on the lower ones with mean values of 1.1 ind. m and 0.4 ind./m, respectively. The species located at a lower elevation with respect to the water level were *A. glutinosa*, *S. eleagnos*, *S. salviifolia* and *S. fragilis* (on average 0.42, 0.60, 0.73 and 0.98 m respectively), while the ones at higher elevation were *P. alba*, *U. minor* and *C. monogyna* (2.15 m, 1.72 m and 1.69 m).

Regarding the zones defined based on the conceptual model of vegetation-hydrogeomorphology interactions (Gurnell et al. 2016) in the Jarama River, Zone 3 (i.e. fluvial disturbed dominated with finer sediment deposition) domains representing 60% on average of the area, followed by Zone 4 (i.e. inundation dominated zone) covering 25% of the area on average, while Zone 2 (fluvial disturbed dominated with coarse sediment erosion and deposition) represents 8% of the area on average and Zone 5 (Soil moisture regime dominated Zone) with only 6% on average are scarce. Although most species are present in all zones, *S. eleagnos* and *S. fragilis* show a marked preference for Zone 2 (coarser sediment erosion and deposition) which is frequently inundated and present high sediment dynamics, while *P. alba*, *S. purpurea*, and *U. minor* individuals prevail in more stabilised areas such as the Zones 4 and 5, which are occasionally and rarely inundated respectively, where the inundation tolerance and the remaining soil moisture are the primary controls for vegetation. Of course, the distribution of these zones on cross-sections interacts with the gradient associated with the distance to the water (Figure 1.7) and this is also reflected in the species distribution due to its different ecological requirements.

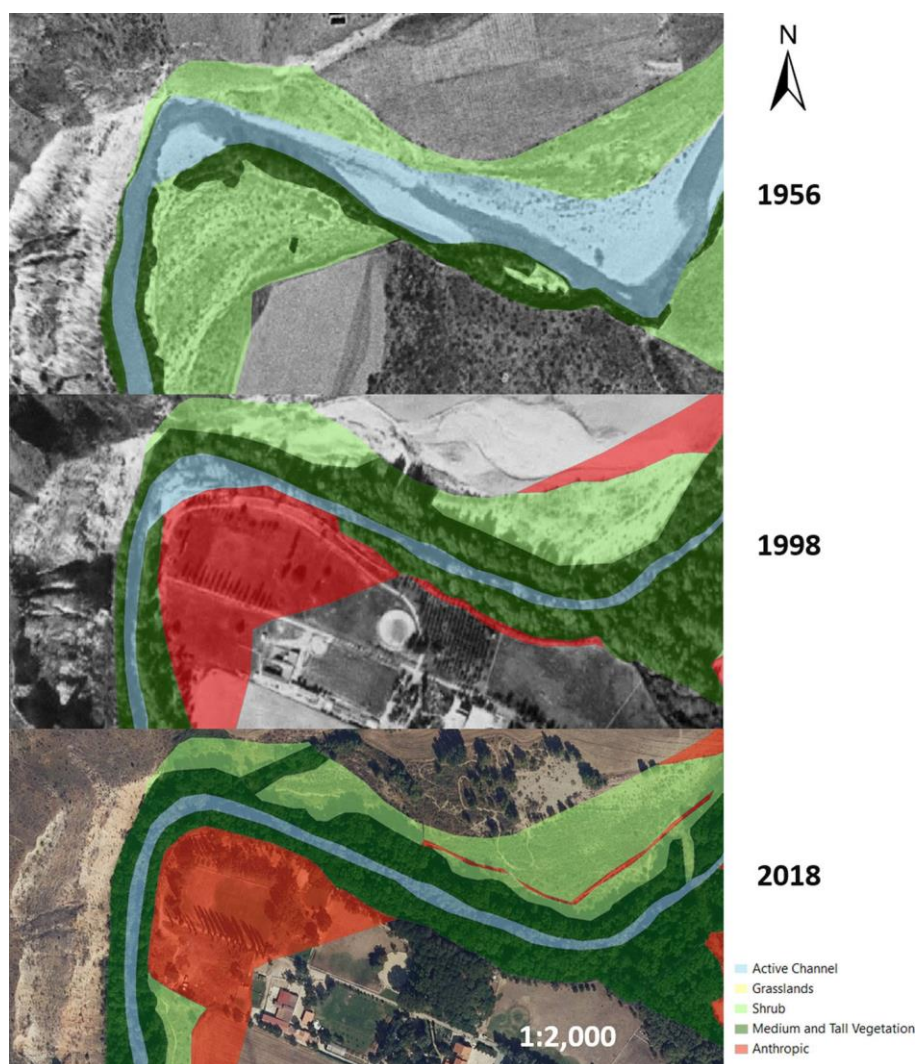


Figure 1. 4. Distribution of different landform and vegetation cover types along a reach (R3) of River Jarama in the studied aerial photographs.

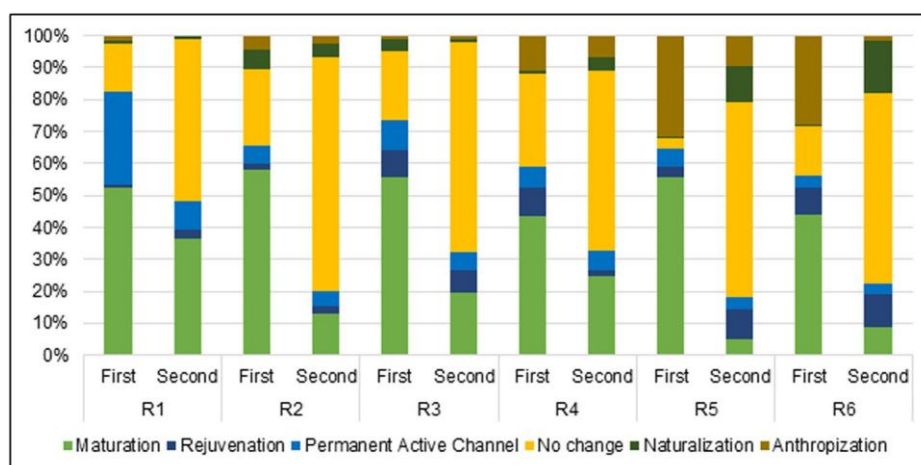


Figure 1. 5. Proportion of area for each transition type in each of the river reaches during the First (since 1956–1998) and the Second period (since 1998–2018).

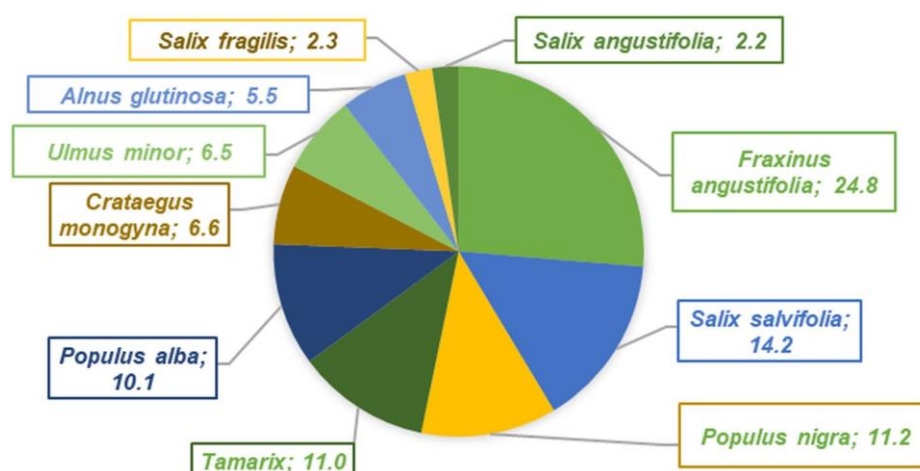


Figure 1. 6.Composition (%individuals) of main woody riparian species in the Jarama River.

Recruitment

In the analysis of the composition of transects, riparian recruitment was found in only 11 cross-sections (mainly below the confluence of the Lozoya River) of the 31 performed. Saplings were found only from seven riparian species and two hillside species (*Juglans regia* and *Acer monpessulanum*). The riparian species with the most abundant recruitment was *F. angustifolia* with 72 specimens distributed in 10 cross-sections, followed by *P. alba* with 30 individuals at only 4 sections and *P. nigra* presenting 19 individuals at six sections. Other species with recruitment were *U. minor* (12 individuals), *C. monogyna* (9 individuals), *S. salviifolia* (8 individuals) and *A. glutinosa* (4 individuals).

During the journeys along the river reaches, very few areas were found with recruitment of riparian vegetation woody species. Areas that could potentially host riparian regeneration were either covered with herbaceous plants that stifle only any attempts at riparian seed germination or covered by a dense canopy of mature forest whose shade also prevented any germination. Specifically, during the visit to various reaches of the Jarama river close to El Molar town (Reach 5), where the Mora-Navarro (2004) plots were located, no indication of regeneration was found. Exceptionally we were able to find some small areas with some riparian recruitment where we were able to establish only five plots all located upstream from Lozoya River confluence (Reach 3).

Table 1.2 shows the results of the analysis of the studied plots comparing before and after summer. We see that almost all the species present in the Jarama River recruit. Again, the ash (*F. angustifolia*) presents greater recruitment densities, but also *S. salviifolia*, *A. glutinosa* and *P. nigra* seedlings abound in the plots. Greater survival rates were found for *S. salviifolia*, *A. glutinosa* and *Tamarix* sp., while *P. alba*, *P. nigra* and *S. eleagnos* present greater mortalities. On the contrary, *P. alba* and *F. angustifolia* show greater length growth while *Tamarix*, *S. salviifolia* and *P. nigra* had negative growth due to grazing (field observation).

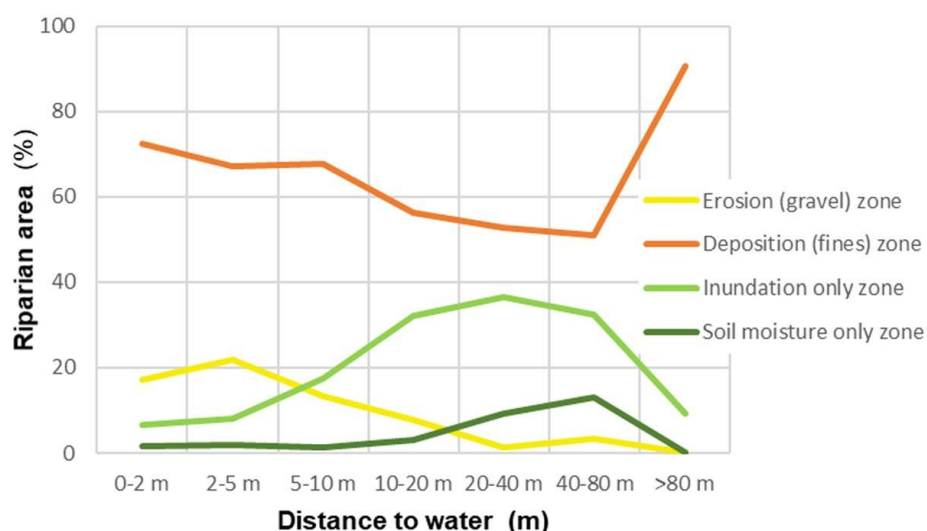


Figure 1. 7. Distribution of vegetation-hydromorphology interaction zones along lateral cross-sections, indicating their percentage area at different ranges of distance to water edge.

4. DISCUSSION

The Jarama River has experienced considerable changes since 1956, both in the braiding of its channels and in the colonisable unvegetated bars, conditioning the current composition and the structure of the vegetation. The reduction in braided index along the two subperiods characterizes a transformation from a wandering river to a single channel river due to the highly alteration of flows by dams, with a decrease of maximum discharges and the increase of minimum discharges that favours the establishment and growth of vegetation cover. This pattern of river simplification and stabilization in response to flow homogenization by dam regulation has been shown in North America rivers (Poff et al. 2007). Moreover, this river was highly affected by gravel mining since 1960s (Uribe Larrea et al. 2003) which led to an incision of the riverbed as well as a severe decline in the area occupied by gravel bars. They quantified that in 1999 more than 30% of the alluvial floodplain was affected by mining operations. Then, after 1960s changes in the Jarama River were mainly due to the combined effect of flow regulation and mining. Changes in Jarama River were similar to other rivers in the Mediterranean region, in which the synergistic effect of several pressures reduced the number of channels and the dimension of active channel (e.g. Segura-Beltrán and Sanchis-Ibor 2013; Martínez-Fernández, González del Tánago, et al. 2017; Batalla et al. 2018).

Associated with changes in braided index, the narrowing process of active channel, mainly in the first period with losses of 1.23 ha/year were strongly associated with changes in channel forms and the loss of secondary channels, which is in agreement with Uribe Larrea et al. (2003). Channel Migration Index decreased between 1956 and 2018, demonstrating a high loss of mobility zone associated with the active channel. Only Reach 1, a confined reach, shows similar values between these years. CMI reduction is a symptom of active channel decreasing dynamism, and this trend was also found in other Mediterranean rivers (Magdaleno and Fernández 2011; Sanchis-Ibor et al. 2019; Fazelpoor et al. 2021). All these variables and indicators show a trend toward the stabilisation of islands and floodplains observed in the temperate context on several rivers (Liebault and Piegay 2002; Gurnell and Petts 2006; Corenblit et al. 2010). Stabilisation of ancient active channels or bars generate a process that conduces to the encroachment of vegetation (O'Briain 2019; García de Jalon et al. 2020). Maturation process, transition from initial or pioneer geomorphic phase to a more complex structures (i.e. biogeomorphic phase based on Corenblit et al. 2010), is the dominant change in

the first period studied, coinciding with the decline of active channel, the reduction of channel mobility and the transformation into a single channel. Additionally, no signs of naturalisation were found in the first period studied but an anthropisation process affected downstream reaches. In the second period, the processes associated to the stabilisation of the channel forms predominated, due to the low capacity for change and probably to the increase in plant density (i.e. encroachment) and soil formation, increasing the resistance of the canopy against the erosive action of floods (Ishikawa et al. 2003; Tal et al. 2004). All these changes are related to several pressures associated with the loss of dynamism, reducing transition to active areas which is of great importance in the temperate context and essential for the pioneer vegetation that colonizes these spaces (Corenblit et al. 2007; Rivaes et al. 2013; González del Tánago et al. 2016) (Table 3).

Consistent with the decrease of bare gravel bars where disturbance-adapted species as willows used to inhabit, which is in agreement with the relatively low proportion of Zone 2 (coarser sediment erosion and deposition) within the fluvial corridor (8% on average), very few areas were found with recruitment of riparian vegetation woody species during field campaigns. Even in those zones where intensive recruitment was found in the past by Mora-Navarro (2004), the present study does not detect regeneration. *S. eleagnos* and *S. fragilis* show a marked preference for Zone 2 (coarser sediment erosion and deposition) which is exposed to frequent flood disturbance, while *P. alba*, *S. purpurea*, and *U. minor* individuals dominate more stabilised areas such as the Zones 4 and 5, which are occasionally and rarely inundated respectively. The regeneration of *Salix* species, among other riparian species here analysed, although restricted to small areas in the riparian corridor, still takes place in the Jarama River. Then, either problems with parent trees availability, seed dispersal or viability seems to be absent. Therefore, main obstacle for the successful regeneration of *Salix* species is link to the lack of adequate areas for recruitment, such as bare gravel bars and sand bars, greatly reduced by the intense gravel mining activities several decades ago together with the construction of dams.

Releasing large pulse flows from dams and reservoirs has been proposed previously in other regions as a cost-effective solution to reactivate the creation of safe-sites where *Salix* can regenerate (e.g. Dixon et al. 2015; Johnson et al. 2015; Glenn et al. 2017). Given the high level of vegetation encroachment presenting by this fluvial system, may other pro-active measures such the reconnection with secondary channels or the removal of some vegetation could help in the recovering process in such a simplified system. Longitudinal and lateral connectivity are also essential for the promotion of *Salix* establishment (Hughes et al., 2012; González et al. 2018). To recover this connectivity, managers could undertake actions to eliminate weirs or levees and other embankments that constraint the channel dynamism and impede its natural migration, which resulted to some extent successful in previous applications (e.g. Rohde et al. 2005; Martínez-Fernández, González, et al. 2017)

Table 1. 3. Density and mean length of saplings found in the five studied plots, before (June) and after (September) the summer, showing survival ratio and mean length growth.

		June		September		Survival (%)	Length Growth (%)
		Density (ind/m ²)	Height (cm)	Density (ind/m ²)	Height (cm)		
Plot 1	<i>Alnus glutinosa</i>	2.20	22.8	3.02	28.5	138	25.1
	<i>Populus nigra</i>	0.27	20.0	0.27	20.0	100	0.0
Plot 2	<i>Populus alba</i>	1.40	24.2	0.47	31.3	33	29.4
	<i>Alnus glutinosa</i>	1.25	14.4	1.25	12.4	100	-13.6
	<i>Salix eleagnos</i>	1.25	16.4	0.78	13.3	63	-18.8
	<i>Populus nigra</i>	0.93	30.3	0.78	17.8	83	-41.3
	<i>Fraxinus angustifolia</i>	0.62	15.6	1.25	23.6	200	51.5
	<i>Salix purpurea</i>	0.16	11.0	0.31	35.0	200	218.2
Plot 3	<i>Salix salviifolia</i>	0.16	21.0	1.09	15.2	700	-27.8
	<i>Salix salviifolia</i>	3.03	34.9	2.42	31.6	80	-9.7
	<i>Populus nigra</i>	0.40	21.0	0.20	8.5	50	-59.5
	<i>Alnus glutinosa</i>	0.20	20.0	0.61	16.6	300	-17.2
	<i>Salix fragilis</i>	0.00	-	0.20	28.0	-	-
	<i>Fraxinus angustifolia</i>	0.00	-	0.40	22.5	-	-
	<i>Salix eleagnos</i>	0.00	-	0.20	32.0	-	-
	<i>Fraxinus angustifolia</i>	5.26	36.24	7.57	36.24	144	0.0
Plot 4	<i>Alnus glutinosa</i>	0.42	35.00	0.42	35.00	100	0.0
	<i>Populus nigra</i>	0.00	-	0.21	22.00	-	-
	<i>Fraxinus angustifolia</i>	5.26	36.24	7.57	36.24	144	0.0
Plot 5	<i>Populus nigra</i>	2.68	21.0	2.35	18.8	88	-10.3
	<i>Salix salviifolia</i>	1.34	30.0	1.68	25.4	125	-15.4
	<i>Salix eleagnos</i>	0.67	35.0	0.67	27.0	100	-22.9
	<i>Tamarix</i>	0.67	44.5	1.01	34.7	150	-22.1
	<i>Fraxinus angustifolia</i>	0.34	11.0	0.34	10.0	100	-9.1

5. CONCLUSIONS

The geomorphic trajectory that the Jarama River has followed is clear. Active channel narrowing and transformation of branched sections into single channel processes, associated with a great loss of its mobility, took place mainly at the end of the twentieth century. Landform evolution shows an intensive 'maturation' associated with anthropisation processes that dominate during this first period, while stability ('no change' process) dominates in this 21st century. On the contrary, the 'rejuvenation' process is practically negligible.

Analysis of the riparian transects showed a dominance of the fine deposition zones (60% on average) even at water margins, while the erosional gravel zones (which is the characteristic habitat of the pioneer willow species) were very scarce (8% on average).

The dominant willow species is *S. salviifolia*, adrought tolerant willow that has been able to withstand the processes of 'maturation', channel narrowing and the loss of channel mobility being widely distributed throughout the riparian section. On the other hand, other strict pioneer willows such as *S. eleagnos* and *S. purpurea* are very rare and are found in the few gravel banks that remain on the shore.

Riparian recruitment along surveyed sections was only found below Lozoya River confluence but did not include willows except for a few specimens of *S. salviifolia*. On the contrary, recruitment plots were only possible to establish at reach 3, upstream Lozoya River confluence. In these plots, recruits of *S. salviifolia* and *S. eleagnos* were found in remarkable densities, although recruits of *S. purpurea* and *S. fragilis* were also present.

The overall scenarios here described are predicting a gradual disappearance of the willows in the Jarama River as there is no significant recruitment along the Jarama River, and they will last as long if those old specimens germinated in the period from 1960 to 1990 may survive.

3.2. El declive de los sauces en corredores riparios sobre vegetados

3.3. TECNOLOGÍAS Y MARCO METODOLÓGICO PARA EL SEGUIMIENTO AMMBIENTAL DE RIBERAS



3.3.1. SEGUIMIENTO AMBIENTAL EN RIBERAS MEDIANTE TECNOLOGÍA LIDAR

1. INTRODUCCIÓN

Los corredores riparios desempeñan un papel fundamental en el funcionamiento de los ecosistemas fluviales, actuando como corredores ecológicos entre el ecosistema acuático y el terrestre (Naiman & Decamps, 1997; Naiman, Decamps, & McClain, 2005), interaccionando con el funcionamiento hidrológico (Decamps et al., 2004; Dixon et al., 2016), proveyendo alimento y refugio a la fauna (Johnson, Richards, Host, & Arthur, 1997), y aportando un valor cultural a sus espacios (Klein et al., 2015). Su composición, atributos y estructura son indicadores del estado de las zonas ribereñas y sus cauces (Gregory et al., 1991; Naiman, Decamps & Pollock, 1993). Las perturbaciones naturales, principalmente las avenidas, son la base del mantenimiento de una zona riparia diversa, por lo que una reducción de su frecuencia e intensidad asociadas a un régimen hidrológico alterado produce cambios en la diversidad de hábitats, afectando a su correcto funcionamiento (Ward, Robinson, & Tockner, 2002), siendo la regulación de caudales por presas y embalses la alteración más frecuente.

Además, los bosques de ribera también se ven afectados globalmente por diversas actividades antrópicas como el cambio de usos en la llanura de inundación, la reforestación de la cuenca vertiente, la entrada de especies exóticas y más recientemente el cambio climático (Gordon & Meentemeyer, 2006; Stromberg et al., 2007; González et al., 2010; González del Tánago, Martínez-Fernández & García de Jalón, 2016). En las llanuras aluviales condicionadas por la actividad humana, los corredores riparios se ven limitados a ocupar espacios estrechos presentando una alta densidad de vegetación donde la regeneración es escasa (Cordes Hughes & Getty, 1997; Cooper & Andersen 2012) y se favorece el proceso de estabilización y maduración de la vegetación (*vegetation encroachment*) (García de Jalón et al., 2020). En estas zonas la construcción de estructuras transversales al cauce, como azudes para derivar agua, están muy extendidas, generando una discontinuidad longitudinal en los cauces tanto para la componente biótica (i.e., peces y macroinvertebrados) como abiótica (i.e., caudales sólidos y líquidos). Aunque sean de pequeño tamaño (altura inferior a 2 m), la presencia de estas estructuras genera cambios en el funcionamiento geomorfológico e hidrológico transversal (Boix-Fayos et al., 2008) así como en la estructura de la vegetación riparia (Göthe et al., 2015).

Una forma de restaurar el buen funcionamiento del ecosistema ripario es eliminando o permeabilizando estas barreras, más aún cuando entran en desuso, con el objetivo de promover los procesos geomorfológicos e hidrológicos naturales, además de favorecer el establecimiento de especies autóctonas pioneras en los espacios perturbados, recuperando los ciclos naturales de sucesión y rejuvenecimiento del corredor (Geerling et al., 2008). La eliminación de pequeños azudes se engloba dentro de las acciones de restauración fluvial, y diversos estudios demuestran una recuperación de la diversidad y heterogeneidad del corredor tras su eliminación (e.g., Im et al., 2011; Martínez-Fernández et al., 2017). La monitorización y seguimiento de la evolución del corredor fluvial tras este tipo de actuaciones de restauración es fundamental para analizar las consecuencias en todos los componentes del ecosistema de manera que sirva de base de conocimiento en otras actuaciones. Por lo tanto, es crucial el diseño de metodologías y protocolos que sirvan a este fin y orienten futuras intervenciones en caso de ser necesarias para alcanzar objetivos establecidos.

Particularmente, para conocer la evolución de la vegetación riparia tras una restauración o para valorar el estado actual en el que se encuentra, se suelen calcular algunos atributos asociados a cualquier masa arbolada mediante la técnica convencional de muestreo de campo. Sin embargo, en los últimos años, los muestreos de campo se han ido complementando con

otras tecnologías más novedosas, como la fotogrametría o la teledetección (e.g., Huylenbroeck et al., 2021), si bien es cierto que los datos de campo son necesarios para la validación de los datos obtenidos con estas tecnologías mediante métodos estadísticos de regresión (Ortiz-Reyes et al., 2015; Laslier, Hubert-Moy & Dufour, 2019). La teledetección ofrece actualmente productos diversos, y metodologías y técnicas aplicables a la medición dendrométrica y dasométrica de masas arboladas, que complementan a los inventarios tradicionales (Ortiz-Reyes et al., 2015), como es el caso de la tecnología LiDAR (Light Detection And Ranging). Existen sistemas LiDAR con alta y baja densidad de puntos, por ejemplo el LiDAR-PNOA tiene una densidad baja. Estos sistemas permiten estimar parámetros forestales como el diámetro a la altura del pecho (DAP), la altura, biomasa y densidad de ramas (Jochem et al., 2010; Moe et al., 2020) con resultados muy precisos (Johansen et al., 2010; Sullivan et al., 2017; Mielcarek, Stereńczak & Khosravipour, 2018; Laslier et al., 2019). Los corredores riparios, a diferencia de otras formaciones boscosas (i.e., repoblaciones de coníferas o masas adehesadas), presentan una alta complejidad estructural debido a su riqueza de especies y su estructura vertical (Fassnacht et al., 2016). Aun siendo complejo el proceso de obtención de parámetros forestales en estas masas arboladas, en las últimas décadas, se han obtenido datos de interés selvícola y forestal a partir de la teledetección para generar mapas precisos de los atributos de los corredores riparios (Riedler et al., 2015; Michez et al., 2016a; Michez et al., 2016b). Los datos LiDAR en corredores riparios aportan una información muy útil a través del Modelo Digital de Copas (MDC), que describe las alturas del corredor a gran escala (Michez et al., 2014). Por esta razón, la tecnología LiDAR podría contribuir al seguimiento ambiental de los corredores riparios haciendo más eficiente la valoración de los cambios a lo largo del tiempo.

En este contexto, el objetivo de este estudio es valorar la utilidad del uso de la tecnología LiDAR para el seguimiento ambiental de riberas. Particularmente, se analizan los cambios experimentados por un tramo de río sometido a una restauración fluvial que consistió en la demolición de un azud considerando el contexto geomorfológico en el que tiene lugar y analizando su evolución.

En este estudio se evalúan los cambios estructurales del corredor ripario y la evolución geomorfológica entre los años 2009-2016 a través de datos LiDAR, ortofotografías aéreas y trabajo de campo tras la demolición de un azud en el año 2009, para conocer si ha mejorado la conectividad funcional y estructural de la vegetación riparia.

2. METODOLOGÍA

2.1. Zona de estudio

En el tramo de estudio tuvo lugar la demolición de un azud en el año 2009 (ETRS89; UTM30N; X:430683, Y: 4530068) dentro del “Proyecto de mejora de la continuidad longitudinal del cauce del río Lozoya, aguas arriba de la presa de Pinilla, ubicado en el Término Municipal de Pinilla del Valle, Comunidad de Madrid” (Figura 2.1), con los objetivos de mejora de la continuidad longitudinal y la mejora de la composición y estructura de la vegetación de ribera (Infraeco, 2009). Con una cuenca vertiente de 1265 km² este río nace en el extremo occidental del Parque Nacional de la Sierra de Guadarrama a 2428 m de altitud y desemboca en el río Jarama a 692 m. La cuenca presenta una pendiente media del 24 % y gran parte de su superficie está ocupada por bosques. (CORINE Land Cover, 2012). Su geología está dominada por materiales silíceos, gneises paleozoicos y granitos del Carbonífero que ocupan casi todos los cursos superiores e inferiores del río. La cuenca está influenciada por un clima mediterráneo húmedo, presentando una temperatura media anual de 10,4 ° C y una precipitación media anual

de 520 mm. El río Lozoya está integrado en el grupo de ríos de media montaña según la clasificación de los ríos Ibéricos de Masachs (1948). Está catalogado dentro de los Ríos de montaña mediterránea silíceo (código del tramo, ES030MSPF0450010). El régimen de caudales se encuentra regulado en sus tramos medio y bajo por una consecución de grandes presas. En periodos previos a 1972 presenta un régimen nival, mientras que en los periodos más recientes la tendencia es hacia un régimen pluvial, debido a la pérdida de su máximo absoluto del deshielo (González del Tánago, García de Jalón & Rincón Sanz, 2016). El caudal medio anual del río según la estación de aforos de Paular (ETRS89; UTM30N; X: 425430, Y: 4522276) es de $1,37 \text{ m}^3 / \text{s}$ de 1967 a 2015 y de $4,84 \text{ m}^3 / \text{s}$ de la estación de aforo de Pinilla (UTM30; X: 434830, Y: 4533015). El embalse de Pinilla tiene caudales regulados desde 1967 para suministro de agua y generación de energía hidroeléctrica.

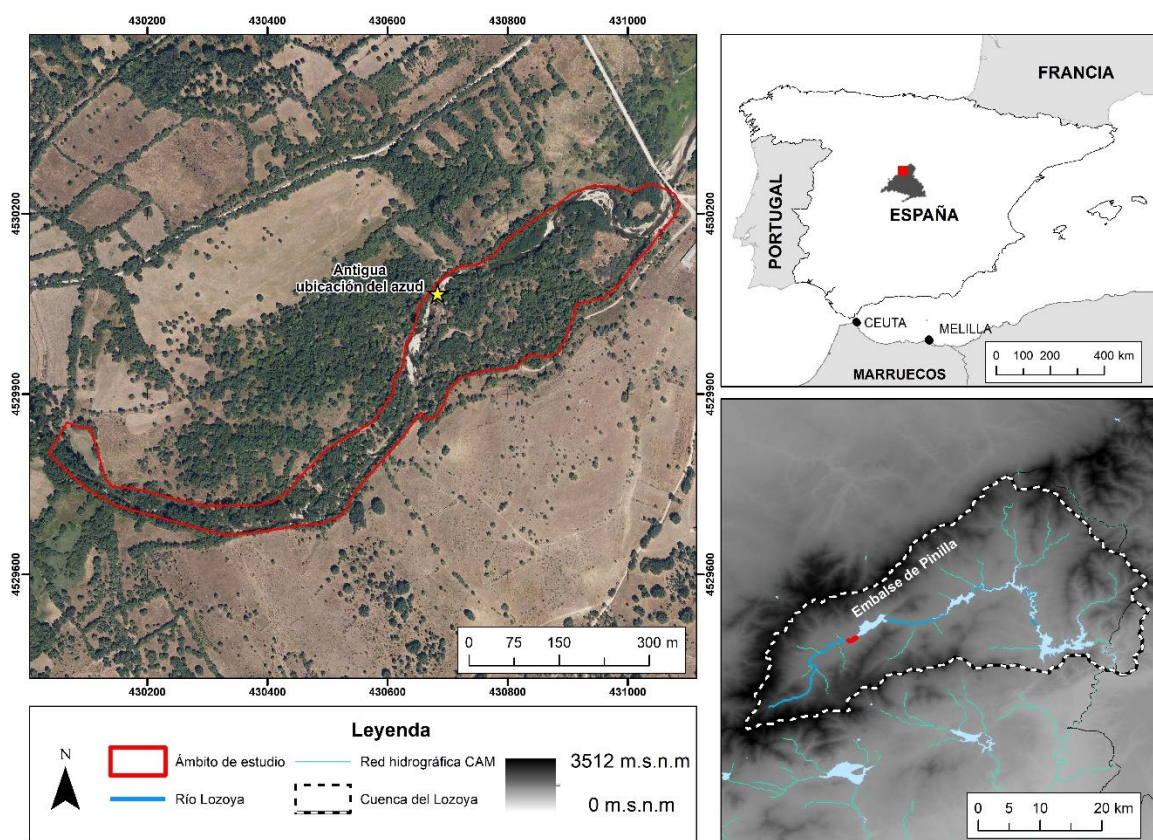


Figura 2. 1. Localización del área de estudio. Ortofoto del PNOA correspondiente al año 2016.

Fuente: Instituto Geográfico Nacional. Elaboración propia de los autores

El tramo de estudio tiene una longitud de 1.4 km y se ubica aguas arriba del embalse de Pinilla, siendo el límite inferior la cola de este embalse. En primer lugar, se digitalizó el cauce, entendiendo por cauce la zona funcional que incluye lámina de agua, sedimentos y llanura de inundación, del río Lozoya en el año 1956. La superficie total del polígono generado fue de 11,95 ha y se utilizó como punto de partida para los análisis posteriores.

2.2. Caracterización geomorfológica del tramo mediante fotointerpretación

Se analizaron los cambios geomorfológicos de los últimos 60 años mediante la interpretación de ortofotos de los años 1956 (junio) 1980 (junio), 2002 (octubre), 2009 (junio), 2014 (julio) y 2017 (agosto), con un tamaño de píxel de 0,5-1 m para las ortofotos de 1956, 0,25-0,50 m para

los vuelos de 1977, 2002, 2009 y 2014, y 0,2-0,35 m para el vuelo más reciente, 2017, disponibles en Centro Nacional de Información Geográfica de España. Las formas del cauce se digitalizaron manualmente en los seis años diferentes para analizar los cambios en la geomorfología del río utilizando como punto de partida el área de ocupación fluvial del año 1956 utilizando ArcGIS (v10.1). Se distinguieron un total de cinco clases: (i) cauce activo (lámina de agua y barras de gravas), (ii) barras de gravas parcialmente vegetadas, (iii) zonas antropizadas (incluyendo sendas, caminos, pistas o cultivos), (iv) zonas parcialmente cubiertas por vegetación leñosa y (v) zonas totalmente cubiertas por vegetación leñosa.

2.3. Caracterización de la estructura de la vegetación riparia mediante tecnología LiDAR entre 2010 y 2016

2.3.1. Procesado de datos LiDAR

Los datos LiDAR fueron obtenidos del proyecto PNOA (Plan Nacional de Ortofotografía Aérea). Según esta fuente, se trata de sensores LiDAR aerotransportados con una densidad de puntos es de 0,5 puntos/m² en la primera cobertura y de 0,5-4 puntos/m² en la segunda cobertura, existiendo excepciones en las que la densidad es aún mayor (proyecto PNOA-LiDAR). La nube de puntos correspondiente al año 2010 se realizó con un sensor de frecuencia de escaneado mínima de 70Hz, debiendo alcanzar un mínimo de 40 Hz con un Campo de visión transversal (FOV) de 50°, la frecuencia de pulso mínima de 45 kHz, asumiendo un FOV de 50° y un máximo alcance de hasta 3000 metros, cumpliendo una densidad media 0,5 puntos por metro cuadrado. En el caso de la nube de puntos del año 2016 se realizó con una frecuencia de escaneado y pulso igual que en el año 2010, aumentando la densidad media de puntos a 1 punto por metro cuadrado en el año 2016.

Para el tramo de estudio se han empleado los archivos LAZ correspondientes a 2 cuadrículas 2x2 km de la primera cobertura LiDAR-PNOA (0.5 pto/m²) con fecha de 23/10/2010 y 26/10/2010 (PNOA-2010-LOTE7-CYL-MAD-430-4530 y PNOA-2010-LOTE7-CYL-MAD-430-4532). En relación a la segunda cobertura se han utilizado 4 archivos LAZ, ya que la malla de la segunda cobertura en algunas zonas es de 1x1 km (PNOA-2016-MAD-430-4530, PNOA-2016-MAD-430-4531, PNOA-2016-MAD-431-4530 y PNOA-2016-MAD-431-4531) con una densidad de 1 pto/m². Las pasadas de estos vuelos (2ª cobertura LiDAR-PNOA) se realizaron en septiembre de 2016.

El procesado de las dos nubes de puntos LiDAR (2010 y 2016) se realizó en Global Mapper V.20. (producido por Blue Marble Geographics Company). Para ello se realizó un filtrado de puntos (mediante la herramienta Filter LiDAR Data), incluyendo en primer lugar los clasificados como suelo. A partir de los puntos clasificados como suelo se generó (mediante el método *Binning* con la opción del mínimo valor) el Modelo Digital de Elevaciones (MDE) con el objetivo de normalizar la nube de puntos, obteniendo las cotas del terreno. A continuación, se incluyeron los puntos clasificados como suelo más vegetación generando el Modelo Digital de Superficies (DSM) mediante el método de *Binning* (con la opción del máximo valor). La diferencia entre ambos modelos (DSM-MDE) tiene como resultado el Modelo Digital de Superficies Normalizadas (MDSn). El MDE se generó para el año 2010 y 2016 con el mismo tamaño de pixel, reduciendo la resolución del año 2016 para igualarla en ambas fechas, al igual que en el caso del DSM. El tamaño del pixel de la capa resultante (MDSn) fue de 1,55 m de paso de malla (2,4 m²).

2.3.2. Estimación de variables dendrométricas y dasométricas de la vegetación riparia

En primer lugar, se realizó la clasificación de las manchas de vegetación en las imágenes con el fin de conocer las clases de cobertura presentes diferenciando entre vegetación leñosa y

otras coberturas, delimitando los contornos de copa. El cálculo de los datos de altura del dosel únicamente se realizó para las manchas con presencia de vegetación media y alta (superior a 1,5 metros de altura).

Para ello, se utilizó el complemento SCP (Semi- Automatic Classification Plugin) en el software QGIS 3.2.3. (Quantum GIS Development Team 2018). Esta clasificación semi-automática o supervisada clasifica las imágenes según su firma espectral mediante un entrenamiento automático utilizando regiones de interés (ROIs), que fue validada mediante el coeficiente Kappa (Cohen, 1960).

La clasificación se obtuvo a partir de las ortofotos del PNOA (años 2009 y 2017), que contienen tres bandas (Rojo, Verde y Azul), junto con imágenes de satélite multiespectrales que contienen la banda del infrarrojo, concretamente Sentinel-2 para agosto de 2017, y Landsat 7 para agosto de 2009. Con el objetivo de mejorar la clasificación de las imágenes se calculó el Índice de Vegetación de Diferencia Normalizada, o NDVI (Rouse et al, 1974) gracias a la incorporación de las imágenes multiespectrales.

Para la realización del entrenamiento previo a la clasificación (mediante ROIs, algoritmo de región incremental obtenido de manera automática), se han definido un total de 4 clases y 22 subclases representativas de la zona analizada. El resultado final es una clasificación de las coberturas en 4 clases: suelo desnudo (referidos a cualquier superficie carente de vegetación), agua, vegetación (vegetación leñosa, ya sea arbustiva o arbórea) y pastizal (Figura 2). Las subclases son empleadas como entrenamiento, no están definidas como tal, por ejemplo, son áreas ocupadas por vegetación leñosa (clase vegetación) y que sirven para mejorar el clasificador (valores espectrales de la imagen), los conjuntos de entrenamientos de cada subclase forman las clases.

En segundo lugar, para la obtención de árbol individual a partir del MDSn se empleó la delimitación de su copa en base a la segmentación de cuencas por morfología matemática (Beucher & Meyer, 2018). Para obtener la cuenca de cada árbol, fue necesario calcular la inversa de la MDSn generando como capa resultante el MDSn'. A partir del MDSn' se calculó la dirección de flujo y el flujo acumulado, como pasos previos a obtener las cuencas del dosel arbóreo. A partir de estas cuencas se obtuvieron los contornos de copa mediante la intersección de las cuencas con la clasificación de imágenes supervisada. La capa resultante se corresponde con los contornos de copa individualizados. Finalmente, se extraen los datos de tipo ráster en base a las geometrías de cuenca y se obtiene el máximo valor que alberga cada contorno que se corresponde con la altura para cada árbol así segmentado (Figura 2.2). Únicamente se incluyeron aquellos pies con altura mayor de 1.5 metros siguiendo a autores previos (Michez et al., 2013).

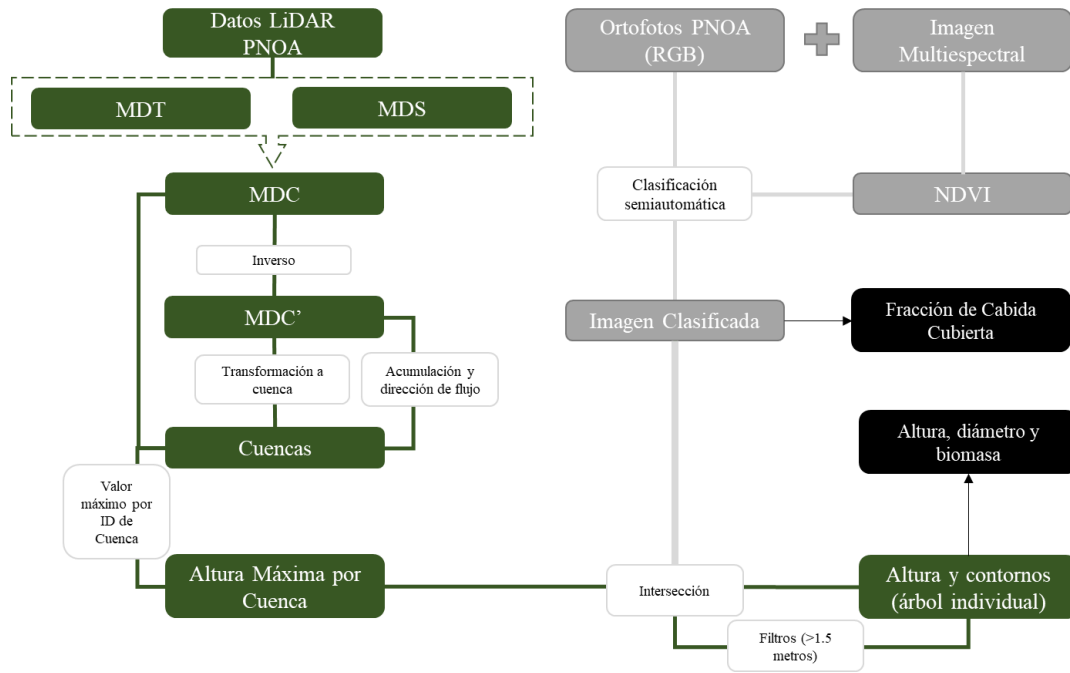


Figura 2. 2. Metodología propuesta para la obtención de las alturas y el contorno de copa individual. Fuente: elaboración propia de los autores

Por último, y una vez obtenidas las alturas de los árboles individuales, en base a la altura de los árboles derivada de la segmentación y del MDSn se estimaron el diámetro a la altura del pecho (DAP, cm), y la biomasa (kg/m²). Además, a partir de la imagen clasificada se estimó la fracción de cobida cubierta (FCC en porcentaje) como parámetro dasométrico de espesura.

El DAP se estimó a partir de la relación obtenida entre la altura y el diámetro de individuos medidos en campo (Figura 3) y considerando una masa riparia arbórea mixta ($R^2 = 0,77$). En el caso de la biomasa, se estimó a partir de la ecuación de Tealdi et al., (2010) que relaciona la biomasa aérea con las características geométricas de los arboles:

$$V = \frac{n_v * \rho_v * H * \pi * D^2}{4} \text{ tn/m}^2 \quad (\text{Eq. 1})$$

Donde n_v es el número de ramas por superficie, ρ_v es la densidad de madera, H es la altura del árbol y D es el diámetro a la altura del pecho (DAP). En referencia a n_v se estima en 0,46 ramas/m² de acuerdo con (Rodríguez-González et al., 2010). Por otro lado, ρ_v para masas mixtas riparias se estima en 0,725 tn/m³ (Wangaard, 1979).

La FCC se obtuvo a partir de una malla regular de 10 x10 metros de tamaño, donde se calculó la superficie total clasificada como vegetación frente a la superficie total del pixel, obteniendo la FCC en % de cada celda.

$$FCC (\%) = \frac{S_{pixel} - S_{classveg}}{S_{pixel}} * 100 \quad (\text{Eq. 2})$$

Donde S_{pixel} es la superficie del pixel en m² y $S_{classveg}$ es la superficie clasificada como vegetación en m².

2.3.3. Validación de variables dendrométricas y dasométricas.

La información obtenida a partir de LiDAR y el procesamiento según la metodología expuesta fue validada con mediciones en campo. Se muestrearon 5 parcelas circulares de radio 15 metros (n=54 individuos) en la zona de estudio, donde se midió mediante telémetro láser (TruPulse 200B) y forcípula de brazo móvil las alturas y diámetros a la altura del pecho (h=1,3 metros) de todos los individuos ubicados en el interior de la parcela circular. Estos datos de

campo servirán para conocer el grado de correlación entre las variables obtenidas a partir de la nube de puntos LiDAR y los datos medidos en campo.

La clasificación automática realizada mediante el “plugin” SCP en QGIS fue validada mediante una evaluación de exactitud utilizando el coeficiente Kappa (Cohen, 1960), con el objetivo de conocer el error entre los entrenamientos y la clasificación final.

3. RESULTADOS

3.1. Validación de la clasificación automática de coberturas y de variables dendrométricas y dasométricas

Tras realizar la clasificación automática de coberturas, el coeficiente Kappa resultante es de 0.94 y 0.89 para los años 2009 y 2017 respectivamente, el cual se considera aceptable.

Respecto a la elevación de los ejemplares de la parcela medidos en campo en comparación con los datos obtenidos a partir de la nube de puntos LiDAR (MDSn), la regresión tuvo un R^2 de 0,96 y un RMSE de 0,77 m (Figura 2.3), siendo la diferencia media de 77 cm entre la altura de los árboles medida a partir del telemetro laser y la Elevación LiDAR. Por lo tanto, las alturas calculadas a partir de la nube de puntos LiDAR son consideradas lo suficientemente precisas para el propósito del presente estudio.

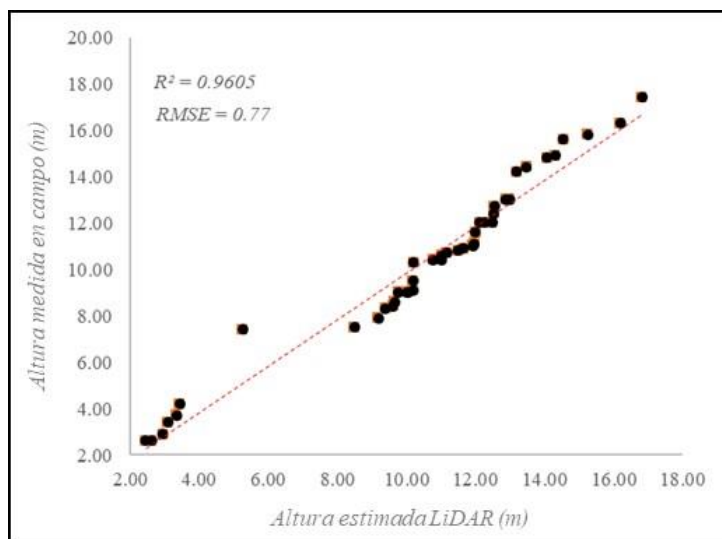


Figura 2. 3. Relación de la variable altura de árbol obtenido con en campo (observado) frente a la altura obtenida con LiDAR (predicho). Fuente: elaboración propia de los autores

3.2. Evolución geomorfológica en las últimas décadas (1956-2017)

La trayectoria geomorfológica del cauce del río Lozoya y su estructura en base a cinco clases de coberturas se expone en la Figura 2.4. En el año 1956 la superficie de cauce activo y barras parcialmente vegetadas era mayor que en los años posteriores, en torno al 25% (2,92 ha) de la superficie total. En el año 1977 la ortofoto muestra una superficie grande ocupada por el embalse de Pinilla debido a que en ese año se encontraba muy próximo al límite de su capacidad, aun así, la superficie vegetada al igual que en el año 1956 era inferior al 50% (5,24 ha) de la superficie total. Entre los años 1977 y 2002 se produjo un aumento considerable de la superficie vegetada en detrimento del cauce activo y las barras parcialmente vegetadas, pasando de 5,24 ha de zonas cubiertas por vegetación leñosa en 1977 a 7,62 en 2002 (Figura 2.4).

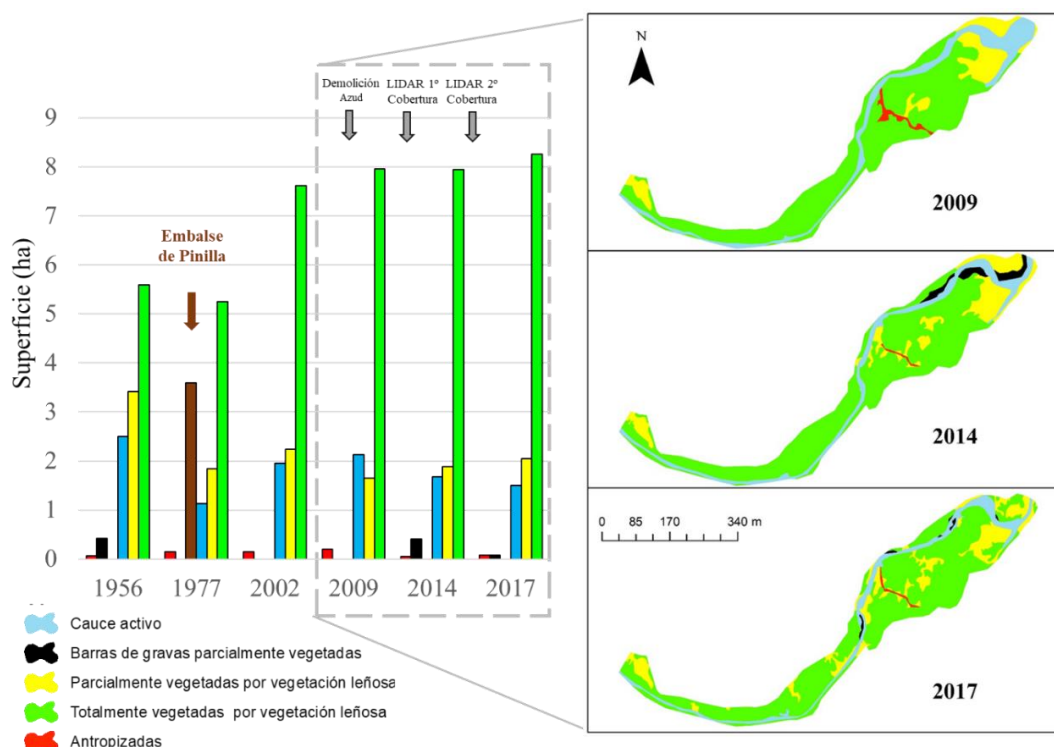


Figura 2.4. Evolución de las clases geomorfológicas consideradas en las ortofotos (1956, 1977, 2002, 2009, 2014, 2017) en el tramo de estudio. La barra marrón en el año 1977 se corresponde con la lámina de agua del embalse de Pinilla. Fuente: elaboración propia de los autores.

En el año correspondiente al inicio del proyecto de demolición (año 2009), la situación del corredor era muy similar a la de siete años atrás (2002), cuando las zonas totalmente vegetadas por vegetación leñosa ocupaban más del 60% (7,95 ha) de la superficie de influencia fluvial. En torno al 15% (1,66 ha) estaba ocupado por espacios de vegetación escasa, un 20% (2,13 ha) de cauce activo y no se encontraron barras de gravas parcialmente vegetadas. Tras la demolición del azud, en el año 2014 se observan cambios en las formas del cauce, aumentan ligeramente las superficies parcialmente vegetadas, aparecen nuevas zonas de colonización tanto barras de gravas desnudas, como parcialmente vegetadas (5%) en las zonas próximas al cauce, pasando de 0 en 2009 a 0,41 ha en 2014. Finalmente, analizando la ortofotografía más actual (2017), se aprecia un ligero aumento de las superficies tanto parcialmente vegetada como totalmente vegetadas, mientras que el resto de las formas se mantienen constantes durante los tres años de transición. Cabe destacar que desde el año 2009 se observa una heterogeneidad mayor en las formas, apareciendo nuevos espacios abiertos en los tramos próximos al cauce activo, que es la zona donde más patentes son los cambios inducidos por la recuperación de la conectividad.

3.3. Evolución de la vegetación mediante LiDAR (2010 - 2016)

Los cambios obtenidos en las variables dendrométricas (altura, DAP y biomasa) siguen una tendencia común de aumento tras la eliminación del azud según sus valores medios expuestos en la Tabla 1. Sin embargo, en el caso de la FCC, se observa un descenso importante de la cobertura vegetal arbórea media tras la restauración, y un aumento de la amplitud de los porcentajes de cobertura (Tabla 1). Este descenso de cobertura contrasta con el aumento de pies arbóreos ($n=956$ en el año 2010 a $n=1018$ en el año 2016) que podría ser debido al incremento de crecimiento vegetativo, así como al regenerado de nuevos individuos gracias a la apertura de nuevos espacios que fomenta esa restauración, más que a un incremento de superficie arbórea dado el reducido aumento que se muestra en la figura 2.4.

Table 2. 1. Resultados de las variables dendrométricas y dasométricas medidas en 2010 y 2016.

*El número de pies totales es en valor absoluto, no se corresponde con la media ni la SD (desviación típica).

Variable	2010 (media $\pm$ SD)	2016 (media $\pm$ SD)
Altura (m)	10,37 $\pm$ 4,01	11,07 $\pm$ 3,33
DAP(cm)	30,44 $\pm$ 16,68	33,21 $\pm$ 15,69
FCC (%)	67,05 $\pm$ 26,62	42,34 $\pm$ 28,42
Biomasa (tn/m ²)	0,35 $\pm$ 0,63	0,42 $\pm$ 0,49
Densidad (pies/ha)	75,20 $\pm$ 80,40	79,25 $\pm$ 83,35
Número de pies totales*	956	1018

En cuanto a la evolución de la distribución de alturas se observa un aumento del número de ejemplares de las clases de altura intermedia, particularmente de la clase 10-15 m (Figura 2.5A). Tras la restauración, el número de pies menores con una altura inferior a 10 m, ha disminuido, al igual que los ejemplares de mayor tamaño (aquellos superiores a 15m). En el caso de las clases diamétricas (Figura 2.5B), se ve un aumento del número de individuos con diámetros comprendidos entre los 20 y 60 cm que probablemente haya sido favorecida por el crecimiento de los individuos de la clase diamétrica más pequeña en este periodo. Por el contrario, los ejemplares pertenecientes a la clase diamétrica menor (< 20 cm) han disminuido ($\approx$ 150 individuos) al igual que los árboles de mayor clase diamétrica tras la demolición del azud. En referencia a la biomasa, se ha observado una reducción considerable de las aportaciones de biomasa de los pies de menor tamaño, compensándose con el aumento de las toneladas obtenidas en los pies medianos (Figura 2.5C).

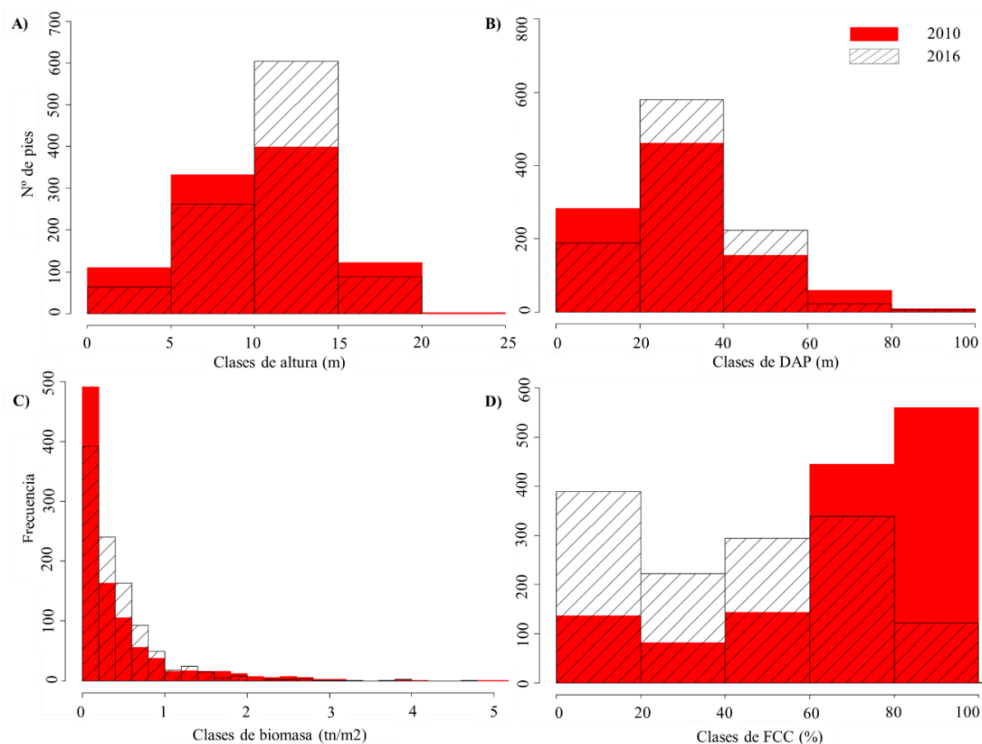


Figura 2.5. Distribución de frecuencias superpuestas (tramas diagonales año 2016, rojo 2010) de las variables A) altura, B) diámetros, C) FCC, y d) biomasa en el tramo de estudio para los años 2010 y 2016.

La FCC es la variable que presenta un cambio más destacado (Figura 2.5D). En el año 2010 las áreas de coberturas superiores al 60% dominaban el corredor ripario, mientras que tras la restauración la apertura de espacios libres ha propiciado que sean más frecuentes áreas con coberturas por debajo del 60 % siendo dominante un valor por debajo del 20 %.

La distribución espacial de los cambios en el tramo proporciona un resultado visual que permite comprender mejor la dimensión de los cambios propiciados por la eliminación del azud en 2009 (Figura 2.6). La magnitud de las alturas, diámetros y biomasa han disminuido en la margen derecha de la parte final del tramo de estudio, además de en la zona próxima al cauce donde se ubicaba el azud (Figura 2.6A – F, recuadros discontinuos 1 y 2).

Por otro lado, en la parte inicial del tramo, más confinado y denso, no se han observado cambios relevantes en la vegetación, salvo el crecimiento natural de la masa tras los 6 años analizados. Pero si analizamos la distribución espacial de la espesura medida en la FCC, se observa una clara disminución de la misma en la mayoría del tramo estudiado, siendo más apreciable en la zona próxima al azud, donde la apertura de espacios y la aparición de bancos de gravas ha propiciado una disminución de la espesura en ambas márgenes (ver figura 2.6G-H, recuadro discontinuo 3).

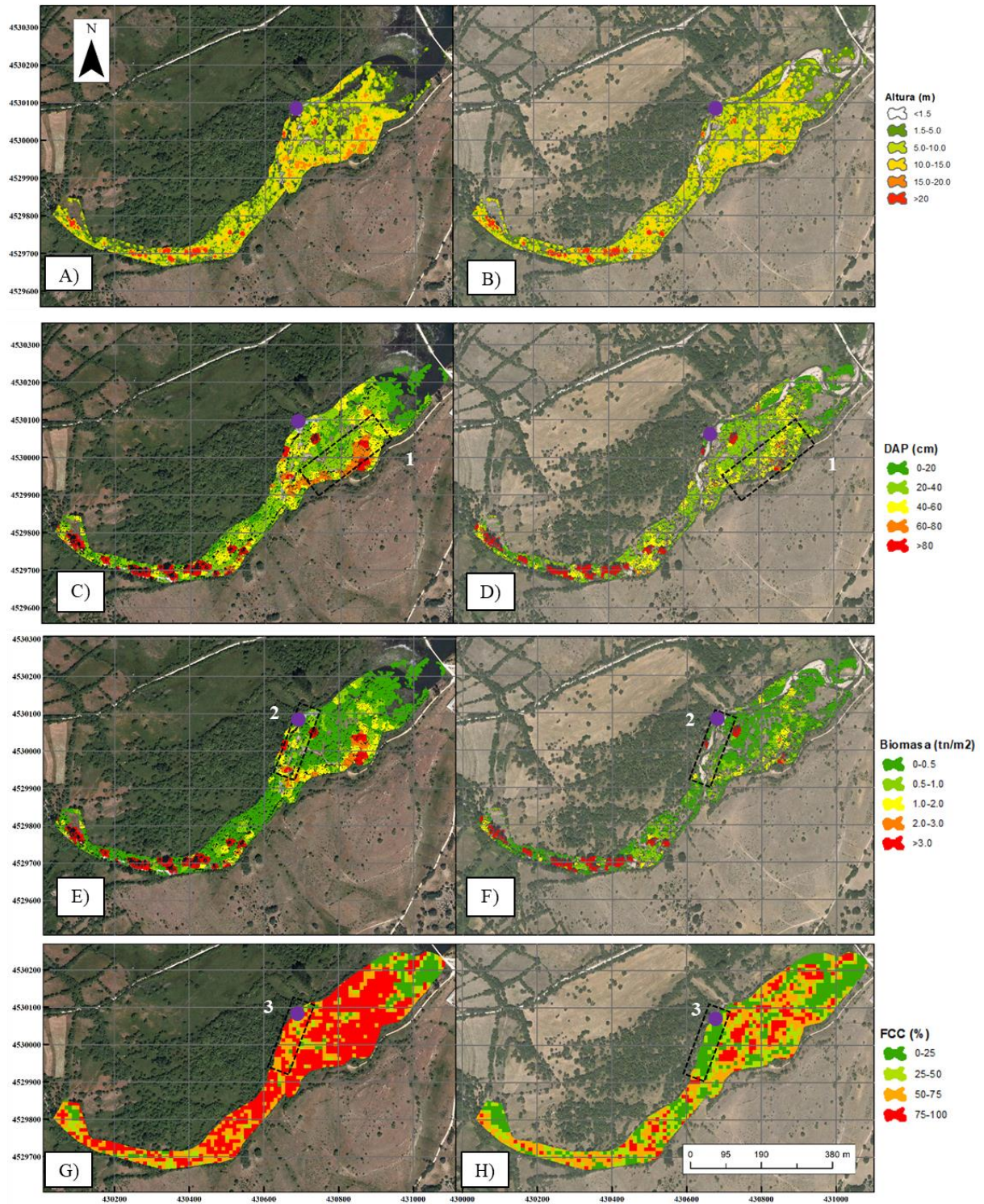


Figura 2. 6. Representación espacial de la evolución de las variables desde 2010 (izquierda) a 2016 (derecha): A y B altura, C y D diámetros, E y F biomasa y, G y H FCC. Las líneas discontinuas negras (1, 2 y 3) muestran las zonas donde los cambios son más apreciables según las variables calculadas. El punto morado indica la antigua ubicación del azud.

4. DISCUSIÓN

4.1. Cambios geomorfológicos y evolución del corredor ripario

La demolición del azud ha tenido un efecto positivo con un aumento del dinamismo geomorfológico en el tramo afectado según los resultados de este estudio. Las presas y pequeños azudes generalmente captan y almacenan sedimentos, a menudo provocan un desequilibrio en el balance líquido-sólido aguas abajo (Williams & Wolman 1984). Al demoler dichas presas o azudes se produce, entre otros procesos, un aumento de la deposición de sedimentos, propiciando el incremento de zonas susceptibles de colonización por parte de la vegetación pionera (Shafroth et al., 2002) entre las que destacan principalmente chopos y sauces.

Los pequeños azudes o grandes presas no generan únicamente efectos sobre el balance líquido-sólido, también transforman la superficie y la anchura del cauce activo, modifican la granulometría, reducen las migraciones laterales de sedimentos, fomentan los procesos de incisión del cauce e inducen a la formación de corredores más densos y estrechos (Boix-Fayos et al., 2007; Bombino et al., 2008; Halifa et al., 2019; García de Jalón et al., 2020). La demolición del pequeño azud del río Lozoya ha originado un aumento de las zonas de cauce activo aguas arriba y aguas abajo del azud (Figura 2.4). Al igual que otros autores, destaca el aumento de dinamismo y la capacidad erosiva lateral en los primeros años después de la actuación (Poeppel et al., 2015; Gilet et al., 2021). A nivel de cuenca, cabe destacar que se trata de un espacio poco alterado por la acción humana, aun así, la superficie forestal ha aumentado desde 1950 donde se impulsaron planes de reforestación en la Comunidad de Madrid (García & Desarrollo, 2011), aumentando la estabilidad de los suelos, disminuyendo los procesos erosivos en laderas y perdiendo parte de la conectividad entre la ladera y el cauce (Boix-Fayos et al., 2007).

En este tramo de estudio, el aumento de barras de gravas y la pérdida de FCC inducidos por la eliminación del azud y posiblemente la ocurrencia de caudales suficientemente altos, propició la aparición local de nuevas zonas potenciales para la colonización vegetal.

La dinámica de la vegetación riparia tiende hacia un desarrollo funcional y estructural más complejo, un corredor maduro (Corenblit et al., 2014). En las últimas décadas, la reducción de la magnitud de las avenidas, ha propiciado la estabilización de la vegetación de ribera generando un estrechamiento del cauce, limitando el reclutamiento ante la poca disponibilidad de espacios abiertos para especies pioneras (Webb & Leake, 2006; Rivaes et al., 2014). La demolición del azud de Pinilla, ha permitido aumentar de manera localizada el dinamismo, produciéndose una apertura de espacios expuestos a la luz, y un aumento de la disponibilidad de barras de gravas colonizables. Efectos similares de incremento notable del dinamismo debido a la demolición de azudes, así como debido a la eliminación o retranqueo de construcciones laterales como motas y escolleras han sido encontrados por otros autores (e.g., Rohde et al., 2005; González et al., 2015; Martínez-Fernández et al., 2017). Por otro lado, la masa arbolada ubicada en las márgenes más próximas al cauce activo también se ha visto alterada, haciendo posible la recuperación de fases iniciales de las etapas sucesionales de la vegetación de ribera.

4.2. Uso de LiDAR e imágenes para monitorizar corredores riparios

En los últimos años, el análisis de los corredores riparios ha experimentado cambios sustanciales debido a la evolución de las imágenes, datos, herramientas SIG y tecnologías espaciales (Johansen et al., 2007; Tormos et al., 2011; Fernandes et al., 2013).

Los resultados muestran que la metodología empleada, utilizando tecnología LiDAR del PNOA, clasificación supervisada de imagen y sistemas de información geográfica, es eficaz en la monitorización, así como en la búsqueda de cambios en el corredor ripario. Actualmente son

escasos los estudios que analizan la evolución del corredor ripario mediante comparación de dos vuelos LiDAR (e.g., Brousse et al., 2021), aunque existen muchos estudios sobre el mapeo de variables asociadas al corredor (Dilts, Yang & Weisberg, 2010; Johansen et al., 2010; Guo et al., 2017; Laslier et al., 2019), y el monitoreo de grandes superficies riparias mediante LiDAR y fotogrametría (Michez et al., 2017).

La utilización de datos LiDAR ha resultado ser muy eficiente en la valoración del cambio ocurrido en el tramo de estudio tras la demolición del azud. Afortunadamente, la práctica coincidencia en el tiempo de la demolición con el vuelo que tomó los datos de 2010 permite disponer de los datos necesarios para saber cómo eran el terreno y la estructura de la vegetación en ese momento. Una frecuencia de vuelo más elevada, como pudiera ser una frecuencia al menos anual, haría posible este tipo de análisis en otros lugares donde las actuaciones de restauración o las presiones existentes tengan lugar en otros momentos al aumentar la probabilidad de que el vuelo LiDAR capte el cambio haciendo posible una monitorización continua en el tiempo que permitiría seguir en detalle la evolución del sistema fluvial. Por ejemplo, si la demolición del azud hubiese tenido lugar unos años antes este análisis no habría tenido el mismo valor; o bien si entre los dos vuelos hubiese tenido lugar otra intervención no habría sido posible separar el efecto. Así mismo, un aumento de la densidad de puntos proporcionaría un modelo más cercano a la realidad. Actualmente se recomienda que para la detección y análisis a escala de árbol individual, las nubes de puntos contengan al menos 2 ptos/m² (Latella et al., 2021), aunque existen estudios que muestran la posibilidad de obtener resultados de árbol individual de buena precisión con densidades de puntos menores (Goodwin et al., 2006; Wu et al., 2016; Ma et al., 2017), así como estudios que demuestran que el aumento de la densidad de puntos a partir de 2 ptos./m² no mejora sustancialmente los resultados (Jakubowski et al., 2013) siendo deficiente el balance coste-beneficio del vuelo. La tendencia del proyecto PNOA-LiDAR es ir aumentando esta densidad. En la actualidad se ha producido un aumento de 0.5 a 1 puntos/m² entre los años 2010 y 2016, aunque hay que tener presente que los tiempos de computación y las tareas de análisis serán más largas y complejas.

Las aplicaciones que el uso de LiDAR tiene en la gestión de recursos naturales y en la monitorización de su evolución tras intervenciones de diversa índole, ya sean presiones o restauración, son muy numerosas (Dilts et al., 2010; Johansen et al., 2010; Guo et al., 2017; Michez et al., 2017; Laslier et al., 2019; Huylenbroeck et al., 2021) y la previsible mejora en la frecuencia de vuelos así como en las resoluciones espaciales potenciaría enormemente su uso aumentando notablemente la eficiencia en este tipo de tareas, si bien es cierto que la consideración de datos de campo continuará siendo necesaria como validación de este tipo de técnicas remotas.

Además de la utilidad de la aplicación de LiDAR para este tipo de estudios, en los últimos años la combinación de esta tecnología con las imágenes ópticas multiespectrales ha permitido en el ámbito forestal estimar la evolución de variables dendométricas y dasométricas (biomasa, carbono o estructura de la vegetación), y distinción de especies a escala individual (Chasmer et al., 2017; Fang et al., 2018; Dalponte et al., 2019; Naik et al., 2021). Su aplicación para conocer la evolución de los corredores riparios, y los efectos en la vegetación bajo escenarios distintos (regulación de caudales, régimen natural, cambio climático o espacios restaurados) podría ser de gran utilidad para la toma de decisiones por parte de los gestores de dichos espacios.

5. CONCLUSIONES

En este estudio se ha evaluado la utilidad de la tecnología LiDAR para el seguimiento ambiental de un proyecto de restauración ecológica, con un caso de estudio real (la demolición del azud de Pinilla en el río Lozoya).

Los resultados obtenidos muestran un crecimiento general esperado de la masa durante el periodo transcurrido entre los dos vuelos (2010 y 2016) observado en las variables (altura,

diámetro, biomasa y densidad), a la vez que se detectan cambios en la distribución de las clases de altura y diámetro, aumentando los pies de tamaños medios y reduciéndose los extremos, tanto menores y mayores. Por otro lado, la FCC ha disminuido considerablemente tras la demolición del azud en las zonas más próximas al cauce principal (zonas más activas) con una apertura importante de nuevos espacios abiertos.

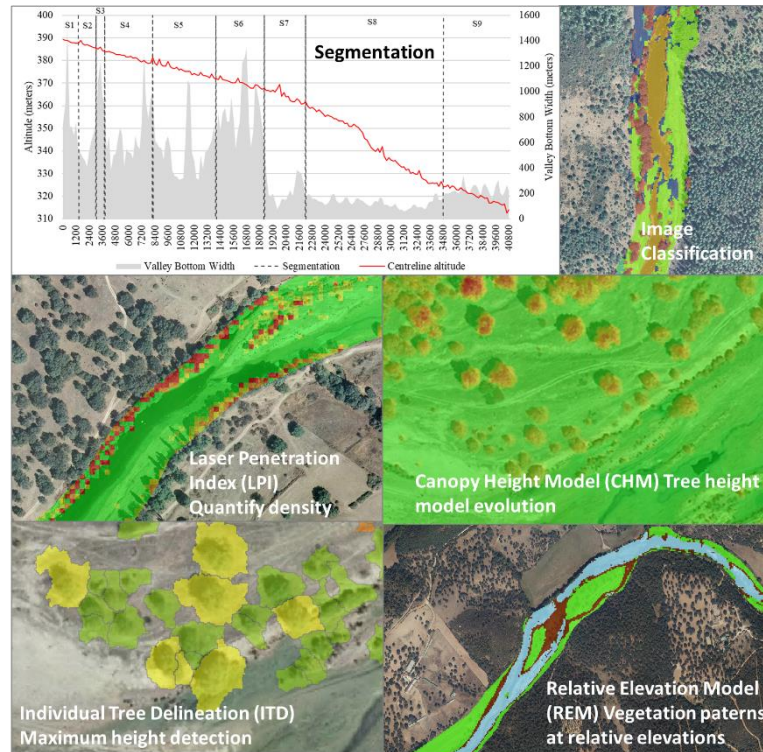
Se ha podido comprobar que la comparación de dos vuelos LiDAR, aunque espaciados en el tiempo, permite analizar de manera eficaz los cambios dendrométricos y dasométricos de la vegetación riparia leñosa, permitiendo valorar los cambios producidos en la estructura del corredor sin disponer de un muestreo de campo previo a la demolición.

La utilización de datos LiDAR de la cobertura de 2016, correspondiente a 5 años anterior a la toma de datos de campo (año 2021), unido a la densidad de puntos LiDAR disponibles en la actualidad ($0,5 \text{ puntos/m}^2$), no ha condicionado las correlaciones significativas encontradas para las variables medidas y las obtenidas a partir de la nube de puntos LiDAR. Si bien es cierto que existen ciertas limitaciones de esta metodología como la alta densidad de ejemplares en ciertas zonas del corredor (tangencia de copas) que dificulta la obtención de la densidad; el todavía bajo número de puntos por metro cuadrado de los vuelos LiDAR disponibles en el Centro Nacional de Información Geográfica; la dificultad de poder obtener datos mediante LiDAR de las especies arbustivas; y finalmente las limitaciones temporales en la disponibilidad de coberturas LiDAR.

El ajuste de los datos medidos y estimados avala la calidad de la nube de puntos LiDAR y permite explorar las respuestas del corredor ante actuaciones de mejora de la conectividad longitudinal, tratamientos sobre la masa arbolada, plantaciones y otras actuaciones ligadas a proyectos de restauración. Esta metodología puede suponer una herramienta eficaz y automatizable que permita realizar un seguimiento de las restauraciones acometidas facilitando la tarea a los gestores de las mismas.

3.2.2. A METHODOLOGICAL FRAMEWORK TO QUANTIFY RIPARIAN CORRIDOR EVOLUTION BY IMAGE CLASSIFICATION AND CONSECUTIVE LIDAR ANALYSIS

Graphical Abstract



1. INTRODUCTION

Riparian corridors connect terrestrial and aquatic ecosystems. The space they occupy within the river ecosystem is essential to maintain the functions and services that these spaces provide (Johnson et al., 1997; Naiman & Decamps, 1997; Maisonneuve & Rioux, 2001; Decamps et al., 2004; Dixon et al., 2016; Klein et al., 2015). The composition and structure of riparian areas are useful indicators of the ecological status of fluvial ecosystems (González del Tánago & García de Jalón, 2006; Macfarlane et al., 2017). Flooding, sediment deposition and erosion processes influence the development and character of riparian vegetation and play a key role in the state of landforms (Bendix & Hupp, 2000; Corenblit et al., 2014; Kleindl et al., 2015). However, changes in land cover and use across riparian habitats transform natural conditions and modify nature succession and natural floods, generating several impacts on fluvial ecosystem dynamism (Elosegui & Sabater, 2013; c et al., 2016; García de Jalón et al., 2019). Then, monitoring riparian corridor status is relevant to detect possible habitat loss or degradation.

In the last century, rivers have been highly altered due largely to flow regulation, irrigation and changes in land use, disrupting the natural functioning of the ecosystem (Stefanidis et al., 2016; Lobera et al., 2017; Fazelpoor et al., 2021). Several studies illustrated an increase of vegetation density or encroachment process associated with flow regime alteration (González et al., 2010; García de Jalón et al., 2020). This process has influenced the fluvial dynamics of rivers changing braided rivers in a single thread river, decreasing the surfaces available for the

regeneration of pioneer species and changing the fluvial geomorphological conditions (Gurnell et al., 2009).

Riparian vegetation dynamics, reliant on hydromorphological conditions, drive the spatial distribution of vegetation that influence the colonization, growth and mortality phases (Corenblit et al., 2014). The availability of zones to be colonized (sexual or asexual) determine vegetation expansion on river channels and floodplains. Conversely, riparian vegetation cover decreases faced with extremes events, whether drought episodes that promote dieback or high flows that cause burial or scour of individuals. In relation to the later, vegetation density generates a natural resistance for flow action, reducing light, soil moisture and nutrients, and hindering its capacity to renew potential pioneer areas (Ghidey and Alberts, 1997; Jansen and Coelho-Netto, 1999), although inside the channel vegetation retain sediments and could favour vegetation establishment (Gurnell et al., 2002). The evolution of density could explain the different processes of vegetation increasing that promote vegetation encroachment (García de Jalón et al., 2020) and locate areas potentially colonizable.

Knowing the distribution of riparian vegetation and its changes over time allows these areas to be managed more effectively. The use of new technologies, such as photogrammetry or remote sensing could increase the capacity of surface analysis with great precision (e.g., Huylenbroeck et al., 2021). Even so, the application is dependent on field validation, contrasted “a posteriori” by statistical methods such as linear regression (Ortiz-Reyes et al., 2015; Laslier et al., 2019). Remote sensing currently offers a wide selection of products, methodologies, and techniques applicable to dendrometric and dasometric measurements, such as diameter at breast height (DBH), height, biomass and branch density (e.g., Jochem et al., 2010, 2012; Moe et al., 2020), which complement traditional inventories and expand their possibilities (Ortiz-Reyes et al., 2015). Given the complexity of riparian corridors in terms of diversity, structure and functionality, studying their evolution from LiDAR and aerial images could improve the ability to understand how different sections of a river corridor present different geomorphological and environmental conditions. In addition, in recent years, advances have been made in the analysis of data from different remote sensing techniques to generate precise information on the attributes of riparian corridors (Riedler et al., 2015; Michez et al., 2016).

The objective of this study is to assess riparian forest structure change in the longitudinal and transversal gradient by using LiDAR data vegetation distribution provided by orthophoto-LiDAR paired with image classification (RGB and NIR) composition along the time. We exemplified this methodology in a Spanish Mediterranean river, the Tiétar river; and demonstrate the utility and efficiency of LiDAR data to monitor riparian vegetation changes along the time. Secondly, the change in riparian vegetation structure (height and density) is explored in relation to geomorphological characteristics and elevation above stream channel. LiDAR data can provide a means of disaggregating the complex effects of geomorphological conditions and position of riparian vegetation relative to the main channel.

2. METHODOLOGY

2.1. Study area

The Tiétar river is located in the central part of the Iberian Peninsula, flows from east to west along 170 km draining an area of 4,468 km². The Tiétar basin, as well as in our study area, the river runs through confined and narrow valleys where the geology is mainly composed of tardi-orogenic Granites. This dominant configuration alternates with wider valleys with quaternary deposits where conglomerates, gravel and sand predominate allowing a higher mobility of the channel that present braided patterns at some reaches. The Tiétar river drains the southern slope of “Sierra de Gredos” mountains, where several temporary streams and steep ravines enter the

3.2.2. A methodological framework to quantify riparian corridor evolution by image classification and consecutive LiDAR analysis

river with a great flow and strong currents in wet periods (Amor Morales et al., 1993), which favour high sediment connectivity and provide geomorphological dynamism. On the left bank we find areas of fertile meadows with smooth relief and lower slopes that decrease the sediment connectivity. This river is regulated by two reservoirs (Rosarito reservoir, since 1958 and Torrejón-Tiétar reservoir since 1967) before flowing into the Tagus River.

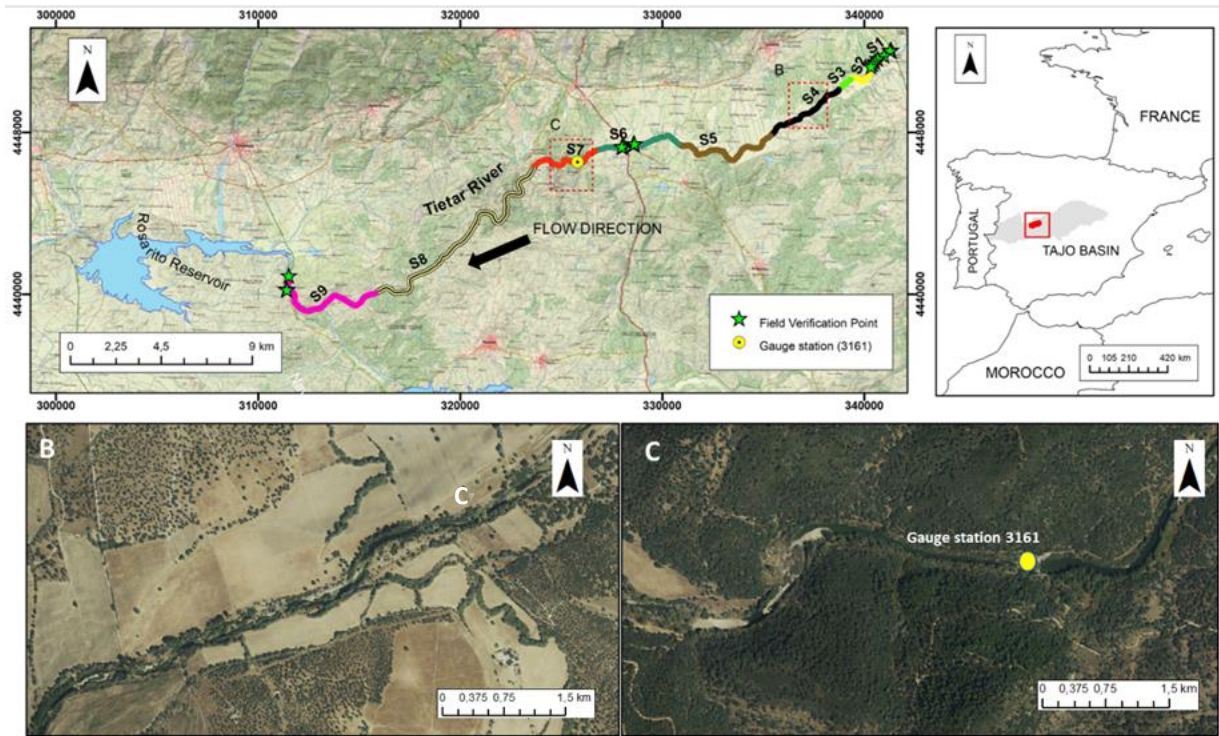


Figure 2. 1. A. Geographical location of the study segment within the river Tiétar in Tajo basin and location of river segments and (B, C, D) aerial images of PNOA RGB 2019, including gauge station (yellow point) and field verification points (green stars).

Particularly, a river segment 41 km-long was selected, which is located upstream from Rosarito reservoir (Figure 2.1). This river segment flows first through an unconfined valley along 18 km that becomes confined along the following 23 km, ranging between 389 and 314 a.s.l. with an average slope of 0.95%. Bedload and margins are mainly composed of medium size sediments.

2.2. Hydrological data

Historical daily flow series from 1968 to 2018 (gauge station 3161, available at <http://hercules.cedex.es/anuarioaforos/default>) were used to characterize flow events in the last decades including the estimation of return periods of flood values

2.3. Fluvial area delineation and segmentation

The first step to characterize riparian vegetation and landforms was to determine the reference fluvial area. This is defined as the area occupied by the active channel in year 1956 (using American Flight 1956-1957, provided by the National Geographic Institute, Spain).

The second step was to differentiate river segments internally homogeneous regarding morphological aspects. Geomorphological conditions influence evolution of riparian vegetation formations at watershed level, contributing in turn to their dynamism (Engelhardt et al., 2012). For example, in the more confined areas, the riparian corridors tend to be narrower than in open

areas, while in the spaces with wider valley bottoms, the colonizable areas represent a greater surface area (Polvi et al., 2011). Then, an automatic segmentation procedure was applied to detect homogenous river reaches based on statistical methods allowing the system discretization on an objective way (e.g., Alber and Piégay, 2011; Martínez-Fernández et al., 2016). In this case, multi-response permutation procedures (MRPP, Mielke, 1991; Orłowski et al., 1993) were applied to segment the river using R software (R core Team, 2019). The segmentation was carried out considering the valley bottom width and channel slope as it is considered that these variables provide an adequate geomorphological context while being not extremely time consuming as other variables that requires a manual procedure (Martínez-Fernández et al., 2019). Both variables were extracted in a Geographic Information System (GIS) environment and standardized before applying the algorithm every 200 m along the river segment 41-km-long with the help of Fluvial Corridor toolbox (Roux et al., 2015) in ArcGIS10.1. To carry out the segmentation and an alpha risk of 0.05 was statistically significant. For more details about the procedure, see Martínez-Fernández et al. (2016).

2.3. Characterization of the structure of riparian vegetation and landforms with LiDAR data.

In order to characterize the structure of riparian vegetation, LiDAR data were used to create digital terrain and surface models, together with the extraction of dendrometric and dasometric variables of the vegetation (Figure 2.2).

2.4.1. Using LiDAR data to create elevation and surface models

The LiDAR data were obtained from the Instituto Geográfico Nacional (IGN) of Plan Nacional de Ortofotografía Aérea (PNOA) of Spain. The point clouds available for the study area correspond to years 2009 and 2019. Points density was 0.5-1 points / m² in the flight of year 2009, while in the flight of year 2019 the points density was 1-2 points/m². These particular flights correspond to code CLM NW (Castilla La Mancha North-West) and CyL SW (Castilla y León South-West). Point clouds were clip and merge using LAStools (LAStools, 2014) to analyse only the area corresponding to the fluvial area (i.e., the area corresponding to active channel in 1956).

In order to process the point cloud, the Global Mapper Software V.20. (Blue Marble Geographics Company) was used to carry out two filter processes. First, the points classified as soil were extracted to define the Digital Elevation Model (DEM). Second, the Digital Surface Model (DSM) that includes the different types of vegetation (i.e., low, medium and high) was obtained. Following Montealegre et al. (2015), DEM and DSM were interpolated by triangulation method which is the optimum method suggested for forestry data.

Finally, the relative elevation model to the river centerline was created using the Inverse distance weighted (IDW) method that is based on construction points, extract multi values to points, IDW and minus (Coe, 2016). This interpolation method are very useful to analyze the configuration of the riparian area and can be created using different methods. Then, the relative elevation model was reclassified in ranges of elevation to assess the riparian vegetation structure in each range. After an exploratory analysis of more than 50 river sections along the river segments, three ranges were selected (0-1 meters, 1-2 meters, and >2 meters) as at these elevations relevant trends are detected.

2.4.2. Land cover classification

The Spanish National Cartographical Institute (IGN) (MTMAU and IGN, 2022) provides open-access aerial imagery from photogrammetric flights conducted in 2009 and 2019 over the study area. The spatial resolutions of the 2009 (PNOA 2009) and 2019 (PNOA 2019) images are 0.25 m, with georeferencing mean square errors of ≤ 0.50 m for both datasets (MTMAU,

2022). To ensure spatial consistency, the images were clipped to match the study area and then geometrically co-registered using a first-order polynomial transformation. Ten planimetric ground control points (GCPs), evenly distributed and extracted from the images, were employed during this process. The alignment between datasets was performed for each acquisition time separately. Given the relatively flat topography of the study area, the co-registration process was highly accurate, ensuring minimal geometric discrepancies. This step ensured robust spatial alignment between the 2009 and 2019 datasets, allowing for reliable comparisons and analyses (Delgado et al., 2022; Alonso et al., 2023).

To identify vegetated areas in the fluvial zone and improve the efficiency of extracting dendrometric and dasometric variables, it was necessary to classify the land cover. For this, an object-based image analysis (OBIA) approach was applied. This method involves dividing the image into meaningful groups of pixels, called "objects," based on their similarities.

The first step was to segment the images into objects, grouping pixels with similar characteristics (e.g., color or texture). This segmentation created a mosaic of objects, each representing an element in the image, such as trees, water, or shadows. The segmentation was performed using the *MeanShift (MS)* algorithm in the Orfeo ToolBox (QGIS), a widely used method for detecting changes in forest vegetation (Viana et al., 2019).

After segmentation, statistical information was extracted for each object (Muñoz et al., 2019), including the mean and standard deviation of various features. These features were then used to classify the objects into five categories: (i) woody vegetation, (ii) water, (iii) brush and low vegetation, (iv) grassland and (iv) shadow.

To train the classification algorithm, a sample of 100 objects was selected for each of the five categories, resulting in a total of 500 training samples. These samples allowed the algorithm to learn and classify the objects in the images accurately. By using this object-based approach, the method provided a more accurate description of the riparian ecosystems analyzed, ensuring reliable mapping of vegetation and other land cover types.

2.4.3. Dendrometric and dasometric variables extraction from LiDAR data

Canopy height model (CHM) is a common method to estimate vegetation canopy height (Pascual et al., 2010), but also allows to estimate biomass or diameter (Tesfamichael et al., 2010). In order to calculate dominant height at pixel resolution and individual tree height and density, the Canopy Height Model (CHM) was generated from the subtraction of the DSM minus the DTM in ArcGIS v 10.1 with a pixel size of 0.33x0.33 m (Figure 2.2A). The resulting layer allows to know the vegetation canopy height for all points classified as vegetation (small, medium and high vegetation). We calculated the dominant height defined as the highest tree in determined surface, in our case we defined the same pixel size like other variables, 25 m².

The individual tree was detected using the segmentation of basins by mathematical morphology (Beucher & Meyer, 2018). To improve the precision of the method, the algorithm focal statistics (type = *maximun as local maxima*) was applied, which analyses each contiguous cell (i.e., within a given radius, 3 meters in circumference and depending also on the pixel size, Niemann et al., 1999) in the raster and calculates the specific maximum with the identified neighbourhood. The result layer was CHM_{max} the basin of each tree was obtained by calculating the inverse of the CHM_{max} generating the CHM_{max}' layer. From the CHM_{max}', flow direction and accumulated flow were calculated as steps prior to obtain the basins of the tree canopy. Finally, the raster data is extracted based on the basin geometries and the maximum value of each contour is obtained, which corresponds to the height for each tree thus segmented (Figure 2.2B). Then, trees were classified into 5 height intervals (1.5-5 m, 5-10 m, 10-15 m, 15-20 m, 20-25 m and 25-30m). Only trees with a height greater than 1.5 meters were included following previous authors (e.g., Michez et al., 2013).

3.2.2. A methodological framework to quantify riparian corridor evolution by image classification and consecutive LiDAR analysis

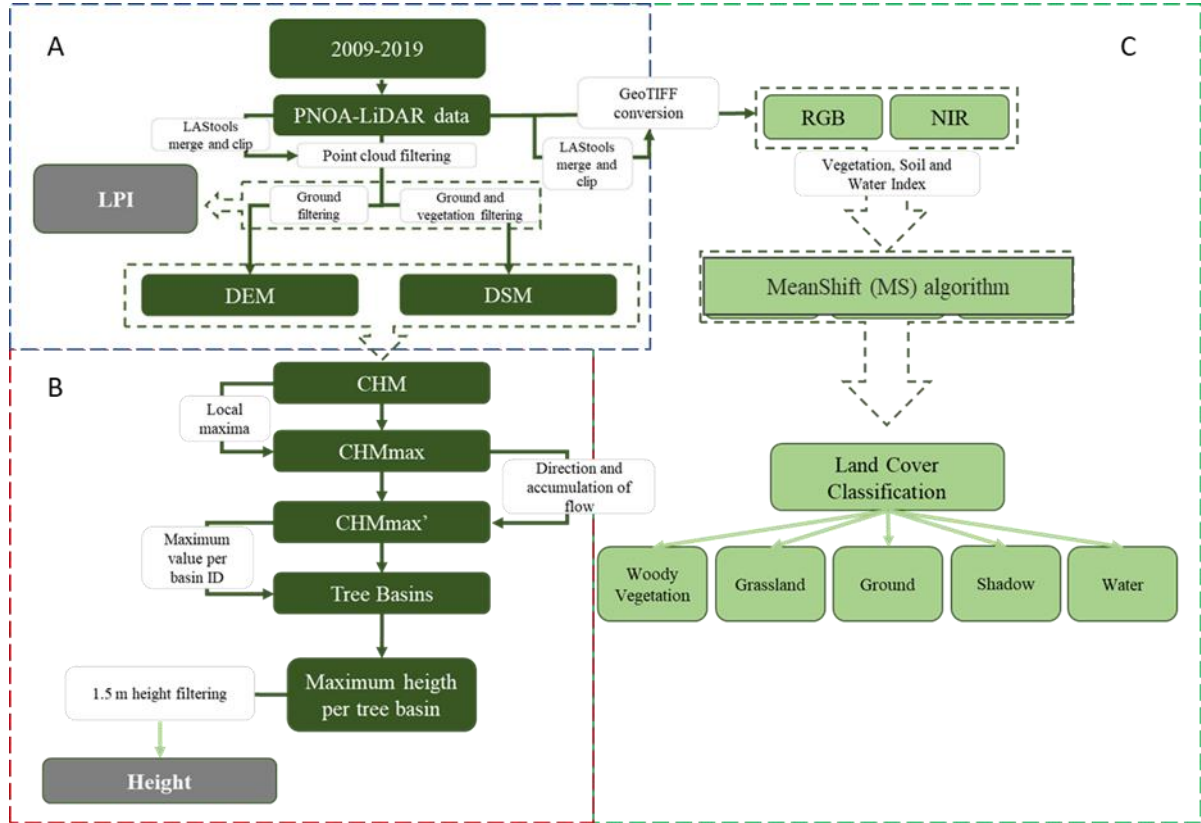


Figure 2. 2. Methodology to analyse riparian vegetation structure based on individual tree (dark green) detection and image classification (soft green).

Dasometric variables are useful to characterise a forest mass. Particularly, as a proxy of tree density and light exposure which is useful to evaluate the riparian forest structure, the Laser Penetration Index (LPI hereafter, Eq. 2) was calculated (Barilotti et al, 2006).

$$LPI_{ij} = \frac{G_{ij}}{G_{ij} + V_{ij}} \quad (\text{Eq. 2})$$

Where G_{ij} is the number of ground returns per unit area and V_{ij} is the number of high vegetation ($h > 1$ meter) returns per unit area. LPI values close to 0 characterise areas with dense vegetation, while LPI values close to 1 describe open areas with low vegetation densities. Values were obtained using a mesh of 5x5 meters of pixel size.

2.4.4. Data análisis

In order to explore the temporal evolution of riparian vegetation structure between 2009 and 2019 changes in LPI has been analysed considering different reaches along the river (see section 2.2) to interpret the possible trajectories of change (i.e., increase, decrease or unchange). Changes were calculated as the subtraction pixel by pixel of the value of LPI in 2019 from LPI in 2009 (i.e., $LPI_{2009} - LPI_{2019}$), obtaining a positive value if there is a decrease of the LPI value (i.e., increase of vegetation) or negative value if there is an increase of the LPI value (i.e., decrease of vegetation). Different trajectories were classified based on natural succession or regression process (Corenblit et al., 2010) and have been represented in a Euclidean system to visually interpret the dominant process occurred in each reach. Trajectories that imply an

increase of vegetation (i.e., $LPI_{2009}-LPI_{2019} > 0$) were named “Encroachment”, while trajectories that imply a decrease of vegetation (i.e., $LPI_{2009}-LPI_{2019} < 0$) were named “Regression”.

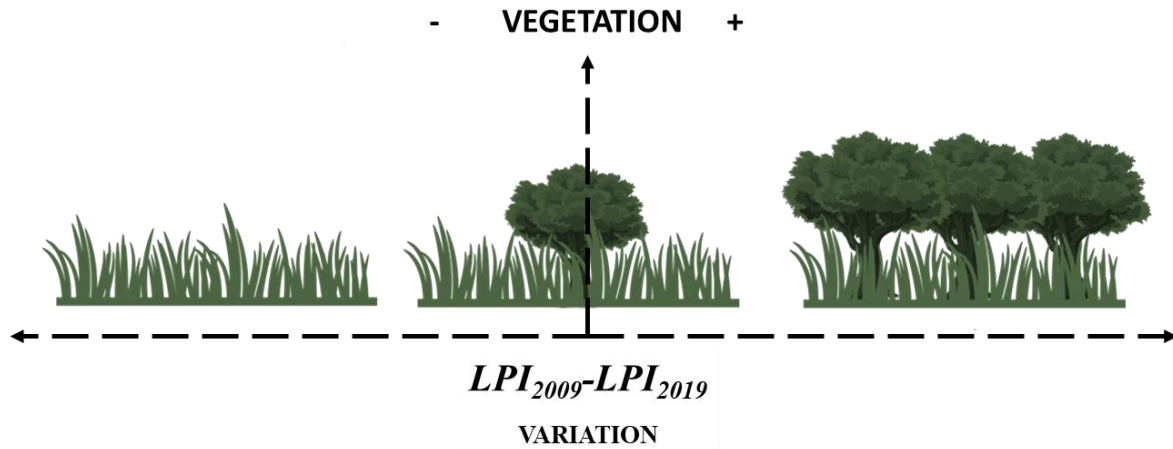


Figure 2. 3. Riparian vegetation changes between 2009 and 2019 ($LPI_{2009}-LPI_{2019}$) according to LPI pixel evolution data.

Complementary to the analysis of the river segments, i.e., the longitudinal dimension of the river, transversal changes of the riparian vegetation structure have been explored. Based on the three elevation ranges resulted from the reclassification of the relative elevation model (REM) (see section 2.3), average LPI values per range in each segment were calculated to show the riparian structure variation with the increase of distance to the channel. The same spatial and temporal analysis was carried out in the case of tree height variable.

2.3.6. LiDAR data and landforms validation.

LiDAR data and the methodology to extract dendrometric variables were validated with field data measures. A total of 14 field plots (circular shape and radius 15 meters) were sampled to obtain individual tree height and density data in the field. A TruPulse 200 and a caliper were used to measure the height and diameter at breast height of the trees respectively. Finally, LiDAR data and field data were correlated and, for the validation and knowledge of error between measured and predicted values, RMSE and R^2 were used.

The automatic classification performed using the SCP plugin in QGIS was validated by an accuracy evaluation using the Kappa coefficient (Cohen, 1960), with the aim of knowing the error between the training sessions and final classification.

Height of the trees of the plot measured in the field compared to the data obtained from the LiDAR point cloud (MDC) had an R^2 of 0.83 and an RMSE 5.27 m (Figure 2.4, Tabla 3.1) that is considered adequate following previous authors (e.g., Huang et al., 2009; Alba et al., 2021).

3.2.2. A methodological framework to quantify riparian corridor evolution by image classification and consecutive LiDAR analysis

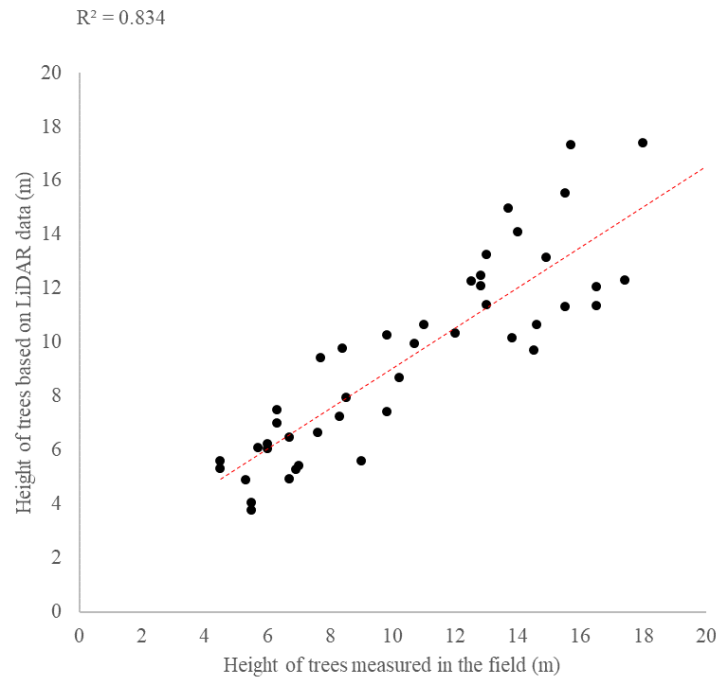


Figure 2. 4. Linear correlation of the tree height variable obtained in the field (horizontal axis) versus the height of trees obtained with LiDAR (vertical axis).

Table 3. 1. Summary of the results obtained from the LiDAR data validation method (in terms of height) Summary of the results obtained from the LiDAR data validation method (in terms of height)

Points	Number of observations	Mean Height Observed (meters)	Mean Height Predicted (meters)
14	59	11.25	9.96

3. RESULTS

3.1. Longitudinal segmentation along the study area and geomorphological characterization

The study area was divided into 9 segments after the application of segmentation algorithms based on channel slope and valley bottom width (Figure 2.5). The mean length of the reaches is 4.4 km, with a minimum length of 0.6 km (segment S3) while the maximum is 12.4 km (segment S8) (Table 2). Segments from S1 to S6 flow over a wide valley, with variations alternating narrow areas of high slope and wider areas where the slope decreases. Average valley bottom width ranges between 528.7 m in S5 and 1045.0 m in S3. From segment S7 the valley becomes narrower, arising minimum values in S8 with an average valley width of 128.0 m, coinciding with steeper slopes (0.15 % in S8 and 0.17 % in S9). Because of these remarkable differences found along the study segment regarding both the valley bottom width and channel slope (significant differences were detected in the case of valley width after Kruskal-Wallis test ($p < 0.05$) but not in the case of slope), two parts are considered to compare the riparian vegetation structure: the unconfined part from reaches S1 to S6, and the confined part from reaches S7 to S9 (Figure 2.6).

3.2.2. A methodological framework to quantify riparian corridor evolution by image classification and consecutive LiDAR analysis

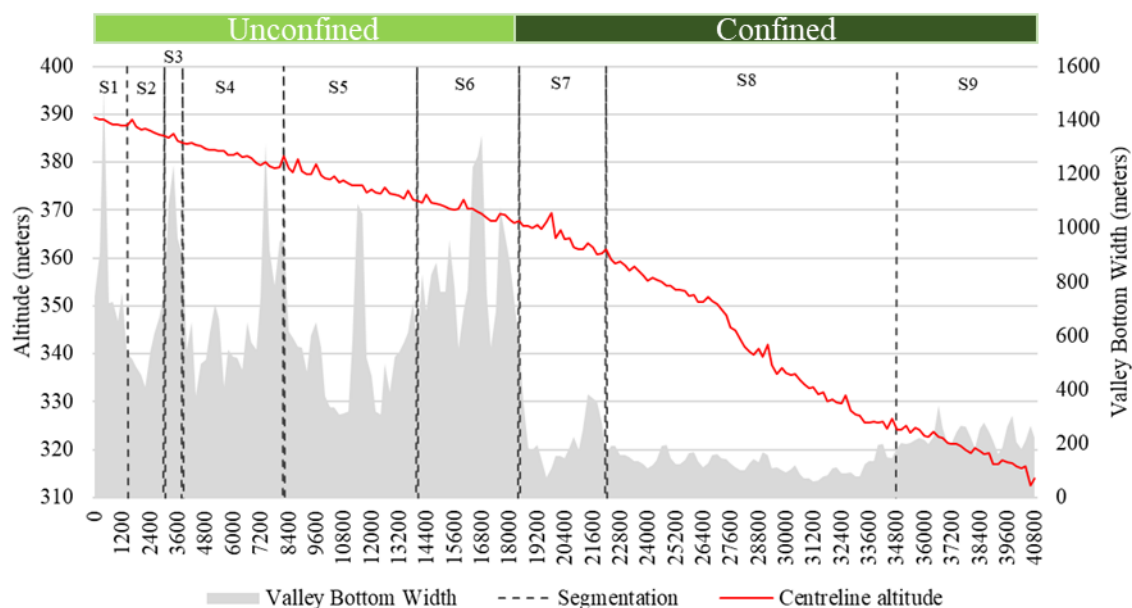


Figure 2. 5. Longitudinal distribution of valley bottom width and river centreline elevation of the study segment. Vertical dashed lines indicate the boundaries of reaches detected by using segmentation algorithms.

Table 3. 2. Characteristics of length, valley bottom width and slope of automatically detected river segments based on the last information (2019 LiDAR data).

Segmentation	Length (m)	Valley Bottom Width (mean $\pm$ std, m)	Slope (mean $\pm$ std, %)
S1	1400	861.1 $\pm$ 296.8	0.09 $\pm$ 0.06
S2	1600	552.0 $\pm$ 109.9	0.06 $\pm$ 0.19
S3	600	1045.0 $\pm$ 147.2	0.10 $\pm$ 0.23
S4	4200	658.9 $\pm$ 219.9	0.03 $\pm$ 0.18
S5	5600	528.7 $\pm$ 192.8	0.08 $\pm$ 0.32
S6	4200	843.7 $\pm$ 219.0	0.05 $\pm$ 0.23
S7	3600	214.3 $\pm$ 92.8	0.08 $\pm$ 0.41
S8	12400	128.0 $\pm$ 35.7	0.15 $\pm$ 0.29
S9	5800	227.6 $\pm$ 39.6	0.17 $\pm$ 0.54

3.2.Hydrological analysis

The study segment of Tiétar river is unregulated as it is located upstream from the reservoir “Rosarito”. The annual average discharge of the last 50 years is 6.8m³/s, being 240.8 m³/s the average of annual maximum flow and 0.1 m³/s the average of annual minimum flow. The last major floods experienced by the river Tiétar were between 1995 and 2002 (Figure 2.6), and it has not experienced a major flood for almost 20 years. Only in 2016 and 2018 the value of the return period T2 flood was exceeded.

3.2.2. A methodological framework to quantify riparian corridor evolution by image classification and consecutive LiDAR analysis

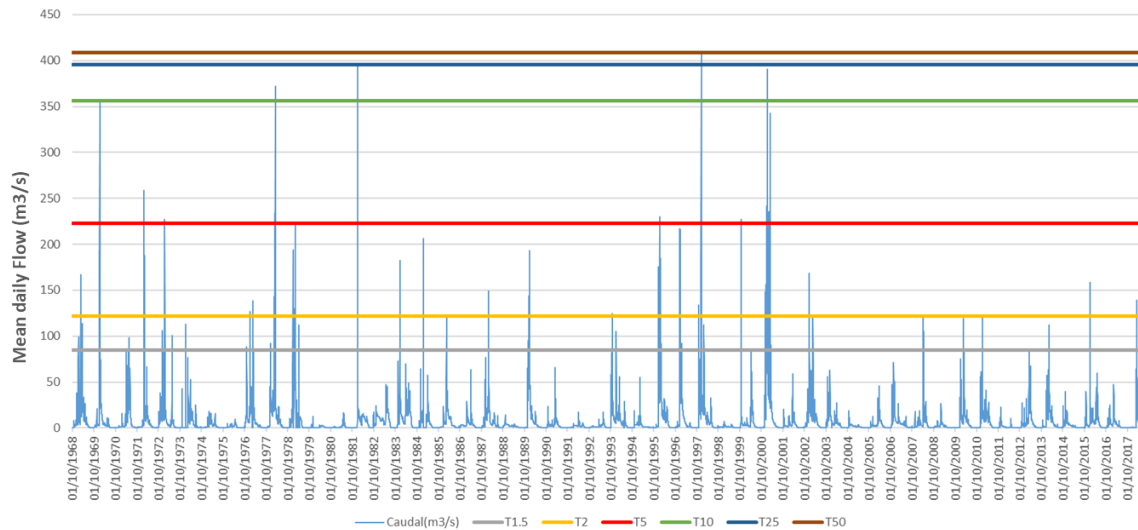


Figure 2. 6. Mean daily flow for the period 1968-2017. Horizontal lines indicate return period thresholds: T1.5 (grey line), T2 (yellow line), T5 (Red line), T10 (Green line), T25 (Blue line), and T50 (brown line).

3.3. Temporal evolution of the longitudinal structure of the riparian corridor and land cover

Based on image classification the initial 5 classes were reduced to 3 classes: (i) non woody vegetated (grassland and shadow), woody vegetated (tree and shrub vegetation?) and (iii) water. The results show important changes in land cover, increasing the woody vegetated areas in unconfined and confined segments except S1, S5 and S7, and decreasing no vegetated areas in confined segments (7-9), and S5. In terms of vegetation increase, we observed an increase of vegetated areas in confined segment and in two unconfined areas. Segment 5 stands out in terms of its change towards less vegetated forms, as can be seen in the large loss of vegetated surfaces between 2009 and 2019, due to the flooding that occurred in 2016. In contrast, the two final (confined) sections have undergone a very substantial increase in their vegetated surface, increasing by more than 25 ha combined.

Table 3. 3. Percentage of change in land cover classes from 2009 to 2019. Positive and negative values refer to increases and decreases respectively. Values higher than 10 % in absolute value are highlighted in bold type. More than 10% in bold font

Land class	cover	Segments								
		1	2	3	4	5	6	7	8	9
Non vegetated	Woody	1.4	5.8	16.3	9.5	-11.7	4.9	-2.2	-5.2	-5.9
	Woody	-8.5	5.7	2.8	8.3	-49.6	9.9	-3.8	14.0	15.8
	Water	0.4	6.3	9.1	8.8	1.2	13.0	13.8	-6.0	5.0

3.2.2. A methodological framework to quantify riparian corridor evolution by image classification and consecutive LiDAR analysis

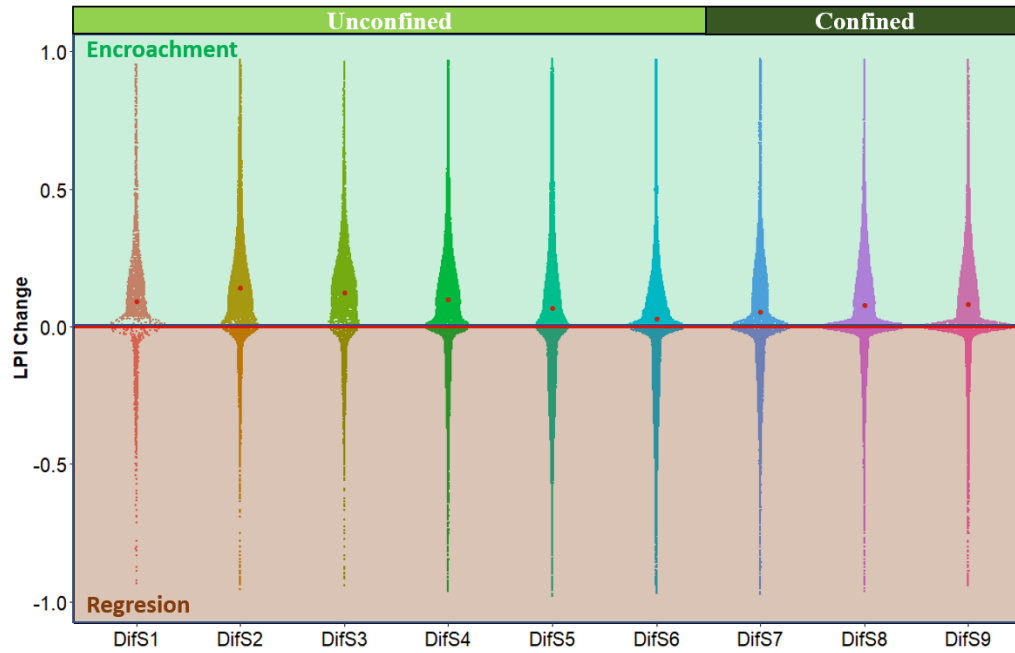


Figure 2. 7. LPI changes per segment (DifSx) represents the difference between LPI values in 2009 and 2019. Positive values represents encroachment processes, negative values represents regression process and zero represent no changes.

Figure 2.7 corresponds to the changes along the study period and show a clear trend towards a higher concentration of pixels with an increase in vegetation density or no changes. However, particularities are also observed in several segments. For example, in the confined segments we observe more surfaces experimenting no change, i.e., tending to zero value than in the unconfined reaches. From S1 to S5 more considerable differences in density than in other reaches further downstream are observed (i.e., less concentration of pixels with value equal zero). Therefore, the general trend is towards a corridor that is either more densely vegetated or with no change in cover, with regression being less frequent.

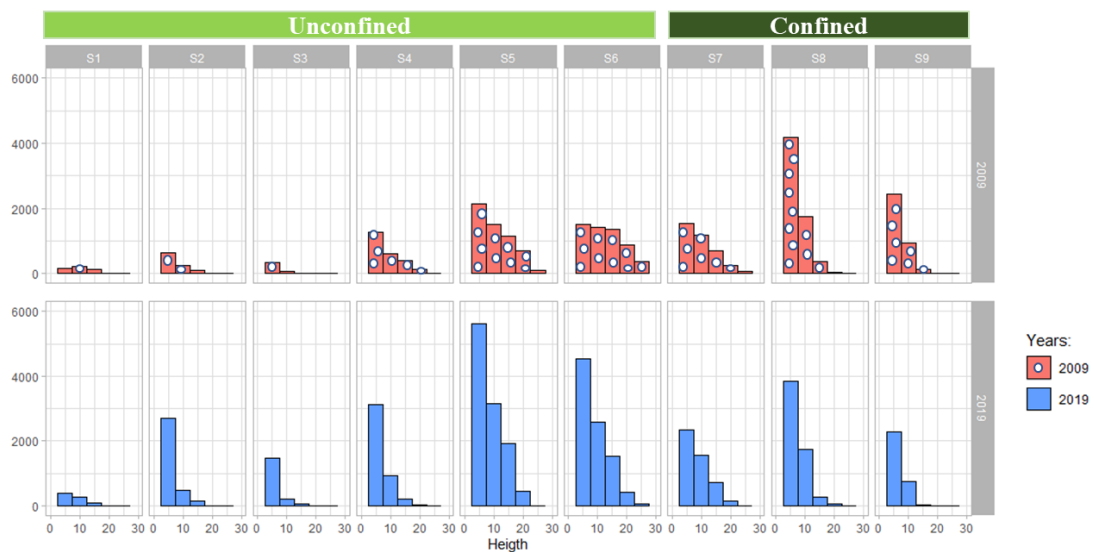


Figure 2. 8. Frequency of individual trees higher than 1.5 m distributed in height classes with an interval of 5 meters.

Based on the frequency distribution of tree height classes, a different pattern is observed in unconfined segments (i.e., from S1 to S6) compared to confined segments (i.e. from S7 to S9) (Figure 2.8). In unconfined segments, the smaller height classes (i.e., from 1.5 m to 5 m-height and from 5 m to 10 m) notably increase from 2009 to 2019 that would be related with more recruitment during the 10 years. For example, the smallest height class increases 78.4 in S1, 150.4 in S2 and, in some cases even triples as in S3 with an increase of 221.8. For the second class, similar increases are found (e.g., 144.4 increase in S1, 314.8 increase in S3 and 113.8 increase in S6). However, in confined segments there is no comparable increase of the smaller height class (e.g., 46.7 increase in S7 and decrease of 5.8 and 9.4 in S8 and S9 respectively).

Regarding the following height classes, the frequency is more stable the taller the trees are. We found a slightly increase in third and fourth class (i.e., 88.5 and 12.8 in S2 and 57.2 and -22.3 in S6 for 10 to 15 m-height class and 10 to 15 m-height class respectively) and even a decrease in taller classes that could be related with big and old trees mortality (e.g., 66.7 decrease in class 20 to 25 m-height in S1 segment, 72.4 decrease in class 15 to 20 m-height in S4).

3.4.Changes of the transversal structure of the riparian corridor

The analysis of the distribution of riparian vegetation among the three elevational bands (2.3.1) relative to the channel allows exploring the evolution of vegetation density in the 10 years period (Figure 2.9). All segments show an altitudinal gradient of density, increasing with the relative altitude, i.e., the higher the band the higher the density of vegetation. Regarding the temporal comparison between 2009 and 2019, segments S1 and S6 present similar density in the three elevation levels with variations lower than 3, segments S7, S8 and S9 show a slightly increase between 5 and 10 of the density of vegetation in all ranges of altitude, while segments S2, S3, S4 and S5 have undergone a very relevant increase in the low level of vegetation (between 15 and 20).

The comparison between confined and unconfined segments shows that confined segments present lower density of vegetation for each elevation level than unconfined segments, although the difference is not significant (Kruskal-Wallis test, $p > 0.1$). All segments, confined and unconfined, were characterized by an altitudinal gradient of vegetation density, the higher the distance to the channel, the higher the density (i.e., lower values of LPI) in both 2009 and 2019 with the exception of unconfined segments in 2019 that present high similar values for the three elevation levels.

3.2.2. A methodological framework to quantify riparian corridor evolution by image classification and consecutive LiDAR analysis

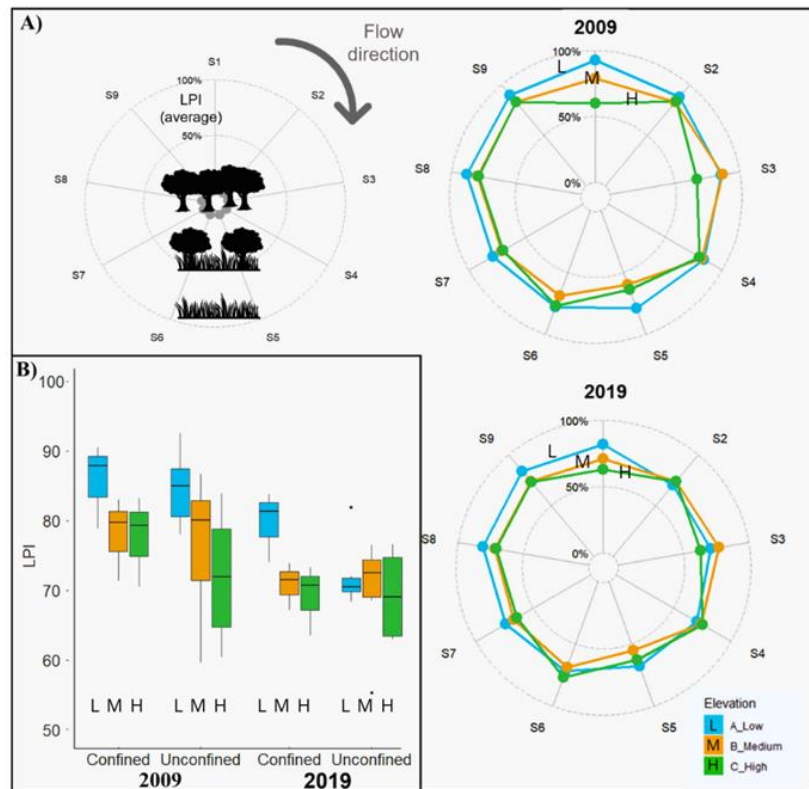


Figure 2. 9. A) LPI values in each segment for each elevational range relative to the channel (i.e., low, medium and high) B) Boxplot with LPI values for each elevational range differentiating confined and unconfined segments. L (Low elevation), M (Medium elevation

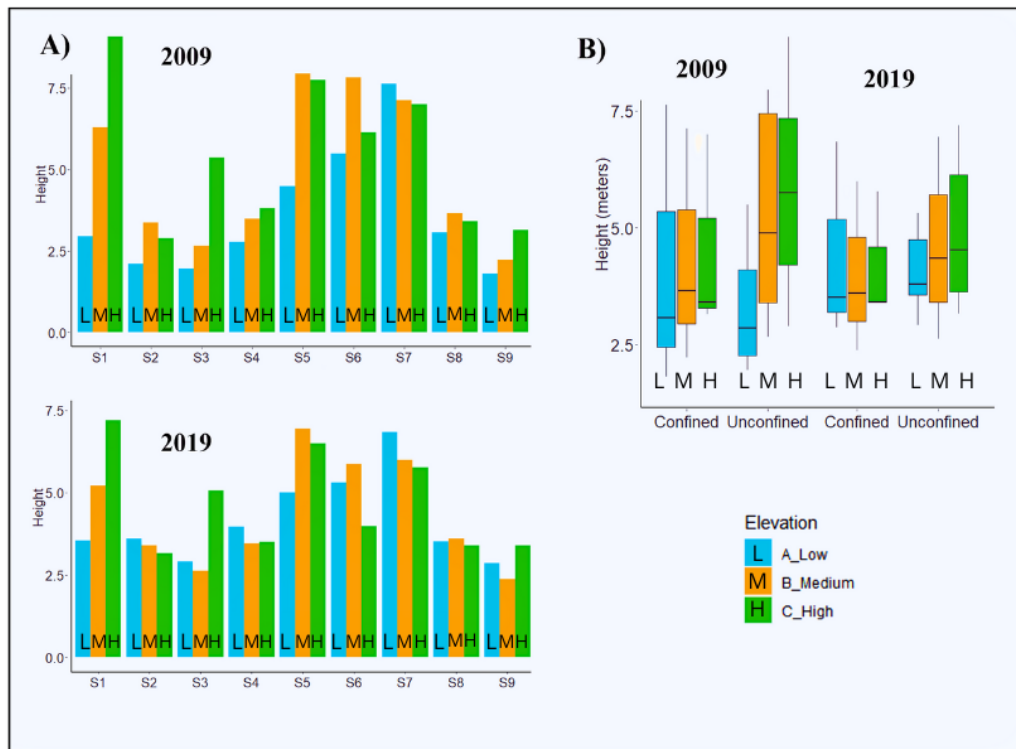


Figure 2. 10. A. Tree height values per segment analyse and relative elevation ratios. B Boxplot results of tree height values in confined and unconfined valleys according to relative elevation rates. L (Low elevation), M (Medium elevation) and H (High elevation).

According to individual height tree, there is a general pattern in most of the segments that consists of the trees being taller the further they are from the channel, although no significant differences were found (Kruskal Wallis test, $p > 0.1$). Most segments follow the same evolutionary behavior in 2009 and 2019, but in some cases the opposite occurs, and we find lower trees as we go up in height relative to the riverbed. This inversion occurs in S2, S4, S6 and S7, where this conversion has become more evident over the years.

In reference to the difference between confined and unconfined sections, we found that in the unconfined sections in 2009 there was a direct relationship between the height relative to the riverbed and the height of the trees (areas close to the riverbed with lower heights), but in contrast in 2019 this distribution of heights becomes very homogeneous, finding a corridor very similar altitudinally to the different heights analysed, e.g., S8 in 2019 (Figure 2.10).

4. DISCUSSION

4.1. Riparian Vegetation mapping challenges

Our approach, which combines high resolution aerial images including near-infrared aerial imagery, topography and LiDAR data provides an objective semi-automatic riparian mapping. The evolution of GIS, satellite imagery and data sources in recent years has generated an important change in the study of forest ecosystems and the environment (Johansen et al., 2007; Tormos et al., 2011). Recent advances are related to the use of high resolution aerial images (Carbonneau et al., 2020), very high resolution (VHR) or VHR near-infrared aerial imagery (Demarchi et al., 2020), satellite images combining DEM and orthophotos (Spada et al., 2018) but also LiDAR data. LiDAR data are particularly relevant for the spatio-temporal characterization of the active geomorphic processes that contribute to the shaping of river landscapes as it could provide detailed mapping in different moments.

In the last decades, studies applying these technologies in riparian contexts have been increasing (e.g., Cavalli et al., 2008; Cavalli and Tarolli, 2011; Dilts et al., 2010; Lallias-Tacon et al., 2017; Laslier et al., 2019; Michez et al., 2017). Moreover, LiDAR technology is more effective than other remote sensing methods in densely vegetated regions such as riparian corridors because its ability to automatically filter vegetation and artificial structures. However, the use of consecutive LiDAR flights to analyse the trajectory and changes of rivers, as it has been done in this work, are still scarce (Brousse et al., 2021). One of the reasons could be the high cost of this technology when private flights are needed. In our case, LiDAR data were available at the Instituto Geográfico Nacional (IGN) of Spain which is a notable advantage although the density of point cloud is less than 2 points/m² and higher density would be desirable for further studies.

In addition to the usefulness of the application of LiDAR for this type of study, in recent years the use of this technology in combination with multispectral optical images has made it possible to estimate the evolution of dendrometric and dasometric variables (i.e., biomass, carbon or vegetation structure) and to distinguish species at the individual scale (Chasmer et al., 2017; Fang et al., 2018; Dalponte et al., 2019; Naik et al., 2021). Their application to understand the evolution of riparian corridors and the effects on vegetation under different scenarios (e.g., flow regulation, natural regime, climate change or restored areas) could be very useful for decision making by riparian corridor managers.

Regarding the object-based image analysis that was conducted to perform a land cover analysis, it has been very useful to understand the evolution of the riparian vegetation of the Tiétar river. When conducting this type of analysis, it is necessary to highlight the importance of each step that must be carried out, as well as the cost-effectiveness of an open-source

software solution (Rocchini and Neteler, 2012). The supervised machine learning method employed was the Support Vector Machine with a Radial Basis Function (SVM-RBF) algorithm in QGIS, applied on three different dates spaced over time. After analysis and verification with other results, the outcomes are considered satisfactory. This kind of machine learning techniques are of paramount importance nowadays as previously used (Beechie and Imaki, 2014; McManamay et al., 2018; Phiri et al., 2020; Rabanaque et al., 2022). allowing for a precise and rapid analysis of the evolution of different land covers, confirming their capability to perform such analyses and provide results as demonstrated in this study.

In summary, the methodology used in this study demonstrates the effectiveness of these technologies for monitoring forest ecosystems, as well as in the search for changes in the riparian corridor at previously unattainable resolutions, accuracies and spatial coverages.

Next potential steps in the use of LiDAR data applied in fluvial ecosystems could be related with the monitoring of geomorphological trajectories of channel forms. The use of LiDAR data in the geomorphological monitoring of rivers holds significant potential due to its ability to capture topographic details with high precision and resolution. LiDAR technology enables the creation of digital terrain models (DTMs) and digital surface models (DSMs) that reveal the shapes and structures of riverbeds and banks with unprecedented accuracy. In this case a points density lower than 2 points/m² was used, but higher densities are feasible (Ruiz et al., 2014). This kind of data are crucial for studying processes such as erosion, sedimentation, and changes in fluvial morphology over time. The high point density and the laser's ability to penetrate vegetation allow for detailed mapping of inaccessible areas, providing valuable information for flood risk management, habitat restoration, and infrastructure planning. In summary, LiDAR offers a powerful and versatile tool for monitoring and analyzing river systems, facilitating a deeper understanding and more effective management of these dynamic environments.

On the other hand, this model also has limitations for its application, as there is an increase in errors in environments where the tree density is excessive, which can increase the error of tree measures (Richardson & Moskal, 2011; Kellner et al., 2019). In addition, the current point density allows a sufficiently precise knowledge of the individual crowns, but the recorded errors can be improved by increasing the point density, as is the case in the third LiDAR-PNOA flight, from which a density of 5 points/m² has been obtained. This increase in the density and quality of the data will allow future studies to provide other relevant aspects of the evolution of riparian corridors.

4.2. The evolution of the riparian corridor in the Tiétar river

The evolution of the riparian corridor shows clear symptoms of lack of dynamism and predominance of “encroachment” processes in all stretches, as previously describe in other rivers (e.g., García de Jalón et al., 2018; Martínez-Fernández et al., 2017; Räßple et al., 2017; García de Jalón et al., 2020). Succession of riparian vegetation tends towards a more complex functional and structural development(Corenblit et al., 2014). In recent decades, the reduction in the magnitude of floods has led to the stabilisation of riparian vegetation in many rivers, generating a narrower channel, limiting recruitment after vegetation colonization and grow due to the limited availability of open spaces for pioneer species (Webb & Leake, 2006; Rivaes et al., 2014).

In unconfined segments of Tiétar river, we have found that smaller height classes (i.e., from 1.5 m to 5 m-height and from 5 m to 10 m) notably increase from 2009 to 2019, that would be related with a higher abundance of seedlings and saplings in 2019 compared to 2009. The potential greater availability of space in non-confined segments together with smaller floods with a return period of 2 years in 2010, 2015 and 2017 could recover certain space could be the reason for this increase of seedlings in the low elevational range. In confined segments a

comparable increase is not observed but rather a maintenance of vegetation density which is in line with the lack of space in this type of valleys (e.g., Brierley C Fryirs, 2005). In addition, it is also important to note that there is a lack of floods with a return period higher than 2 years since 2001 (Figure 2.6), which has led to the decrease of river dynamics and the lack of generation of new spaces for the regeneration of pioneer species such as the willows (Dixon, 2003; Fischer et al., 2021). As a result of this lack of extraordinary floods, there has been a process of substrate fixation, leading to the growth of riparian species in less dynamic functional areas (García de Jalón et al., 2022). Currently, these areas are less susceptible to erosion, so that the geomorphological processes that encourage the creation of bare areas for the regeneration of pioneer species have been considerably affected.

Most of the changes are observed in smaller height classes, which can be easily explained by the higher turnover of smaller classes in these dynamic environments. However, taller classes are more stable in the number of individuals, and even a decrease in taller classes was found (e.g., in segments S2, S4, S6 and S7) that could be related with big and old trees mortality or windy events (Figure 2.11).



Figure 2. 11. Image taken in River Tiétar in 2022 durnig field campaings showing a senescence tree (left) and uprroted tree (right).

Relative DEM is a very novel methodology for assessing the evolution of riparian vegetation structure and density at different elevations along the river centreline. We conducted the study of relative altitude in order to know in which parts of the river, according to its relative elevation, and in confined or unconfined segments, the vegetation was undergoing encroachment or ageing processes with lack of regeneration.

According to the observed results, the unconfined river stretches in 2009 exhibited a vegetation structure consistent with the geomorphological and ecological processes typical of a moderately wide valley reach. This structure presented an initial regeneration zone with sparse, low-density vegetation, progressing to denser and more mature vegetation as elevation increased relative to the riverbed. However, in subsequent years, due to the absence of flood

events (higher than 2 years return period) and anthropogenic factors such as riverbed occupation, areas near the riverbed have not experienced significant geomorphological changes sufficient to support regeneration processes as documented in other European rivers, such as the Jarama (García de Jalón et al., 2022), Lower Tisza (Nagy et al., 2018; Fehérváry et al., 2021). See also other global examples (Thorne, 1990; Gordon and Meentemeyer, 2006; Crosato and Saleh, 2010; Oorschot et al., 2016; Magliulo et al., 2021; Merritt and Cooper, 2000). The comparison between confined and unconfined segments shows that the confined segments have lower vegetation density for each elevation level than the unconfined segments, and that in 2009 for the unconfined sections it follows a perfect increment gradient. This trend may be mainly due to the natural functioning of a river, where in the lower areas we find a less dense and variable corridor, which suffers more disturbances at times when the channel is above average, as occurs in other rivers (Shafroth et al., 2002; Hupp and Rinaldi, 2007; Stromberg et al., 2010). Even so, there is a clear difference between confined and unconfined stretches, since in the former this direct relational gradient between density and height is not completely fulfilled, as the density of vegetated points being more constant. This may be largely due to the section of the river and the velocity that occurs in these sections, which maintains a more constant altitudinal gradient of density, although there is also a higher overall density, due to the high resistance of the plant species found at different heights. Relating LPI values to the forms of the riverbed, we find a direct relationship between the areas vegetated with woody species, and the densest and most changed areas in terms of positive values of LPI (Figure 2.6) and negative values of change (Table 3.2, row 2).

5. CONCLUSIONS

This study provides a clear and efficient methodology to characterize vegetation structure in riparian corridors. Through the remotely detection of tree crowns and their location, the classification of images according to spectral bands and the geomorphological analysis of the stretch, our methodological approach provides advantages: (1) the use of a replicable and objective methodology to segment the river corridor, and (2) a semiautomatic analysis of the spatial distribution of riparian vegetation that could characterize the structure of river corridor over long rivers with moderate effort.

The method has validated with field measures which manifest the power and versatility of LiDAR data for monitoring and analyzing river systems in the short term.

In the particular case of Tiétar river, a vegetation encroachment process has been found showing the succession trend of the corridor with the higher stability in the structure of vegetation in confined segments. Although a higher abundance of seedlings was found in year 2019 in the case of unconfined rivers revealing the dynamism still present in Tiétar river.

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3.2.2. A methodological framework to quantify riparian corridor evolution by image classification and consecutive LiDAR analysis

4.DISCUSIÓN



DISCUSIÓN

La presente tesis aborda distintas fases del ciclo biológico de la vegetación riparia y su interacción con los procesos hidromorfológicos del entorno. Desde el estudio bibliográfico de las primeras fases del regenerado o la dispersión de semillas, hasta su evolución en bosques maduros sobre suelos formados y con alta competencia. La fotointerpretación ha sido una metodología fundamental para conocer las trayectorias geomorfológicas y la variación de las formas del cauce en varios ríos peninsulares junto con la evolución de la cobertura de vegetación. Esta técnica más tradicional se ve notablemente reforzada por avances tecnológicos en el campo de la teledetección y los sistemas de información geográfica mejorando la precisión y ofreciendo una herramienta útil a los gestores y restauradores para la conservación y mejora de los ecosistemas fluviales del entorno mediterráneo, principalmente.

A continuación, se discuten los resultados generales de esta tesis, junto con otros desafíos teóricos y prácticos, y se hacen propuestas para la comprensión de los corredores riparios y la gestión de los ecosistemas fluviales.

4.1. DESAFÍOS Y OPORTUNIDADES EN LA INVESTIGACIÓN SOBRE EL RECLUTAMIENTO DEL GÉNERO *SALIX*.

En la presente tesis, se planteó como parte inicial del estudio conocer el estado del arte sobre los factores que afectan de algún modo al regenerado del género *Salix*. Esto permitirá conocer las carencias de conocimiento, los retos y las oportunidades a las que se enfrenta este género claramente amenazado por los impactos derivados de la actividad humana (Palm 2020; Díaz-Alba et al., 2023) y el cambio climático (Kalita et al., 2021) entre otros muchos factores.

Se han estudiado un total 35 especies del género *Salix* en la fase de reclutamiento a nivel global, principalmente en América del Norte y Europa. De aproximadamente 526 especies de *Salix* en el mundo (según Zhen-Fu, 1987), la proporción estudiada en la literatura científica es limitada, y solo el 1% de las especies que ocurren en Asia han sido investigadas. Además, se observa una falta de estudios en entornos áridos y semiáridos. Una de las razones por la escasa presencia de estudio puede ser la complejidad de los requisitos para el reclutamiento de este género, tales como la adaptación a regímenes con altas perturbaciones, así como el diseño adecuado de experimentos que permitan obtener conclusiones con un grado aceptable de fiabilidad.

Los experimentos de campo se enfrentan a desafíos, como la pérdida de dispositivos de monitoreo, o la medición durante la ocurrencia de eventos extremos (por ejemplo, inundaciones o sequías extremas), y la replicación de estos mismos experimentos puede ser un obstáculo adicional. A pesar de estas dificultades, la investigación sobre las adaptaciones y requisitos de diversas especies de *Salix* es crucial para resaltar su papel en los ecosistemas fluviales y mejorar su estado de conservación.

Se identificaron condiciones óptimas para la germinación de los sauces a distintas elevaciones respecto del cauce (0,5-2 metros o próximos al cauce), o en rangos de temperatura variables (10-25 °C), además se observó una necesidad de mejorar el régimen de caudales en ríos regulados como limitante del germinado, lo que sugiere que estudios comparativos pueden ser valiosos para el éxito en los planes de gestión.

Este análisis también destaca que los factores edáficos e hidrológicos, junto con la distribución espacial y la elevación sobre el canal, son los más estudiados en relación con la regeneración de *Salix*. En contraste, factores atmosféricos como la exposición a la luz y la temperatura del aire son menos investigados. Con el contexto actual del cambio climático, la

investigación sobre estos factores es crucial. Por ejemplo, se necesitan respuestas sobre cómo un aumento hipotético de temperatura podría afectar a la germinación y el crecimiento de las plántulas de *Salix*, así como la interacción de variables climáticas con otros factores abióticos en la regeneración de *Salix*.

Las presiones humanas, como la alteración del régimen de caudales y la competencia de especies invasoras, han afectado negativamente a la regeneración del género *Salix*. Aunque estos factores se han estudiado de forma independiente, se ha encontrado una relación entre ellos, especialmente en el caso de *Tamarix spp.* en EE. UU. Una aproximación más holística, que considere las interacciones de múltiples presiones antropogénicas, podría ofrecer nuevos conocimientos sobre esta cuestión.

Las especies de *Salix* son ampliamente utilizadas en proyectos de restauración y rehabilitación en zonas fluviales, donde tanto la siembra como la plantación se aplican con diversos grados de éxito (Gage y Cooper, 2004; Pezeshki y Shields, 2006; Ministerio de Medio Ambiente, 2007). Aumentar el conocimiento sobre la ecología y requisitos de *Salix* mejorará significativamente el éxito de las iniciativas de restauración a nivel mundial.

Se sugieren varias líneas para futuras investigaciones: (1) ampliar el conocimiento sobre las numerosas especies de *Salix* aún inexploradas, (2) realizar estudios comparativos sobre las variaciones en los efectos de gradiente entre especies, (3) investigar los efectos de eventos climáticos extremos en ecosistemas fluviales, prestando especial atención al aumento de temperaturas y concentraciones de gases de efecto invernadero, y (4) considerar múltiples presiones interactivas. El estudio de estos aspectos podría contribuir significativamente a la gestión y conservación de paisajes fluviales.

4.2. EL CAMBIO GEOMORFOLÓGICO DEL RÍO JARAMA Y EL DECLIVE DE LOS SAUCES

El río Jarama ha experimentado cambios significativos desde 1956, tanto en sus múltiples cauces como en las barras de sedimentos desprovistas de vegetación aptas para la germinación y colonización de especies pioneras, lo que ha condicionado la actual composición y estructura de la vegetación. La reducción del índice de trenzamiento a lo largo de los dos subperíodos analizados indica una simplificación del trazado, debido a la intensa alteración de los caudales por las presas, con una disminución de los caudales que favorece el establecimiento y crecimiento de la vegetación. Este patrón de simplificación y estabilización de los ríos en respuesta a la homogenización del flujo por regulación de presas ha sido observado ampliamente (por ejemplo, Grant et al., 2003; Poff et al., 2007; Kiss y Blanka, 2012; González del Tánago et al., 2016; Martínez-Fernández et al., 2017).

Otra presión relevante que afectó gravemente a este río fue la extracción de grava desde la década de 1960 (Uribelarrea et al., 2003), lo que provocó una incisión en el lecho del río y una fuerte disminución en la extensión de las barras de gravas. En 1999, más del 30% de la llanura aluvial fue impactada por las actividades mineras. Estos cambios son similares a los observados en otros ríos de la región mediterránea, donde el efecto sinérgico de diversas presiones redujo el número de cauces y la dimensión del cauce activo (Martínez-Fernández, González del Tánago et al., 2017; Batalla et al., 2018; Fu et al., 2023).

En cuanto a los procesos asociados a la movilidad del cauce activo, se ha observado una clara tendencia entre los años 1956 y 2018 a perder movilidad tal y como se ha observado en otros ríos mediterráneos (Magdaleno y Fernández, 2011; Sanchis-Ibor et al., 2019; Fazelpoor et al., 2021). Estos indicadores calculados muestran una tendencia hacia la estabilización de islas y llanuras aluviales, un fenómeno observado en varios ríos de climas templados (Liébault

y Piégay, 2002; Gurnell & Petts, 2006; Corenblit et al., 2010). La estabilización de antiguos canales activos o barras genera un proceso de colonización de la vegetación (O'Briain, 2019; García de Jalón et al., 2020). Los procesos de maduración de la vegetación, que implica una transición desde una fase geomorfológica pionera hacia estructuras más complejas (biogeomorfología, según Corenblit et al., 2010), fue el cambio dominante en el primer periodo estudiado, coincidiendo con la reducción del canal activo y su movilidad, y la transformación en un canal único. Cabe destacar que no existieron signos de naturalización en este primer periodo, sino todo lo contrario, procesos de antropización en tramos bajos asociados a la expansión urbanística y el recreo. En el segundo periodo, predominaron los procesos de estabilización de las formas del canal, con una baja capacidad de cambio, probablemente debido al aumento en la densidad de la vegetación (“encroachment”) y la formación de suelo del periodo anterior, lo que incrementó la resistencia del dosel vegetal frente a la acción erosiva de las inundaciones (Ishikawa et al., 2003; Tal et al., 2004).

Estos cambios están relacionados con diversas presiones que reducen el dinamismo del canal, lo que es crucial para la vegetación pionera que coloniza estas áreas (Corenblit et al., 2007; Rivaes et al., 2013; González del Tánago et al., 2016). Consistente con la disminución de las barras de grava desnuda, donde solían habitar especies adaptadas a perturbaciones, como los sauces, solo se encontraron áreas limitadas con regeneración de especies leñosas ribereñas durante las campañas de campo. Por lo tanto, los principales obstáculos para su regeneración exitosa parecen estar vinculados a la falta de áreas adecuadas para el reclutamiento, como barras de grava y de arena, que han sido reducidas por la intensa extracción de grava y la construcción de presas. A pesar de las limitaciones, la regeneración de especies de *Salix* aún se produce en el río Jarama

4.3. TECNOLOGÍAS Y MARCO METODOLÓGICO (LiDAR) PARA EL SEGUIMIENTO AMBIENTAL DE RIBERAS

En los últimos años, el análisis de los corredores riparios ha avanzado considerablemente gracias a la evolución de las imágenes, los datos, las herramientas de sistemas de información geográfica (SIG) y las tecnologías espaciales (Johansen et al., 2007; Tormos et al., 2011; Fernandes et al., 2013). Los resultados de esta tesis demuestran que la metodología empleada, que combina tecnología LiDAR del PNOA, clasificación supervisada de imágenes y SIG, es eficaz para monitorear y detectar cambios en los corredores riparios. Además, en los últimos años se han experimentado muchos avances relacionados con el uso de imágenes aéreas de alta resolución (Carbonneau et al., 2020), e imágenes aéreas en infrarrojo cercano de muy alta resolución (VHR) (Demarchi et al., 2020). La aplicación de estas tecnologías, aunque escasas para la toma de decisiones, ha permitido por ejemplo analizar la evolución de corredores riparios mediante la comparación de dos vuelos LiDAR consecutivos (por ejemplo, Brousse et al., 2021), mapear variables asociadas a estos corredores (Dilts, Yang & Weisberg, 2010; Johansen et al., 2010; Guo et al., 2017; Laslier et al., 2019), así como monitorizar grandes superficies riparias usando LiDAR y fotogrametría (Michez et al., 2017).

El uso de LiDAR ha demostrado ser muy eficiente para evaluar los cambios producidos entre dos fechas determinadas en entornos sin cambios aparentes, o en entornos con transformaciones (por ejemplo, tras una perturbación o tras una iniciativa de restauración como la demolición de barrera longitudinal). La realización de vuelos propios debido a su elevado coste se hace algo inviable, no obstante, una mayor frecuencia de vuelos, al menos anual, permitiría realizar este tipo de análisis aplicado a gestión de espacios fluviales o restauración de los mismos. Además, permitiría la monitorización casi continua de nuestros ríos a nivel de vegetación y formas del cauce. Otro aspecto para destacar es la densidad de puntos de los vuelos (relación positiva entre

mayor densidad, mayor coste), si se aumentara la densidad de puntos se conseguiría un modelo más detallado de la realidad. En la actualidad se recomienda una densidad de al menos 2 puntos/m² para detectar árboles individuales (Latella et al., 2021), aunque algunos estudios muestran resultados precisos incluso con densidades más bajas (Goodwin et al., 2006; Wu et al., 2016; Ma et al., 2017), mientras que otros indican que aumentar la densidad por encima de 2 puntos/m² no mejora significativamente los resultados y puede no justificar los costos adicionales (Jakubowski et al., 2013). En la presente tesis se han utilizado varios vuelos del proyecto PNOA-LiDAR con densidades comprendidas entre 0.5 y 1 puntos/m² entre 2010 y 2019. En septiembre de 2024 se ha publicado la tercera cobertura LiDAR en algunas comunidades con una densidad de puntos mucho más alta lo que abre una línea de aplicación de estas metodologías muy interesante para los gestores.

Las aplicaciones del LiDAR en la gestión de recursos naturales y en el monitoreo de su evolución tras diversas intervenciones, ya sean presiones o restauración, son múltiples (Dilts et al., 2010; Johansen et al., 2010; Guo et al., 2017; Michez et al., 2017; Laslier et al., 2019; Huylenbroeck et al., 2021). El aumento de la frecuencia de vuelos y la mejora en la resolución espacial aumentarían enormemente la eficiencia de estas tareas, aunque los datos de campo seguirán siendo necesarios para validar estas técnicas remotas.

Además de su utilidad en estudios como este, en los últimos años la combinación de LiDAR con imágenes ópticas multiespectrales ha permitido en el ámbito forestal estimar la evolución de variables dendométricas y dasométricas, como la biomasa, el carbono o la estructura de la vegetación, y también distinguir especies a nivel individual (Chasmer et al., 2017; Fang et al., 2018; Dalponte et al., 2019; Naik et al., 2021). Su aplicación en el monitoreo de corredores riparios, y en el análisis de los efectos en la vegetación bajo distintos escenarios (por ejemplo, regulación de caudales, regímenes naturales, cambio climático o restauración) sería de gran valor para los gestores de estos espacios.

Tras la demolición del azud en el río Lozoya, se observó un incremento en la formación de barras de gravas y una reducción de la cobertura de canales secundarios. Este proceso, inducido por la eliminación de la barrera y posiblemente facilitado por la ocurrencia de avenidas, favoreció la aparición de nuevas áreas aptas para la colonización vegetal, produciéndose una apertura de espacios expuestos a la luz, y un aumento de la disponibilidad de barras de gravas colonizables. Efectos similares de incremento notable del dinamismo debido a la demolición de azudes, así como debido a la eliminación o retranqueo de construcciones laterales como motas y escolleras han sido encontrados por otros autores (e.g., Rohde et al., 2005; González et al., 2015; Martínez-Fernández et al., 2017).

Los resultados del monitoreo y el análisis de la vegetación muestran en el río Tietar, una clara evolución del corredor ripario hacia una falta de dinamismo y predominio de procesos de "encroachment" (invasión de la vegetación) en todos los tramos, tal como se ha descrito previamente en otros ríos (por ejemplo, García de Jalón et al., 2018; Martínez-Fernández et al., 2017; Räßple et al., 2017; García de Jalón et al., 2020). La dinámica evolutiva de la vegetación ribereña tiende hacia un desarrollo funcional y estructural más complejo, formando un corredor maduro (Corenblit et al., 2014). En las últimas décadas, la reducción en la magnitud de las inundaciones ha provocado la estabilización de la vegetación riparia en muchos ríos, generando un canal más estrecho y limitando el reclutamiento tras la colonización de la vegetación, debido a la limitada disponibilidad de espacios abiertos para las especies pioneras (Webb & Leake, 2006; Rivaes et al., 2014). Se establece una clara diferencia atendiendo a su configuración geomorfológica, con una esperada mayor disponibilidad de espacios para el regenerado en los segmentos no confinados, que junto con una inundación extraordinaria ocurrida en enero de 2016 (316 m³/s), medida en la estación de aforo de Arenas de San Pedro, pudo ser la razón del

aumento de plántulas en el rango de elevación más bajo (al igual que ocurre en el río Lozoya tras la eliminación del azud) del modelo digital relativo de elevaciones. En los segmentos confinados no se observa un aumento comparable, sino más bien un mantenimiento de la densidad de vegetación que además crece en altura, lo cual está en línea con la falta de espacio en este tipo de valles (por ejemplo, Brierley y Fryirs, 2005). La mayoría de los cambios se observan en las clases de menor altura, lo que se puede explicar fácilmente por el mayor recambio de estas clases en estos entornos dinámicos. Sin embargo, las clases de mayor altura son más estables en cuanto al número de individuos.

Analizando la densidad medida a través del LPI, encontramos que los tramos confinados presentan una menor densidad de vegetación en cada nivel de elevación en comparación con los tramos no confinados, y que, en 2009, en las secciones no confinadas, sigue un gradiente de incremento de densidad correlacionado positivamente con la altitud relativa. Esta tendencia puede deberse principalmente al funcionamiento natural de un río, donde en las áreas más bajas encontramos un corredor menos denso y más variable, que sufre más perturbaciones en momentos en los que el caudal está por encima de la media, como ocurre en otros ríos (Shafroth et al., 2002; Hupp y Rinaldi, 2007; Stromberg et al., 2010). Aunque también hay una mayor densidad global, debido a la alta resistencia de las especies vegetales que se encuentran a diferentes alturas. Para concluir, si relacionamos este LPI con las formas del lecho del río, encontramos una relación directa entre las áreas vegetadas con especies leñosas y las áreas más densas.

4.4. PRÓXIMO RETOS Y PERSPECTIVAS DE CARA A LA GESTIÓN

De las experiencias descritas en esta tesis surge el planteamiento de nuevos retos científicos y su posible aplicación a la gestión de los corredores riparios, donde se destacan principalmente dos.

Tras la revisión bibliográfica sistemática sobre los factores que se han comprobado que afectan a las especies del género *Salix* de forma experimental, se concluye que la parte de especies estudiada del total existente es muy pequeña, y que existen procesos cuyo efecto a largo plazo aún desconocemos. Las distintas adaptaciones que han ido adquiriendo estas especies podrían marcar la diferencia en el uso de unas u otras ante iniciativas de restauración ante determinadas carencias, presiones o cambios. Por ejemplo, el estudio de cómo afectará un posible incremento de temperaturas a la germinación y desarrollo de estas especies, o una tendencia creciente de estrés hídrico causadas por el cambio climático es aún escaso. Por lo tanto, los huecos de conocimiento detectados en la revisión deberían servir como propuesta para futuras líneas de investigación que traten de anticiparse a cambios futuros que pueden afectar a los ecosistemas riparios.

El avance y desarrollo de tecnologías LiDAR, “remote sensing” y SIG, han resultado muy útiles para evaluar la evolución del corredor ripario en una gran extensión, de forma eficiente y rápida. La validación con datos en campo valorando así la incertidumbre de los datos obtenidos de forma remota es un paso fundamental del proceso. En esta tesis hemos visto que una densidad de puntos no muy elevada permite monitorizar la vegetación, por lo que un incremento de la densidad de puntos y un aumento de la frecuencia de esos vuelos arrojaría información muy valiosa y más precisa del estado de la vegetación contribuyendo a la toma de decisiones ante cualquier medida de gestión, restauración o rehabilitación.

Las nuevas tecnologías permiten además analizar grandes superficies de terreno con pocas parcelas de campo, esto puede permitir realizar una correcta gestión y tener un conocimiento actualizado de las riberas de los ríos mediterráneos, o extrapolarse a otros ecosistemas o casos

de estudio.

Actualmente el Plan Nacional de Ortofotografía Aérea (PNOA-LiDAR) está implementando la tercera cobertura con una densidad de 5 puntos por m² lo que permitirá realizar estudios más detallados de la vegetación de ribera y las formas del cauce, aunque aparecerán nuevas limitaciones asociadas a la gran capacidad de procesamiento para grandes superficies. No solo el incremento de la densidad es algo positivo, sino el n° de coberturas ya que la comparativa de 3 coberturas permitirá establecer una evolución y aumentar la información disponible para la toma de decisiones. A raíz de esta metodología se podría plantear la programación de una herramienta que valide los datos LiDAR de manera automática, y extraiga una serie de variables como resultado que sirvan de información a los gestores o expertos para evaluar la dinámica fluvial del río a nivel de vegetación de ribera.

Cada vez observamos tramos fluviales menos sinuosos, más regulados, menos trenzados, y más transformados, por ello este tipo de herramientas puede ayudar a que las labores de restauración fluvial mejoren adaptándose a las necesidades reales de dinámica fluvial de los ríos mediterráneos. Actualmente las labores más destacadas son la plantación de árboles o la eliminación de motas, actuaciones útiles pero que a veces no se estudian con verdadero detenimiento y la necesidad fluvial es completamente distinta. Es por ello que esta tesis permite establecer un marco metodológico novedoso para mejorar la gestión y la restauración ecológico de nuestros entornos fluviales.

5.CONCLUSIONES



5. CONCLUSIONES

A continuación, se muestran las principales conclusiones de la tesis:

- I. Tras la revisión bibliográfica realizada sobre el género *Salix*, se ha concluido que existen carencias de conocimiento sobre los sauces a nivel mundial, debido a su complejidad a la hora de estudiar, las limitaciones de replicar estudios y la gran cantidad de especies existentes. (Apartado 3.1.1.).
- II. En cuanto a los factores analizados en la revisión, se concluye que el regenerado del género *Salix* está limitado principalmente por la aridez del suelo, la sequía, los cambios repentinos del nivel freático, la salinidad del suelo, los caudales extremos y los escasos en verano y el elevado CO₂ atmosférico. (Apartado 3.1.1.).
- III. Tras el análisis del género *Salix* en el review, se concluye que la viabilidad del regenerado ocurre cuando el suelo se encuentra saturado, a altitudes respecto del cauce principal entre los 0,17 metros y 1,5 metros, a temperaturas oscilantes entre los 5-30°C, en zonas inundadas de manera frecuente, en zonas con alta exposición a la luz y libre de vegetación, y cuando los caudales invernales y primaverales son altos (Apartado 3.1.1.).
- IV. Analizando los diferentes artículos relacionados con el regenerado de sauce, se ha concluido que las fases críticas de regeneración se ven afectadas por los siguientes impactos; regulación de caudales, herbívora, presencia de especies vegetales exóticas o competencia, el cambio climático y el fuego. (Apartado 3.1.1.).
- V. El estrechamiento del cauce activo y la transformación de tramos ramificados en un cauce único se encontraron asociados a una gran pérdida de movilidad en el río Jarama. En el primer periodo analizado se observa una evolución de las formas del cauce hacia escenarios de “maduración” intensiva de las riberas, y procesos de antropización, mientras que la estabilidad (proceso de 'no cambio') domina en el segundo periodo estudiado. Por último, la regresión hacia estados pioneros (rejuvenecimiento) es prácticamente nula en la ribera de los tramos estudiados en el río Jarama (Apartado 3.2.1.).
- VI. El análisis de los transectos de la vegetación en el río Jarama mostró un predominio de las zonas de deposición de finos incluso en los márgenes del canal, mientras que las zonas de grava erosionadas (que es el hábitat característico de las especies pioneras de sauce) eran muy escasas, únicamente de un 8% de media (Apartado 3.2.1.).
- VII. La especie de sauce dominante en el río Jarama es *Salix salviifolia*, un sauce tolerante a la sequía que ha sido capaz de soportar los procesos de «maduración», estrechamiento del cauce y pérdida de movilidad del cauce estando ampliamente distribuido por todo el tramo. Por otro lado, otros sauces pioneros como *S. eleagnos* y *S. purpurea* son muy escasos y se encuentran en los pocos bancos de grava que quedan en la orilla (Apartado 3.2.1.).
- VIII. Los escenarios globales aquí descritos predicen una paulatina desaparición de los sauces en el río Jarama, ya que no existe un reclutamiento significativo a lo largo del río Jarama, y durarán lo que sobrevivan aquellos ejemplares maduros germinados en el periodo comprendido entre 1960 y 1990, donde existía una mayor movilidad fluvial y presencia de barras de grava óptimas para el regenerado. (Apartado 3.2.1.).
- IX. Los resultados obtenidos a partir del análisis de las formas del cauce y los datos LiDAR en el río Lozoya tras la demolición del azud evidencian un crecimiento generalizado de la masa vegetal durante el periodo comprendido entre los dos vuelos (2010 y 2016), reflejado en variables como altura, diámetro, biomasa y densidad. Asimismo, se

observan cambios en la distribución de las clases de altura y diámetro, con un incremento en los individuos de tamaño medio y una disminución en los tamaños extremos, tanto los más pequeños como los más grandes. Por otro lado, se ha detectado una reducción significativa de la cobertura de canales secundarios en las áreas más cercanas al cauce principal (zonas más activas), lo que ha generado la apertura de nuevos espacios desprovistos de vegetación. (Apartado 3.3.1.).

- X. En el caso específico del río Tiétar, se ha identificado un proceso de invasión de la vegetación que refleja una tendencia sucesional en el corredor, caracterizada por una mayor estabilidad en la estructura de la vegetación en los segmentos confinados. Además, se ha observado un gradiente altitudinal de densidad positivo, y un incremento de la densidad en las zonas más próximas al cauce. No obstante, se observó una mayor abundancia de plántulas en 2019 en los tramos no confinados, lo que revela el dinamismo aún presente en el río Tiétar. (Apartado 3.3.2.).
- XI. El análisis de los dos vuelos LiDAR, aunque espaciados en el tiempo, permite analizar de manera eficaz los cambios dendométricas y dasométricas de la vegetación riparia leñosa, permitiendo valorar los cambios producidos en la estructura del corredor ripario, y tener conocimiento de su estado actual y trayectoria de cara a la gestión de estos espacios. (Apartado 3.3.1. y 3.3.2.).
- XII. El ajuste entre los datos medidos y estimados respalda la calidad de la nube de puntos LiDAR, permitiendo explorar las respuestas del corredor ripario ante intervenciones orientadas a la mejora de la conectividad longitudinal, tratamientos de la masa arbolada, plantaciones, y otras acciones vinculadas a proyectos de restauración. Esta metodología puede constituir una herramienta eficaz y automatizable, facilitando el seguimiento de las restauraciones implementadas y simplificando las tareas de los gestores encargados de su supervisión.
- XIII. Si bien es cierto que existen ciertas limitaciones de esta metodología como la alta densidad de ejemplares en ciertas zonas del corredor (tangencia de copas) que dificulta la obtención de la densidad; el todavía bajo número de puntos por metro cuadrado de los vuelos LiDAR disponibles en el Centro Nacional de Información Geográfica; la dificultad de poder obtener datos mediante LiDAR de las especies arbustivas; y finalmente las limitaciones temporales en la disponibilidad de coberturas LiDAR. (Apartado 3.3.1. y 3.3.2.).

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