Assessment of Riparian Ecosystems for Sustainable Management in the Face of Climate Change: A Practical and Interdisciplinary Approach

Évaluation des écosystèmes ripariens pour une gestion durable face au changement climatique : une approche interdisciplinaire et pratique.

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RÉSUMÉ

Les écosystèmes ripariens jouent un rôle essentiel dans le maintien de l'équilibre écologique, la régulation de la qualité de l'eau et le soutien à la biodiversité. Cependant, ces écosystèmes sont de plus en plus vulnérables en raison du changement climatique et des pressions anthropiques, qui intensifient le stress hydrique, modifient les régimes hydrologiques et accentuent le besoin de mesures de restauration et de renaturation. En réponse à ces défis, le SAGE Loire en région Rhône-Alpes a encouragé des approches interdisciplinaires pour atténuer ces menaces et promouvoir une gestion durable. L'objectif de ce projet est d'évaluer l'état de santé et la fonctionnalité de la ripisylve, en intégrant les dimensions spatiales, écologiques et hydrologiques, afin d'élaborer des stratégies de restauration et de gestion adaptées face au changement climatique. En mobilisant les disciplines de la géomatique, de l'écologie et de l'hydrologie, ce projet vise à créer une base de données interdisciplinaire et à développer un indice permettant de caractériser la végétation riparienne. Cet indice intégrera la cartographie spatiale (basée sur SIG), des indicateurs écologiques du stress hydrique de la végétation, ainsi que des données hydrologiques sur la température de l'eau, offrant ainsi un outil global pour une gestion et une restauration efficace des écosystèmes ripariens.

ABSTRACT

Riparian ecosystems are vital for maintaining ecological balance, regulating water quality, and supporting biodiversity. However, these ecosystems are increasingly vulnerable due to climate change and anthropogenic pressures, which intensify water stress, alter hydrological regimes, and heighten the need for effective restoration and renaturation efforts. In response to these challenges, the SAGE Loire in the Rhône-Alpes region has advocated for interdisciplinary approaches to mitigate these threats and promote sustainable management. This project aims to assess the health and functionality of riparian vegetation, integrating spatial, ecological, and hydrological perspectives to inform restoration and management strategies in the face of climate change. By combining geomatics, ecology, and hydrology, the project will create a comprehensive interdisciplinary database and develop an index to characterize riparian vegetation. This index will incorporate GIS-based spatial mapping, ecological indicators of vegetation water stress, and hydrological data on water temperature, providing a holistic tool for effective riparian ecosystem management and restoration.

KEYWORDS

Climate resilience, evaluation matrix, mapping, restoration, riparian vegetation, water-stress.

Cartographie, matrice d'évaluation, résilience climatique, restauration, ripisylve, stress hydrique.

1. INTRODUCTION

Global change poses increasing threats to hydrosystems, driven by urbanization, agricultural intensification, and climate change. These forces disrupt hydrological cycles, intensifying droughts, reducing freshwater availability, and amplifying ecosystem vulnerabilities. Riparian vegetation, as critical components of riparian zones, are particularly affected, yet they play an essential role in maintaining ecological functions and providing key ecosystem services.

Those ecosystem services include riverbank stability (Macfarlane et al., 2017; Michez et al., 2017), sediment and nutrient filtration (Godfroy et al., 2022; Michez et al., 2017), erosion control (Michez et al., 2017), groundwater recharge (Camporeale et al., 2013; Dufour et al., 2019), habitat provision (Macfarlane et al., 2017; Michez et al., 2017), and temperature regulation for aquatic ecosystems (Camporeale et al., 2013; Godfroy et al., 2022). Europe has already lost or heavily modified significant portions of its riparian vegetation, emphasizing the urgent need for their conservation and restoration (Macfarlane et al., 2017; Michez et al., 2017).

In the context of the SAGE (Schéma d'Aménagement et de Gestion des Eaux) Loire Rhône-Alpes, riparian ecosystems are under specific pressures. Hydrological alterations, such as damming and channelization, along with urban encroachment and agricultural expansion, have fragmented riparian zones and diminished their ecological functionality (Dufour et al., 2019; Godfroy et al., 2022). Climate change further exacerbates these threats, altering precipitation patterns, increasing temperatures, and stressing native species (Camporeale et al., 2013). These combined pressures necessitate the integration of local restoration strategies within larger frameworks, such as the SAGE, which aligns with the European Union's Water Framework Directive (WFD). The WFD prioritizes riparian zones as key areas for achieving ecological objectives, making their evaluation and restoration a critical step for improving the status of water bodies.

Addressing these challenges requires an interdisciplinary approach. This cluster internship combines ecology, geomatics, and hydrology to develop an assessment framework tailored to the SAGE Loire Rhône-Alpes. Ecological analyses assess riparian vegetation health and species resilience, linking vegetation status to ecosystem functioning. Geomatics methods enhance spatial understanding, delineating riparian zones, evaluating connectivity, and detecting structural changes. Hydrological analyses examine riparian shading's impact on water temperature and energy balance under varying climatic and hydrological scenarios. Together, these disciplines contribute to a unified evaluation matrix, advancing riparian management practices while aligning with the WFD's objectives and addressing the local needs of the SAGE Loire Rhône-Alpes by trying to answer the question on **how to assess forest status and functionality of riparian ecosystems, integrating spatial, ecological, and hydrological dimensions, to guide restoration and management strategies in the context of climate change?**

2. MATERIALS AND METHODS

We will select three highly contrasted sites (e.g. land use, geology, management) to have a broader description of this Loire sub-basin and to better understand the complexity of the area. These sites will need to integrate the scales of each internship, with a maximum length of river of maximum 1.5 to 2 kilometers.

2.1. Ecology

To assess the ecological status of riparian vegetation, four evaluation indices will be applied, each leveraging different metrics such as vegetation structure, density, height, width, species composition, and land use. Additionally, ecological functioning will be analyzed through physiological stress and water use measurements on 12 trees per site, focusing on representative species identified with SAGE input. Given the small dataset, contextual metadata will complement the results to provide insights and trends for further research. The assessments will take place from March to May, aligning with vegetation growth phases and including six evaluation periods. Riparian zone evaluation relies on indices such as Riparian Connectivity and Biodiversity Index (IBC-R), Potential Biodiversity Index (IPB), Riparian Forest Quality Index (QBR) and tools like RIPASCAN. Functional metrics will be Leaf Area Index (LAI), Surface Leaf Area (SLA), Water Use Efficiency (WUE) and Minimal

Water Potential (MWP) evaluate water and vegetation dynamics, supported by key metadata (e.g. precipitation, humidity, temperature, topography and land use).

To ensure accurate application, standardized protocols and preparatory training will precede fieldwork. Potential redundancies between evaluation metrics, such as forest density and canopy cover, will be managed by prioritizing field collection of standardized data and focusing on ecological functioning metrics. Complementary datasets, including land use and atmospheric conditions, will be pre-acquired via GIS tools and open-access databases. Physiological metrics will be collected during midday to minimize variability and stored in cool, dark conditions before laboratory analysis. Statistical analyses will reduce redundancy and refine the metrics for inclusion in a simplified evaluation matrix. Principal Component Analysis (PCA) will help identify correlations, while additional tests, such as ANOVA (or Kruskal-Wallis) and Pearson (or Kendall), will analyze site effects, riparian evaluation results, and the influence of cofactors.

2.2. Geomatics

The geomatics analysis will begin by delineating riparian zones using topographic data. Valley bottom extraction algorithms will identify floodplain boundaries, defining the spatial extent of riparian corridors. Key datasets on topography, forest cover, and habitat classification will further refine the delineation of forested areas within these zones.

Connectivity metrics will assess the interaction between riparian vegetation and the river system. Lateral connectivity will evaluate forest coverage across floodplains and the proximity of vegetation to the river, while longitudinal connectivity will focus on the continuity of vegetation along the riverbanks. Vegetation health will be assessed through spectral indices such as NDVI (Normalized Difference Vegetation Index) and NDWI (Normalized Difference Water Index), providing insights into vegetation vigor and moisture status. LiDAR data will offer additional detail on canopy density and structure, distinguishing between regenerating and aging vegetation.

2.3. Hydrology

The study will analyze several characteristics of riparian vegetation, including height, width, position, and density, to evaluate their impact on shading and, consequently, on the energy balance of water bodies. Initial mapping of water temperature and shading will be conducted for each selected site during particularly hot summer days to establish a reference state. Shading will be determined using either hybrid modeling techniques or LiDAR-based methods, with the support of GIS software. These initial observations will also serve as the foundation for predictive modeling over future timeframes. Restoration scenarios for riparian vegetation will be developed based on recommendations from scientific literature, while also incorporating perspectives from local managers to ensure that the proposed actions are both feasible and aligned with management objectives. The shading effects generated by these scenarios will be modeled and evaluated using GIS tools, with a focus on spatial mapping to assess the impacts. The influence of shading on solar radiation will then be modeled using the "r.sun" solar radiation tool within GRASS GIS, which will allow for an estimation of its effect on water temperature. This analysis will apply the thermal energy balance equation, integrating parameters such as projected flow rates for the Loire basin under various scenarios, as well as simulated atmospheric conditions generated through the DRIAS climate model for different climate scenarios (RCP 2.5, RCP 4.5, and RCP 8.5).

3. EXPECTED RESULTS

In ecology, we will identify riparian evaluation methods that accurately reflect ecosystem functioning, incorporating them into an evaluation matrix to improve understanding across different sites. This evaluation will include four assessment methods, alongside analyses of ecological functioning, such as water stress and tree health. By comparing these metrics, we will highlight their respective strengths and limitations. While the small dataset and variability between sites may limit generalizability, we will integrate findings from other studies to strengthen the analysis and draw more robust conclusions. This will inform future research and challenge existing management practices.

Geomatics will complement these analyses by providing spatial insights into the structure and connectivity of riparian zones. By linking these spatial data with ecological and hydrological findings, we will support the identification of restoration priorities and provide actionable data to support decision-making.
In the hydrological analysis, we aim to identify key riparian characteristics—such as buffer zone size, vegetation height, and density—that optimize shading under various climatic and hydrological scenarios. These factors will help evaluate the shading function's role in regulating water temperature and energy balance in rivers. The scenarios will be analyzed alongside ecological results, focusing on species resilience to climate change. If certain species are found to be less resilient, they may need to be replaced, potentially altering their height and structure, which could affect shading. The results will provide key metrics to guide restoration strategies, assess the current state of riparian ecosystems, and evaluate their long-term effectiveness. These findings will be integrated with ecological and geomatics data to ensure a comprehensive approach to riparian management.
Counting on the complementary strengths of ecology, geomatics, and hydrology, this study will produce a unified assessment matrix as a base to support both future scientific research and practical decision-making in riparian forest management. This matrix will merge indicators such as vegetation structure, species resilience, canopy connectivity, shading potential, and water temperature regulation into a cohesive framework. This integrated tool will highlight the interplay between riparian forest composition, spatial configuration, and hydrological processes, providing a holistic understanding of ecosystem functioning under current and projected climate conditions. By offering a clear and scalable method for evaluating ecological health and restoration potential, the matrix will guide the identification of priority areas for intervention, inform adaptive management strategies, and establish a robust baseline for future research. Through this synthesis of multiple perspectives, the resulting assessment matrix will not only enhance our comprehension of riparian ecosystems but also strengthen our capacity to safeguard their resilience in the face of ongoing environmental change.

4. CONCLUSION

This study represents an exploratory approach, emphasizing the need for specific tools to improve riparian forest management. Based on a case study of the Loire SAGE, the limited time and sample size constrain the generalization of results. However, the originality of this work and the lack of similar studies address a clear demand from both the scientific and practitioner communities. Despite the limitations, this project aims to establish a foundation for future research, providing methodological guidelines and recommendations for similar initiatives.
The expected goal is to produce a robust evaluation matrix, transitioning from a broad dataset to a focused tool that supports practitioners in identifying critical areas and guiding management decisions. This interdisciplinary and intersectoral approach is well-suited to addressing the challenges posed by global change and offers a promising pathway for advancing riparian forest conservation.

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