MINISTERE DE L'ENSEIGNEMENT SUPERIEUR ET DE LA REÇHERCHESCIENTIFIQUE

****

UNIVERSITE DES SCIENCES, DES TECHNIQUES ET DESTECHNOLOGTES DE BAMAKO (USTTB)

****

ECOLE DOCTORALE DES SCIENCES ET TECHNOLOGIES DU MALI (EDSTM)

REPUBLIQUEDU MALI

****

Un Peuple - Un But - Une Foi

DOCTORATE THESIS

Option: Agronomic Sciences *Specialty: Climate Change and Agriculture*

THEME:

OPTIMISING AGROECOSYSTEM RESILIENCE AND SUSTAINABILITY OF INLAND VALLEYS TO CLIMATE CHANGE IN WEST AFRICA: BENIN'S SUDANO-GUINEAN AND GUINEAN ZONES CASE

A THESIS

IN THE RURAL POLYTECHNIC INSTITUTE OF TRAINING AND APPLIED RESEARCH IN PARTNERSHIP WITH THE WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE (WASCAL), SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN CLIMATE CHANGE AND AGRICULTURE OF THE UNIVERSITY OF SCIENCES, TECHNIQUES AND TECHNOLOGIES OF BAMAKO (USTTB)

Submitted and defended by:
Mr. Abiola David AKODEKOU

JURY

President :	Mr. Bocar AHAMADOU	*Full Professor*	IPR/IFRA
Examiner :	Mr. Mahamadou KEITA	*Associate Professor*	IPR/IFRA
Reporter :	Mr. Kapoury SANOGO	*Senior Researcher*	ICRAF
Reporter :	Mr. Adama KORBO	*Senior Researcher*	IER
Director :	Mr. Sabaké T. DIARRA	*Associate Professor*	IPR/IFRA
Co-Directors	Mr. Romain L. GLELE KAKAÏ	*Full Professor*	FSA/UAC
	Mr. Elliott R. DOSSOU-YOVO	*Senior Researcher*	Africa Rice
Advisor :	Mr. Udo NEHREN	*Full Professor*	TH Köln

April, 2025

Table of contents

Dedication

To Almighty God and Jesus Christ for enabling this work.

To my parents, Seveho Pierre AKODEKOU and Félicité OKE, for their unwavering support.

To my wife, Victoire Ablavi KOUHEVI, and daughters, Faith and Kindness, for their love and encouragement.

Acknowledgements

I extend my deepest gratitude to the West African Science Service Centre on climate Change and Adapted Land Use (WASCAL), particularly the Doctoral Research Programme on Climate Change and Agriculture, for the technical, financial, and logistical support that made this thesis possible. This opportunity has been invaluable to my academic and professional growth.

I am also profoundly grateful to:

The Rural Polytechnic Institute (Institut Polytechnique Rural de Formation et de Recherche Appliquée (IPR/IFRA)) and the University of Science, Technique and Technologies of Bamako (USTTB) for providing the academic framework and resources necessary for this doctoral research. Their support was instrumental in laying the foundation for this work.

The Laboratoire de Biomathématiques et d'Estimations Forestières (LABEF/FSA/UAC) and its dedicated staff which offered invaluable technical and administrative support throughout this research. Their expertise and commitment significantly enhanced the quality of this study.

The Africa Rice Center, which played a crucial role in providing technical, financial, and administrative assistance for the successful execution of this research. Their contributions were important in achieving the objectives of this study.

The University of Applied Sciences of Köln in Germany, for providing critical administrative and technical support, particularly in advancing this research's methodological and analytical aspects. Their collaboration was key to the realisation of this work. Beyond these institutions, this research would not have been possible without the invaluable contributions of numerous individuals. I would like to specifically acknowledge:

Professor Yacouba Diallo (Former Director of WASCAL CC-Agri), Professor Emmanuel Wendsongré (Former Director of WASCAL), and Professor Moumini Savadogo (Former Director of WASCAL) for their guidance and support during this study.

Professor Sabaké Tianegue Diarra, my thesis supervisor at IPR/IFRA, for his technical advice, mentorship, and unwavering motivation throughout this journey.

Professor Romain Lucas Glèlè Kakaï, my supervisor at the University of Abomey-Calavi (UAC) and Executive Director of LABEF/FSA/UAC, for his exceptional academic and technical support. Dear Professor, I am eternally grateful for your invaluable contributions.

Dr. Elliott Ronald Dossou-Yovo, my co-supervisor from Africa Rice, for his technical, financial, and academic guidance. Your mentorship has been a source of inspiration, and I am deeply indebted to you.

Professor Udo Nehren from the University of Applied Sciences of Köln, my adviser, for his technical, academic, and moral support. Thank you, dear Professor, for your dedication.

Dr. Kolawolé Valère Salako, Scientific Coordinator of LABEF/FSA/UAC, for his significant contributions to the quality of this study and his mentorship throughout this thesis. You are a role model for young scientists.

Dr. Justin Djagba and Mr. Constant Gnansounou for their immense contributions to the success of this research.

The research assistants who contributed to data collection, processing, and analysis: Mr. Josué Akpoli, Mr. Dominique Agonman, Mr. Christian de Paul Kouhevi, and Mr. Ezéckiel Akodékou. Your hard work is deeply appreciated.

The smallholder farmers who collaborated with us during this research, particularly Mr. Léonard Houngbedji, Carine Houngbedji, and Janvier Fagnon, whose dedication was crucial to the success of this work. Thank you for your trust and cooperation.

Finally, I would like to express my heartfelt gratitude to my family for their unconditional love, patience, and support. Your encouragement has been my greatest strength.

List of acronyms and abbreviations

AfricaRice: Consultative Group on International Agricultural Research Center, working on Rice

ARICA: Advanced Rice Varieties for Africa.

ATDA: Agricultural Technology Delivery Agency.

CC-Agri : Climate Change and Agriculture.

FAO: Food and Agriculture Organization.

GPS: Global Positioning System.

IFAD: International Fund for Agricultural Development.

IPCC: Intergovernmental Panel on Climate Change.

IR841: International Rice Research Institute (IRRI) Rice N° 841

IRRI: International Rice Research Institute.

NARS: National Agricultural Research Systems.

NERICA: New Rice for Africa.

Orylux 6: Oryza Luxury N° 6.

QGIS: Quantum Geographic Information System.

UNDRR: United Nations Office for Disaster Risk Reduction.

UNICEF: United Nations Children's Fund**.**

WASCAL: West African Science Service Centre on Climate Change and Adapted Land Use

WeedManager app: Mobile app for weed management in agriculture.

WorldClim: World climate data database.

List of Figures

List of tables

Résumé

Les vallées intérieures (VI) sont des systèmes socio-agroécologiques essentiels en Afrique subsaharienne, fournissant des services écosystémiques (SE) cruciaux tels que des services d'approvisionnement, de régulation, de soutien et culturels. Cependant, ces écosystèmes sont de plus en plus menacés par les aléas climatiques et les pressions anthropiques, qui compromettent leur durabilité et leur productivité agricole. Cette recherche doctorale explore les voies pour conserver et optimiser les SE des VI au Bénin, en se concentrant sur l'interaction entre les approches de gestion des terres et de l'eau, les aléas climatiques et les stratégies d'adaptation des petits exploitants agricoles. L'étude utilise une approche mixte, intégrant des données quantitatives et qualitatives provenant de 298 agriculteurs répartis dans 41 VI, ainsi que des données biophysiques, climatiques (1991–2021), socio-économiques de 76 VI, et une expérience agricole mettant en lumière l'approche des vallées intelligentes (Smart Valley) et des vallées non aménagées, les niveaux de fertilisation basés sur la technologie RiceAdvice et le niveau standard des agriculteurs durant les années 2022 et 2023 dans les zones guinéenne et soudano-guinéenne du Bénin. L'étude aborde quatre objectifs spécifiques. Premièrement, elle analyse l'état des SE fournis par les VI sous différentes approches de gestion, identifiant l'approche Smart Valley comme la plus efficace pour fournir des services d'approvisionnement, de régulation et de soutien (indices d'importance relative de 0,85; 0,81 et 0,68, respectivement), tandis que les vallées non aménagées excellent dans les services culturels (IIR : 0,45). Deuxièmement, elle évalue la vulnérabilité des VI aux aléas climatiques, révélant que la sécheresse affecte 35 % des VI, principalement dans la zone soudano-guinéenne, et est prédite par le carbone organique du sol, la teneur en sable et l'indice standardisé de précipitation et d'évapotranspiration (SPEI). Les inondations, qui touchent 30 % des VI, sont plus fréquentes dans la zone guinéenne et sont liées aux précipitations annuelles, à la teneur en sable et au SPEI. Troisièmement, elle évalue les stratégies d'atténuation des petits exploitants, mettant en avant des pratiques telles que l'agriculture biologique, l'irrigation et l'agroforesterie pour la sécheresse, et les ajustements des saisons culturales et l'utilisation de jachères naturelles pour les inondations. Ces stratégies sont influencées par l'accès au marché, les services de vulgarisation et les infrastructures. Quatrièmement, elle évalue l'impact des approches de gestion sur la durabilité et la productivité, démontrant que les approches Smart Valley améliorent significativement l'humidité du sol (8,62 % de plus que les approches non aménagées) et les rendements du riz (35,42 % de plus), avec une fertilisation augmentant encore la productivité jusqu'à 13,65 %. Cette recherche fournit des perspectives actionnables pour les décideurs politiques et les praticiens afin de promouvoir la gestion durable des Vallées Intérieurs, en assurant leur résilience et leur productivité face au changement climatique et aux pressions anthropiques.

Mots clés : Vallées intérieures, risques climatiques, durabilité des agroécosystèmes, Smart vallées, Afrique subsaharienne.

Abstract

Inland valleys (IVs) are critical socio-agroecological systems in Sub-Saharan Africa, providing essential ecosystem services (ES) such as provisioning, regulating, supporting, and cultural services. However, these ecosystems face increasing threats from climatic hazards and anthropogenic pressures, undermining their sustainability and crop productivity. This doctoral research investigates the pathways for conserving and optimizing the ecosystem services of Inland valleys in Benin, focusing on the interplay between management approaches, climatic hazards, and smallholder farmers' adaptive strategies. The study employs a mixed-method approach, integrating quantitative and qualitative data from 298 farmers across 41 Inland valleys, as well as biophysical, climatic (1991–2021), socio-economic data from 76 Inland valleys and an agricultural experiment highlighting the smart and undeveloped valley approach, fertilization levels based on RiceAdvicce technology and the standard level of farmers during 2022 and 2023 in Benin's Guinean and Sudano-Guinean zones. The study addresses four specific objectives. First, it analyses the state of ES provided by Inland valleys under different management approaches, identifying Smart Valley as the most effective in delivering provisioning, regulating, and supporting services (with a relative importance index of 0.85, 0.81, and 0.68, respectively), while undeveloped valleys excel in cultural services (with a relative importance index of 0.45). Second, it assesses the vulnerability of Inland valleys to climatic hazards, revealing that drought affects 35% of Inland valleys, primarily in the Sudano-Guinean zone, and is predicted by soil organic carbon, sand content, and the Standardized Precipitation Evapotranspiration Index (SPEI). Flooding affecting 30% of Inland valleys, is more frequent in the Guinean zone and linked to annual rainfall, sand content, and SPEI. Third, it evaluates smallholder farmers' mitigation strategies, highlighting practices such as organic farming, irrigation, and agroforestry for drought, and crop season adjustments and natural fallow use for flooding. These strategies are influenced by market access, extension services, and infrastructure. Fourth, it assesses the impact of management approaches on sustainability and productivity, demonstrating that Smart Valley approaches significantly improve soil moisture (8.62% higher than undeveloped approaches) and rice yields (35.42% higher), with fertilization further enhancing productivity by up to 13.65%. This research provides actionable insights for policymakers and practitioners to promote the sustainable management of Inland valleys, ensuring their resilience and productivity in the face of climate change and anthropogenic pressures.

Keywords: Inland valleys, climatic hazards, agroecosystem sustainability, Smart developed valleys, Sub-Saharan Africa

CHAPTER 1. GENERAL INTRODUCTION

1.1. Problem and Justification
1.2. State of the knowledge
1.3. Research hypothesis
1.4. Objectives

1. General introduction

1.1. Problem and Justification

Climate change poses a major threat to agricultural systems due to increased variability in rainfall patterns, prolonged droughts, and rising temperatures (IPCC, 2007). In West Africa, the droughts of the 1970s and 1980s have significantly altered the region's climatic regime, leading to major disruptions in the hydrological cycle. Studies have documented shifts in precipitation patterns, including delayed onset of the rainy season, a decrease in the number of rainy days, and an increase in extreme weather events, rising from 17% between 1970 and 1990 to 21% between 2001 and 2010 (Sultan and Gaetani, 2016). The impacts of these changes include declining agricultural yields, increasing food prices, and heightened social instability (Partey et al., 2018). These challenges are compounded by rapid population growth, as the global population reached 7.9 billion in 2022 and is expected to continue increasing to approximately 10.9 billion by 2100 (Arsenovic, 2024). This demographic expansion raises significant concerns regarding food security. In 2016, approximately 815 million people were affected by food insecurity, with the highest concentration in sub-Saharan Africa (23%) (FAO, IFAD, UNICEF, 2017). By 2017, around 306.7 ± 8.3 million people in this region were experiencing severe food insecurity (FAO, IFAD, UNICEF, 2017). In West Africa, where agriculture accounts for 80% of the food consumed and contributes 35% to the regional GDP (Belem and Saqalli, 2017), this climatic variability, combined with demographic pressures, undermines the efforts of governments, development agencies, and agricultural projects to improve food security and reduce poverty in the region.

To reduce these constraints, inland valleys (IVs) are increasingly exploited due to their reliable water availability and agricultural potential. Inland valleys are defined as hydromorphic landscapes located in the upper parts of watersheds, comprising valley floors and their associated slopes (Dossou-Yovo et al., 2022; Page et al., 2022; Totin et al., 2013). Covering approximately 190 million hectares worldwide, these valleys represent a strategic ecosystem for agriculture, livestock farming, and fisheries (Rodenburg, 2013). Because of their consistent moisture levels and rich sediment, they function as highly fertile reservoirs and are viewed as promising future food hubs for sub-Saharan Africa (Rodenburg, 2013).

Beyond their role in food production, inland valleys provide essential socio-ecological functions by delivering multiple ecosystem services. They contribute to carbon sequestration, thermal regulation, and water management, offering natural protection against erosion and floods.

However, these ecosystems are increasingly threatened by unsustainable exploitation driven by demographic pressure, agricultural intensification, and expanding urbanization. The progressive degradation of inland valleys results in the loss of their ecological functions, undermining their role in addressing food insecurity and climate change. According to the Millennium Ecosystem Assessment (Asselen et al., 2013), poorly managed agricultural expansion has historically been the leading cause of wetland degradation worldwide, including inland valleys in sub-Saharan Africa. Agricultural pollution, soil erosion, and sediment accumulation further weaken these ecosystems, jeopardizing their sustainability.

In this context, it is imperative to establish a sustainable and effective management plan for inland valleys, based on detailed and accurate data to assess their status and ecological dynamics (Djagba et al., 2019). Additionally, examining the influence of climate change on these ecosystems and analyzing the historical distribution of climate-related hazards are crucial for developing better-adapted management strategies. A comprehensive assessment of the ecosystem services provided by inland valleys, their significance for smallholder farmers, and the recurring climate risks they face is necessary to define more sustainable management approaches. These elements serve as key indicators for advancing the understanding of these ecosystems and guiding the formulation of an appropriate exploitation and conservation strategy in response to current and future challenges.

1.2. State of the knowledge

Several studies have elaborated on the state, the spatiotemporal changes, the greenhouse gas emission, and the conservation and restoration of mangrove wetlands areas (Sinsin et al., 2021; Ward et al., 2016; ZANVO et al., 2022). Especially in Benin, regarding inland valleys, some studies have focused on the diversity and opportunities of inland valleys for crop production, especially for rice production and rice improvement (Djagba et al., 2018; Dossou-Yovo et al., 2022, 2017; Worou et al., 2012). Elsewhere, such as in Burkina Faso, Mali, and Nigeria, some studies have focused on predictors of drought in inland valleys (Bachmair et al., 2015). Furthermore, few studies have focused on the relationship between agriculture and sustainable management of inland valleys in a changing climate context. In addition, the current status of Benin's inland valleys, the ecosystem services provided by Inland valleys, and the management practices that mitigate climate hazards and conserve Inland valleys remain to be explored. According to (Asselen et al., 2013), there is a need to avoid the biased or unbalanced use of ecosystem services in many Inland valleys wetlands and achieve a more balanced use of services.

This can only be achieved after a proper investigation of the different pressures on Inland valleys, the predictors of climatic extremes, and the low-cost solutions that smallholder households can easily adopt to increase the sustainability of this ecosystem (Figure 1).

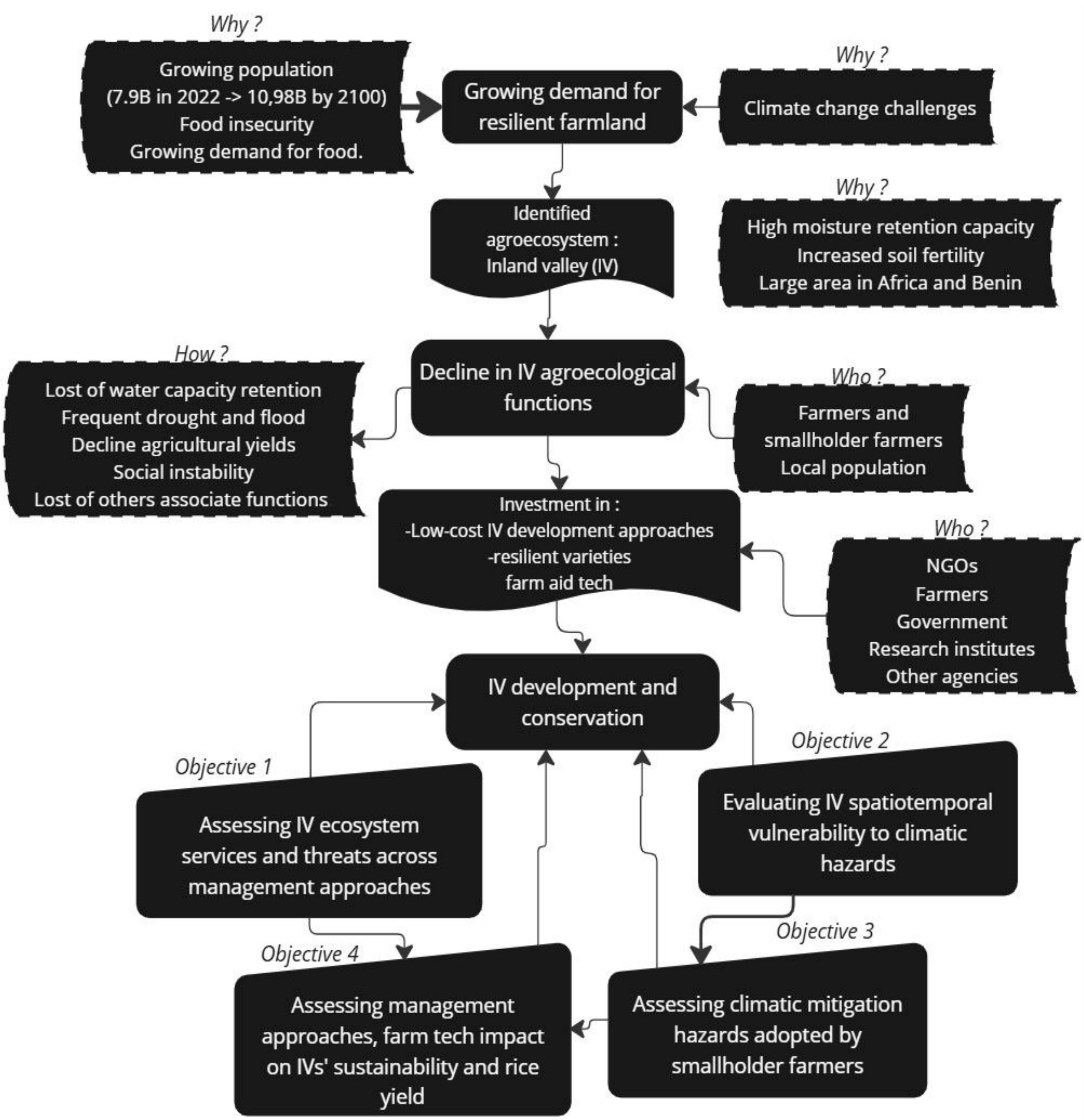

Figure 1. Flowchart illustrating the study's theoretical framework

1.3. Research hypothesis

In the context of this study, the following research hypotheses have been formulated to explore ecosystem services and the factors influencing the conservation and sustainable management of inland valley ecosystems while promoting food production.

- **Hypothesis 1**

Management approaches applied to inland valleys, particularly the developed Smart Valley approach to land and water management, significantly enhance the conservation of inland valley ecosystem services, while mitigating threats to their sustainability.

- **Hypothesis 2**

Climate change significantly exacerbates the frequency and intensity of extreme climatic events in the inland valley landscapes of Benin. Specifically, flooding hazards are more frequent and intense in the country's southern regions, whereas droughts are more prevalent and severe in the central areas of Benin.

- **Hypothesis 3**

The commitment of smallholder farmers to implementing drought and flood mitigation measures is significantly influenced by the biophysical and socio-economic characteristics of inland valley landscapes and smallholder farmers.

- **Hypothesis 4**

Management approaches used in inland valleys, especially developed (Smart Valley) versus undeveloped approaches, greatly impact the resilience and sustainability of ecological conditions, mainly by enhancing hydrological factors in inland valleys, and positively affect the rice productivity of smallholder farmers.

1.4. Objectives

1.4.1. General objective

This study aim to develop pathways for conservation, sustainable management, and optimization of ecosystem services provided by inland valleys in the face of climatic hazards and anthropogenic pressures.

1.4.2. Specific Objectives

- **Objective 1**: Analyze the state of ecosystem services provided by inland valleys in relation to management approaches.

This objective aims to characterize the types, status, and importance of ecosystem services (provisioning, regulating, supporting, and cultural) provided by inland valleys and the threats to their sustainability. It also examines the interactions with management practices implemented by local stakeholders and institutions.

- **Objective 2:** Assess the vulnerability of inland valleys to climatic hazards and identify predictors of hazard occurrence.

The objective focused on quantifying the exposure, sensitivity, and adaptive capacity of inland valleys to climatic hazards (e.g., drought, flooding) and identifying the environmental, social, and economic variables that influence the likelihood and intensity of these hazards.

- **Objective 3:** Evaluate mitigation strategies adopted by smallholder farmers to address climatic hazards.

This objective identified, assessed, and categorized mitigation measures implemented by smallholder farmers to mitigate the impacts of climatic hazards. It highlighted innovative practices adopted by smallholder farmers.

- **Objective 4**: Assess the impact of management approaches on the sustainability of inland valleys and agricultural productivity.

Through an experimental approach, the objective was to evaluate how management practices (Developed [Smart Valley] and Undeveloped) influence the ecological resilience and sustainability of inland valley ecosystems, while also analyzing their effects on smallholder farmers' rice productivity.

CHAPTER 2. LITERATURE REVIEW

2.1. Current knowledge and prospects

2.2. Current distribution patterns of Inland Valleys

2.3. Ecosystem services of Inland Valleys and potential perturbations

2.4. Effects of climate change on Inland Valleys

2.5. Potential exploitation of Inland Valleys

2. Literature review

2.1. Current Knowledge and Prospects

2.1.1. Inland Valley in the World

Inland valleys are globally recognized as critical agroecosystems, particularly in regions where water availability and soil fertility are limiting factors for agriculture. They are part of wetlands which encompass the upper sections of river drainage systems, including rainfed uplands, flooded lowlands, and the hydromorphic fringes as the sloping transition zones between them(Alemayehu and Bewket, 2017; Rodenburg, 2013). These valleys are characterized by their hydromorphic conditions, which make them suitable for sustainable agricultural practices, especially rice cultivation (Djagba et al., 2018; Rodenburg et al., 2014). Globally, inland valleys cover approximately 190 million hectares and provide several societal, ecological, and economic services to the local population (Dossou-Yovo et al., 2018). Inland valleys provide critical habitats for diverse animal and plant species and offer key ecosystem services for climate change mitigation, such as carbon sequestration, climate regulation, water regulation, and pollination (Djagba et al., 2019). Inland valleys are found in various parts of the world, including Asia, Africa, and South America, where they play a significant role in food security and rural livelihoods. In Asia, for example, they have been extensively utilized for rice production, contributing significantly to the region's food supply (Gumma et al., 2009). The global interest in Inland valleys stems from their potential to support intensified and sustainable agricultural practices, especially in the face of climate change and increasing food demand (Van Oort and Zwart, 2018).

2.1.2. Inland Valley in Africa

In Africa, inland valleys are crucial in addressing food insecurity and supporting rural economies. Sub-Saharan Africa, in particular, hosts a significant number of these valleys, with an estimated coverage of approximately 85 million hectares (Dossou-Yovo et al., 2017; Andriesse, 1985). Although inland valleys exhibit ecological and dynamic variations, they are recognized under diverse local names across the continent. For instance, Benin, Burkina Faso, Mali and Togo are commonly referred to as *bas-fonds*, while in Nigeria, they are known as *fadama* (Mandishona & Knight, 2022). Further, in Zambia, they are termed *dambos*; in Zimbabwe as *mapani* or *mataro*, in Sierra Leone as *bolis*, and in South Africa as *vleis* (Mandishona & Knight, 2022; Mbereko et al., 2007). In Namibia, Lesotho, and Botswana, they are called *malapo*; in Angola, they are referred to as *naka* (Mbereko et al., 2007).

These valleys serve as vital ecosystems, providing a perennial water source that supports agricultural production, particularly in Africa's semi-arid regions (Dixon et al., 2021).According to Rodenburg et al. (2014), inland valleys in Africa are considered potential "food baskets" that, if managed effectively, could significantly enhance food security. Their strategic importance lies in their ability to sustain agricultural activities and contribute to the resilience of rural communities.

2.2. Current Distribution Patterns of Inland Valleys

2.2.1. In the World

Inland valleys are distributed across various continents, with significant concentrations in tropical and subtropical regions. In Asia, Inland valleys are predominantly found in countries like India, China, and Southeast Asia, where they are extensively used for rice cultivation (Gumma et al., 2009). In South America, they are found in countries such as Brazil and Colombia, which support a diverse range of agricultural activities. The distribution of Inland valleys is closely linked to the presence of river systems and floodplains, which provide the necessary hydrological conditions for their formation (Windmeijer and Andriesse, 1993).

2.2.2. In West Africa

West Africa boasts a vast network of inland valleys, particularly in countries such as Benin, Mali, Sierra Leone, and Côte d'Ivoire. These valleys are estimated to cover between 22 and 52 million hectares, with significant variations in their utilization across different regions (Windmeijer & Andriesse, 1993). The Inland valleys in West Africa are characterized by their hydromorphic fringes and valley bottoms, which are often seasonally waterlogged, making them suitable for rice cultivation (Windmeijer and Andriesse, 1993).

2.2.3. In Benin

In Benin, inland valleys are widely distributed across the country, particularly in the Upper Ouémé catchment and the Collines, Zou, Mono, and Couffo departments. A study by Giertz et al. (2012) identified 817 inland valleys in central Benin, covering a total area of 5,563 hectares. These valleys are primarily used for rice cultivation across different regions. Their distribution in Benin is influenced by topography, lithology, climate, and socioeconomic factors, with higher densities observed in areas with more extended growing periods and higher rainfall.

2.3. Ecosystem services of inland valleys and potential perturbations

2.3.1. Global Perspective

Inland valleys are multifunctional ecosystems with significant ecological and socio-economic benefits due to their unique physical and hydrogeological characteristics. These ecosystems serve as critical habitats for biodiversity conservation, hosting native flora and providing natural environments for aquatic and terrestrial species, including fish, crustaceans, birds, reptiles, and primates (Datta et al., 2022; Gnansounou et al., 2021). The physical functions of Inland valleys include water storage, sediment and pollutant retention, and flood mitigation, which are essential for maintaining ecological balance and reducing natural disaster hazards (Mandishona and Knight, 2022; Dar et al., 2020; Rodenburg et al., 2014). The fertile soils of Inland valleys support diverse agricultural activities, enhancing food security and rural livelihoods. These valleys are also vital for income generation through various livelihood-supporting activities, such as rice cultivation, which is particularly significant in Africa's changing climatic conditions (Djagba et al., 2018; Rodenburg, 2013). Globally, millions of people rely on Inland valleys for rice production, highlighting their importance in food systems (Hutchison et al., 2014). However, Inland valleys face threats from land degradation, climate change, and unsustainable agricultural practices, which can undermine their ability to deliver these essential services (Van Oort & Zwart, 2018).

In addition to their ecological functions, Inland valleys provide a range of socio-economic and cultural benefits, particularly in developing regions. These include supporting local economies, preserving cultural practices, and enhancing community resilience (Reid et al., 2005). Furthermore, mapping these services and understanding their significance from the beneficiaries' perspective remains a key area of interest that requires further exploration.

2.3.2. In West Africa

In West Africa, inland valleys are critical for agricultural production, particularly in regions where upland soils are degraded. Their hydromorphic conditions make them highly suitable for rice cultivation, a staple crop essential for food security (Rodenburg et al., 2014). However, the intensification of agricultural practices in Inland valleys can lead to adverse environmental degradation, including soil erosion, nutrient depletion, and biodiversity loss. Climate change further exacerbates these challenges by threatening the hydrological balance of Inland valleys, potentially undermining their agricultural productivity and resilience (Giertz et al., 2012).

Inland valleys offer a diverse range of ecosystem services that extend beyond provisioning services, including food and water supply. These ecosystems also deliver critical regulation, supporting, and cultural services, including flood mitigation, water purification, soil fertility maintenance, carbon sequestration, and habitat provision for biodiversity (Dar et al., 2020; Mandishona & Knight, 2022). Additionally, Inland valleys contribute to cultural and recreational values, supporting the livelihoods and well-being of local smallholder farmers. Despite their multifaceted importance, non-provisioning ecosystem services have received limited attention in research and development agendas. This oversight is concerning, as the sustainable management of Inland valleys requires a holistic understanding of all their services, not just those directly linked to agricultural production.

In the context of climate change, Inland valleys are increasingly viewed as strategic sites for developing rice production in Africa (Djagba et al., 2018). These ecosystems serve as vital sources of income for local communities through livelihood-supporting activities such as rice and vegetable cultivation (Datta et al., 2022; Mandishona & Knight, 2022). However, poor water management has historically been a significant constraint to the agricultural development of Inland valleys. Ineffective water management practices often result in waterlogging, drought, erosion, and reduced crop yields, which hinder farmers' ability to utilize these lands efficiently and disrupt the ecological balance of surrounding ecosystems (Dossou-Yovo et al., 2022). The lack of adequate irrigation infrastructure, coupled with irregular rainfall patterns, exacerbates these challenges, threatening the sustainability of Inland valleys and the stability of agricultural activities.

To address these issues, numerous initiatives have been implemented to improve water control in Inland valleys. Over the past decade, research and development organizations have promoted the adoption of a novel management approach known as the "smart-valley" system. Developed by the Africa Rice Center, the smart-valley approach employs a participatory, step-by-step process to design and implement cost-effective water control systems. Studies have demonstrated that the adoption of smart-valley systems increases rice yields by 0.9–2.4 t/ha and farmers' net income by $ 267–$ 1,157 (Arouna & Akpa, 2019). Due to its significantly lower implementation cost (averaging $ 700/ha) compared to classical inland valley development (approximately $ 5,000/ha), the smart-valley approach has gained widespread adoption among farmers in West and Central Africa. Currently, over 50,000 farmers across nine countries such as Benin, Burkina Faso, Côte d'Ivoire, Ghana, Liberia, Sierra Leone, Mali, Niger, and the Democratic Republic of Congo have adopted this approach (Dossou-Yovo, 2024, personal communication).

Despite the growing dissemination and adoption of the smart-valley approach, there is limited understanding of its impacts on the ecosystem services provided by Inland valleys compared to traditional approaches such as bund-valley and undeveloped-valley systems. This knowledge gap is critical, as agricultural development in Inland valleys risks compromising or losing vital ecosystem services if these services are not adequately integrated into development plans (Rodenburg, 2013; Sayer and Cassman, 2013). Previous studies have listed the adverse effects of agricultural expansion on lowland ecosystems, including reduced water quality, biodiversity loss, diminished flood regulation, soil degradation, reduced carbon sequestration, and disruptions to hydrological cycles. Integrating these often-overlooked services into development plans is vital for the long-term resilience and sustainability of these critical ecosystems.

2.3.3. In Benin

In Benin, inland valleys are indispensable for rice production and other agricultural activities. It is widely reported that this ecosystem provides essential services, such as water regulation and soil fertility maintenance, which are crucial for sustainable farming practices (Giertz et al., 2012). However, the intensification of agriculture in Inland valleys has led to challenges such as soil degradation and biodiversity loss. Additionally, the importance of these services at the local level for beneficiaries, particularly smallholder farmers, remains under-researched, despite several studies highlighting the inadequacy of water management technologies and the prevalence of water-related diseases, which further complicate the sustainable use of these valleys (Rodenburg et al., 2014; Djagba et al., 2019). The evaluation of these gaps remains of little interest for the inland valleys of Benin, although significant efforts have been made for other wetlands, such as mangroves (Gnansounou et al., 2022; Sinsin et al., 2022).

There are different ways of assessing ecosystem services provided by social-ecological systems; however, there is a need to adopt a systemic approach in evaluating goods and services provided by ecosystems (Christie et al., 2019). The notion of ecosystem services has dynamically evolved over the years, and investigating them using adequate approaches or methods is critical for requisite decision-making (Carpenter et al., 2009). As part of the methods commonly used to assess ecosystem services, the sociocultural valuation focuses on understanding the attitudes and perceptions of local populations regarding ecosystem services and, therefore, remains a relevant method to evaluate ecosystem services (Martín-López et al., 2019; Cabell and Oelofse, 2012).

Many scholars have discussed the importance of socio-cultural valuation of ecosystem services (Gnansounou et al., 2022; Reyes-Arroyo et al., 2021; Martín-López et al., 2019; Cabell and Oelofse, 2012). The approach is known for its ability to provide first-hand information critical for informed decision-making on ecosystem protection and the maintenance of ecosystem services delivered by ecosystems (Overå, 2011). It also provides essential quality information on community perceptions that can inform conservation strategies. Although the economic assessment of ecosystem services is vital, Lau et al. (2019) explained that valuing ecosystem services through non-monetary evaluation is critical to understanding the interplay among services. Socio-cultural valuation is also instrumental in making decisions to improve the well-being of local people and to incorporate their will and desires into decision-making. Other relevant research indicated that listening to local populations and factoring their concerns and perceptions into decision-making is essential in successfully managing ecosystem-based projects (Felipe-Lucia and Comín, 2015; Owuor et al., 2019). Over the last decade, the socio-cultural valuation of ecosystem services has gained keen attention owing to the large body of research dedicated to the issue (Scholte et al., 2015).

Studies that covered the socio-cultural valuation of ecosystem services in Inland valleys, particularly in Benin, are sparse. The socio-cultural valuation of ecosystem services can be done through quantitative and qualitative methods (Scholte et al., 2015). Gnansounou et al. (2022) suggested that the socio-cultural valuation of ecosystem services can be quantitatively explored through ranking and scoring methods. In contrast, Reyes-Arroyo et al. (2021) proposed approaches, including narratives and free listening, as qualitative means of capturing the extent to which people value the ecosystem services they derive from their surrounding ecosystems. Lau et al. (2019) also emphasized that qualitative methods are crucial in identifying intangible ecosystem services, such as spiritual values. Most socio-cultural assessments of ecosystem services conducted worldwide have employed quantitative methods (Walz et al., 2019), whereas research that combines quantitative and qualitative approaches is limited (Lee et al., 2023; Lau et al., 2019).

Several authors advocate for combining many approaches when conducting the socio-cultural valuation of ecosystem services (Martín-López et al., 2019).

2.4. Effects of climate change on inland valleys

2.4.1. Global Perspective

Inland valleys, despite their significant ecological and socio-economic benefits and favorable hydrological conditions, are increasingly vulnerable to climate change. These ecosystems face considerable climatic hazards that threaten the well-being of residents and farmers. Natural ecosystems, including Inland valleys, are increasingly exposed to climatic hazards characterized by shifts in climatic conditions, rising biodiversity loss, reduced agricultural productivity, and heightened risks to goods and people (UNDRR, 2021). According to McBean and Rodgers (2010), climatic hazards are adverse events linked to changes in climatic parameters, such as precipitation and temperature, including floods, storms, and droughts. These hazards can lead to catastrophic events with severe economic and ecological costs when mismanaged. Recent studies indicate that 75% of global disasters over the past few decades are attributable to climatic hazards, resulting in billions of dollars in losses worldwide(Zhang and Wang, 2022)

2.4.2. In West Africa

Among the various climatic hazards, increased flooding and drought events are becoming more frequent globally, particularly in developing countries in West Africa. Coulibaly et al. (2020) highlight that developing countries exhibit heightened vulnerability to flooding and drought due to their economic, climatic, and agricultural conditions. For instance, Dossou-Yovo et al. (2017) reported that drought affected 38% of exploited inland valleys in Sub-Saharan Africa in 2008, leading to an estimated 29% loss in total rice production. The impact of these disturbances is becoming increasingly significant and requires more precise evaluation, particularly at national and local scales. A detailed analysis at these levels would enable a better understanding of region-specific dynamics and vulnerabilities while providing contextualized data to guide policies and interventions (Martín-López et al., 2019). Such a fine-grained and localized approach is crucial for effectively addressing the identified challenges and ensuring the sustainable management of affected ecosystems.

2.4.3. In Benin

In Benin, the effects of climate change on inland valleys are particularly alarming. For example, the 2010 flood event caused an estimated loss of 100 million dollars to the national economy (Bonou et al., 2024). These climatic hazards pose significant risks to Inland valleys, where agricultural practices depend heavily on normal precipitation levels. The recurrence of drought and flooding events in Inland valleys operated by smallholder farmers with limited income exacerbates these challenges (Markantonis et al., 2018). According to Bonou et al. (2024), four major flood events with significant losses have occurred in recent decades in Benin. In 2012, crop losses in most agricultural inland valleys reached nearly 100% due to flooding, severely impacting smallholder farmers who rely entirely on Inland valleys for their livelihoods.

Smallholder farmers are acutely aware of the losses caused by these extreme events and recognize the need to develop adaptation measures to mitigate their effects (Lechowska, 2018). Farmers have adopted various mitigation strategies, including nature-based solutions (agroforestery, water retention ditches), infrastructure development, and improved farming practices, to reduce the effects of climatic hazards (Dossou-Yovo et al., 2017). However, the distribution of these hazards and the mitigation measures adopted by farmers must be systematically understood, mapped, and evaluated locally. Such an approach is crucial for better informing resilience-building actions and policies that support the sustainable management of inland valleys.

By integrating localized data and community-driven insights, policymakers and stakeholders can develop targeted strategies to enhance the resilience of Inland valleys and the communities that depend on them. This approach aligns with the broader need for context-specific solutions to address the multifaceted challenges posed by climate change in vulnerable ecosystems.

2.5. Potential exploitation of inland valleys

2.5.1. In the World

Globally, inland valleys are recognized for their significant agricultural potential, particularly for rice cultivation. In Asia, Inland valleys have been extensively used for rice production, which is crucial in ensuring food security (Gumma et al., 2009). In South America, these valleys support a diverse range of agricultural activities, including the cultivation of crops such as maize and beans. The exploitation of Inland valleys is closely tied to their hydromorphic conditions, which provide essential water resources and fertile soils for intensive farming (Windmeijer and Andriesse, 1993). The strategic utilization of these valleys has been instrumental in boosting agricultural productivity and food security across various regions.

2.5.2. In West Africa

In West Africa, inland valleys have substantial potential for agricultural development, particularly for rice production. Despite being underutilized, Inland valleys are often viewed as potential "breadbaskets" that could significantly enhance food security if managed effectively (Rodenburg et al., 2014). Increasing rice cultivation in these valleys could help address food insecurity and support rural livelihoods. However, careful management is required to avoid adverse environmental impacts, such as soil degradation and biodiversity loss (Giertz et al., 2012). Recent initiatives have introduced various technologies and approaches (Sawah valley management, Smart-Valley management, RiceAdvice technology…) to optimize the sustainable use of Inland valleys for agriculture.

West African countries possess significant irrigation potential (Worou et al., 2013). Large-scale projects aimed at developing irrigated rice have been implemented, though the outcomes have been mixed (Dossou-Yovo et al., 2022). Since the 1980s, the development of water resources in inland valleys has been a focus of rural development projects, with increased efforts in recent decades by government agencies, NGOs, and international organizations such as GIZ, AIDB, and FAO (Arouna et al., 2017).

Research institutions like AfricaRice, International Rice Research Institute (IRRI), and National Agricultural Research System (NARS) have developed improved rice varieties tailored to African cropping conditions, particularly for inland valley agroecosystems. Varieties such as NERICA, IR841, Orylux 6 and ARICA, suitable for different ecologies (upland and lowland), have been introduced (Arouna et al., 2017). These institutions also focus on enhancing access to rice technologies and innovations, including Smart-Valleys, Ricelabices, multi-stakeholder platforms (MSP), motorized weeders, direct seeding, alternate wetting and drying (AWD), the WeedManager app, and good agricultural practices (GAP) (Ishfaq et al., 2020; Arouna & Akpa, 2019; Saito et al., 2019).

2.5.3. In Benin

In Benin, inland valleys hold significant potential for agricultural exploitation, particularly for rice cultivation. Giertz et al. (2012) found that 67% of the surveyed Inland valleys in central Benin are currently used for crop cultivation, mainly during the rainy season. The intensity of exploitation varies across regions, with higher utilization in densely populated areas like Savalou, Ouinhi, Djougou, and Parakou. Expanding rice cultivation in Inland valleys, especially during the dry season, could address water scarcity in upland areas. However, challenges such as limited experience in wetland cultivation and water-related problems need to be addressed for sustainable exploitation (Giertz et al., 2012).

Several inland valley development technologies have been introduced to enhance agricultural productivity in Benin (Dossou-Yovo et al., 2022; Arouna et al., 2017; Rodenburg et al., 2014). These technologies encompass systems and methods for water and land management to meet human needs (Baki et al., 2022; Dossou-Yovo et al., 2022). Smallholder farmers in Benin are adopting various inland valley management systems, including Smart-developed inland valleys (Smart-IV) and Bund-developed inland valleys (Bund-IV), as well as undeveloped inland valley approaches (undeveloped-IVs).

Smart-IVs are innovative land and water management strategies introduced in West Africa by the Africa Rice Center and its partners in Benin and Togo. These strategies aim to enhance rice production systems in inland valleys, emphasizing participation, sustainability, and cost-effectiveness (Dossou-Yovo et al., 2022; Arouna et al., 2017; Defoer et al., 2017). The development of Smart-IVs involves a systematic process, including exploration, assessment, validation, design, formulation of land-use management plans, and construction of water management infrastructure. Site selection is based on socioeconomic and biophysical criteria and local farmers' knowledge (Defoer et al., 2017).

The Bund-IV approach involves building bunds, contour bunds, and water retention dikes to support agricultural production. While this approach may not involve stakeholder participation to the same extent as Smart-IV, it aims to conserve water and increase agricultural output (Danvi et al., 2018; Rodenburg et al., 2014). The undeveloped-IV approach refers to valleys without specific land and water management structures, where land is prepared for sowing crops (Danvi et al., 2018).

These diverse approaches highlight the potential of inland valleys to play a crucial role in advancing agricultural development and enhancing food security in Benin and other regions, provided that sustainable management practices are effectively implemented. It is essential to assess the impact of these management practices on the overall sustainability of inland valleys and their contribution to agricultural productivity and profitability. Additionally, identifying the most resilient rice varieties developed by research institutions is vital to ensure better adaptation to the various management strategies and the differing hydrological conditions of inland valleys.

CHAPTER 3. RESEARCH METHODOLOGY

3.1. Study areas

3.2. Data

3.3. Equipment

3.4. Data analysis

3. Research methodology

3.1. Study areas

3.1.1. Geographical and administrative situation

This study selected the research area based on the specific objectives. However, the overall objectives were achieved in two departments of Benin, a coastal country in West Africa, located between 6.20° and 12.48° North latitude and 0.7° and 3.95° East longitude (decimal degrees).

More specifically, the study area for Objectives 1, 2, and 3 (Figure 2), located between 6.9° **-** 8.25° North latitude and 1.56° - 2.65° East longitude, encompasses four communes located within two departments of Benin: Savalou in the Collines department and Ouinhi**,** Zogbodomey, and Zagnanado in the Zou department. The presence of inland valleys influenced the selection of these areas, the agricultural exploitation of these valleys, accessibility, and the availability of other facilities.

For Objective 4, which focuses on agricultural experimentation related to management approaches, the study area includes the communes of Ouinhi in the Zou department and Savalou in the Collines department (Figure 2). The selection of these sites was motivated by the training provided to farmers in these areas by AfricaRice in 2012 on the Smart-Valley approach for experimentation purposes. Additionally, these sites have continued to adopt the Smart-Valley approach and are considered reference points for its application.

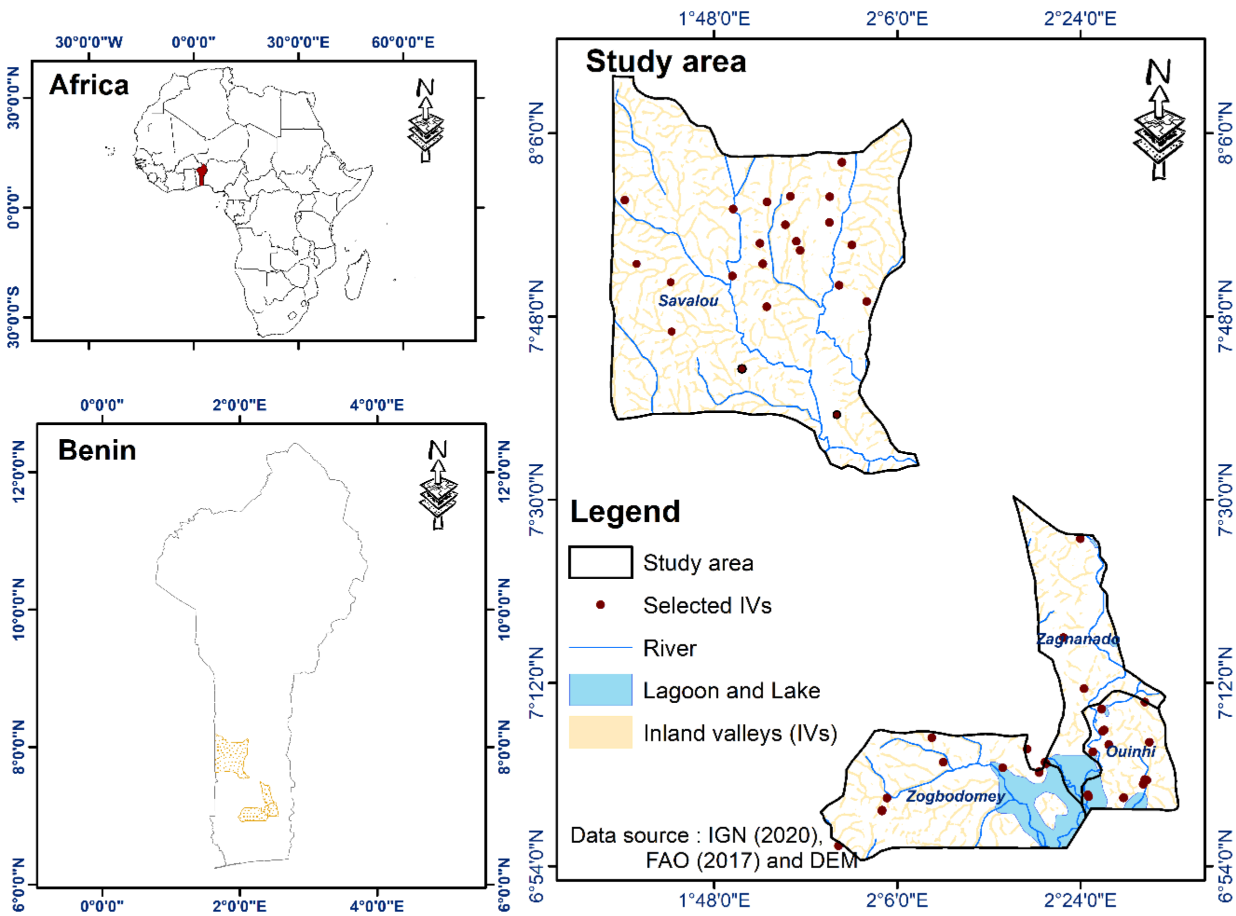

Figure 2.Map illustrating the selected Inland Valleys in the communes of Ouinhi, Zogbodomey, Zangnando in the Zou department and Savalou in the Collines department: Results of the July 2022 survey.

3.1.2. Environmental factors

- Abiotic factors

The abiotic factors shaping the environmental dynamics of the inland valleys primarily include precipitation, temperature (maximum and minimum), evapotranspiration, and soil types. These factors interact to maintain the environmental conditions essential for the formation and sustainability of these ecosystems.

Benin experiences annual precipitation ranging between 850 and 1500 mm. The country is divided into three distinct climatic zones, each with specific characteristics. These zones are:

(a) The Southern Zone (Guinean Zone)

This zone is characterized by a bimodal rainfall regime consisting of two rainy seasons (mid-March to mid-July and mid-September to mid-November) and two dry seasons (mid-July to mid-September and mid-November to mid-March). The average annual precipitation is approximately 1200 mm, with relative humidity ranging from 69% to 97%. Temperatures fluctuate between 25°C and 29°C (Montcho et al.,2025).Ferritic and vertisol soils, with hydromorphic soils present along rivers and watercourses, dominate the Guinean zone (Figure 3). This climate influences the inland valleys considered in the communes of Ouinhi, Zogbodomey, and Zagnanado in the Zou department, as studied during this investigation.

(b) The Transitional Zone (Sudano-Guinean Zone)

The Sudano-Guinean region is characterized by an unimodal rainfall regime, with a rainy season extending from March to October (Lokonon, 2017). The annual precipitation ranges from 900 to 1110 mm, with temperatures varying between 25°C and 29°C. The relative humidity ranges from 31% to 98% (Montcho et al., 2025). This zone is defined by tropical ferruginous soils underlain by a crystalline bedrock with highly diverse properties. The commune of Savalou, located in the Collines department and encompassed by all four objectives of this study, is situated within this climatic zone.

(c) The Northern Zone (Sudanian Zone)

The Sudanian zone experiences a rainfall regime with a single rainy season (April to October) and a distinct dry season (November to March). Annual precipitation ranges from 850 to 1000 mm, temperatures vary from 24°C to 31°C, and relative humidity fluctuates between 18% and 99%. This zone is characterized by tropical ferruginous soils (Houètchégnon et al., 2015).

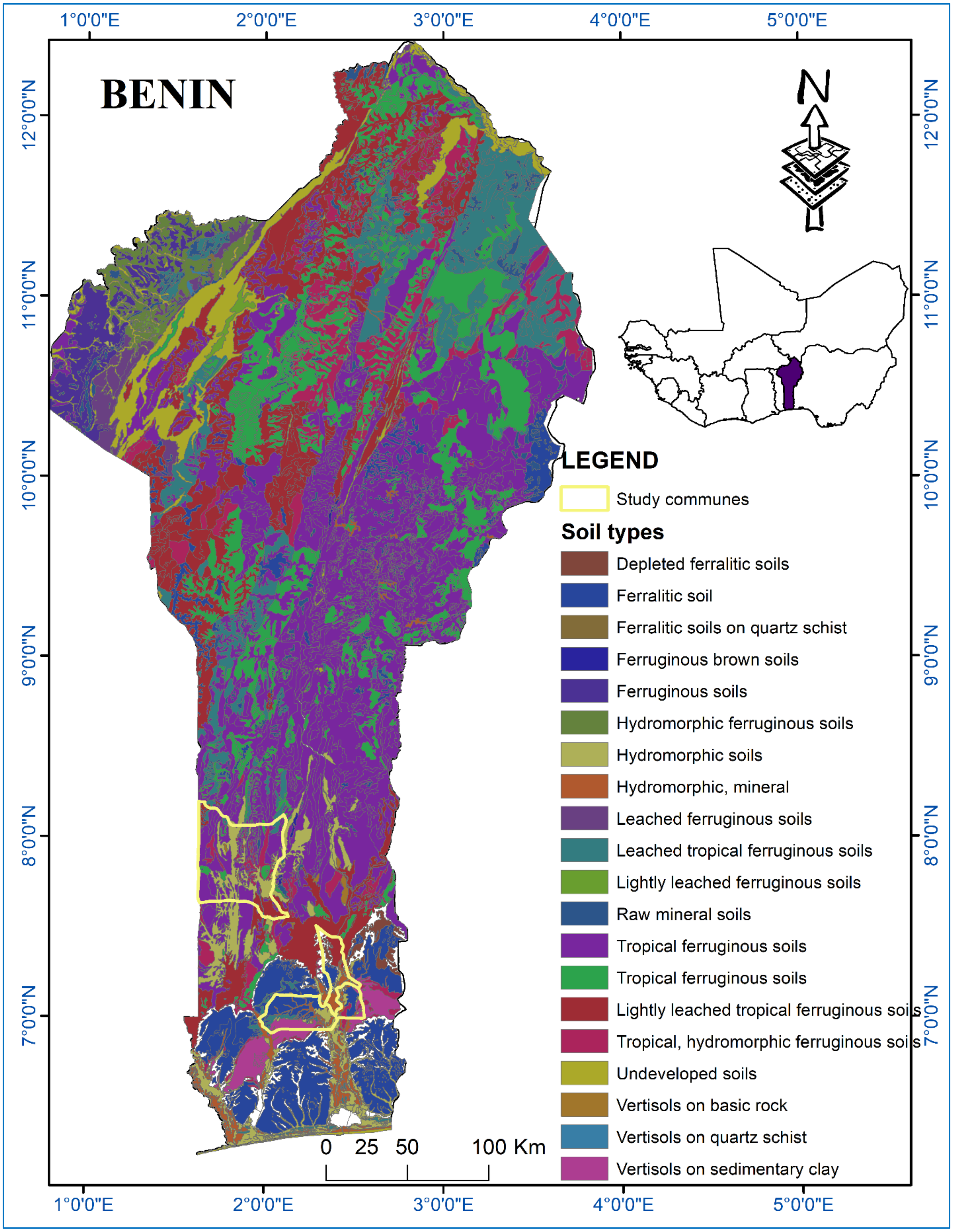

Figure 3. Map illustrating the spatial distribution of key soil types of Benin

- Biotic factor

Based on vegetation cover, climate, and agricultural potential, Benin has been subdivided into eight main agroecological zones, which define the key biotic factors (Figure 4 and Table 1). These zones include the Extreme North Zone (ENZ), North Cotton Zone (NCZ), South Borgou Crops Zone (SBCZ), West Atacora Zone (WAZ), Centre Benin Cotton Zone (CBCZ), Clayey Earth Zone (CEZ), Depression Zone (DZ), and Fishering Zone (FZ).

Table 1. Characteristics of Benin's agroecological zones
Source: Based on literature reviews

Agroecological Zone	**Main Crops**	**Natural Vegetation**	**Climate**
Extreme North Zone (ENZ)	Market gardening (onions, potatoes), millet, sorghum, cotton, maize, rice	Shrubby savannah	Soudanian
North Cotton Zone (NCZ)	Millet, sorghum, maize, cowpeas, groundnuts, cassava, yams, cotton, cashew nuts	Relics of forest	Soudanian
South Borgou Crops Zone (SBCZ)	Millet, sorghum, yams, cassava, cotton, cashew nuts, rice	Shrubby savannah	Soudanian and Soudanian-Guinean
West Atacora Zone (WAZ)	Millet, sorghum, rice, cotton, yams, cassava, groundnuts	Arboreous savannah	Soudanian and Soudanian-Guinean
Centre Benin Cotton Zone (CBCZ)	Cotton, yams, cassava, maize, rice, cowpeas, groundnuts	Arboreous savannah and associated forests	Soudanian, Soudanian-Guinean, and Guinean
Clayey Earth Zone (CEZ)	Maize, groundnuts, cowpeas, pineapple, citrus, oil palm	Shrubby savannah	Guinean
Depression Zone (DZ)	Maize, cassava, cowpeas, market gardening (peppers, tomatoes), rice, pineapples	Relics of forest	Guinean
Fishering Zone (FZ)	Maize, cassava, cowpeas, market gardening, coconut	Swamps, mangroves forests	Guinean

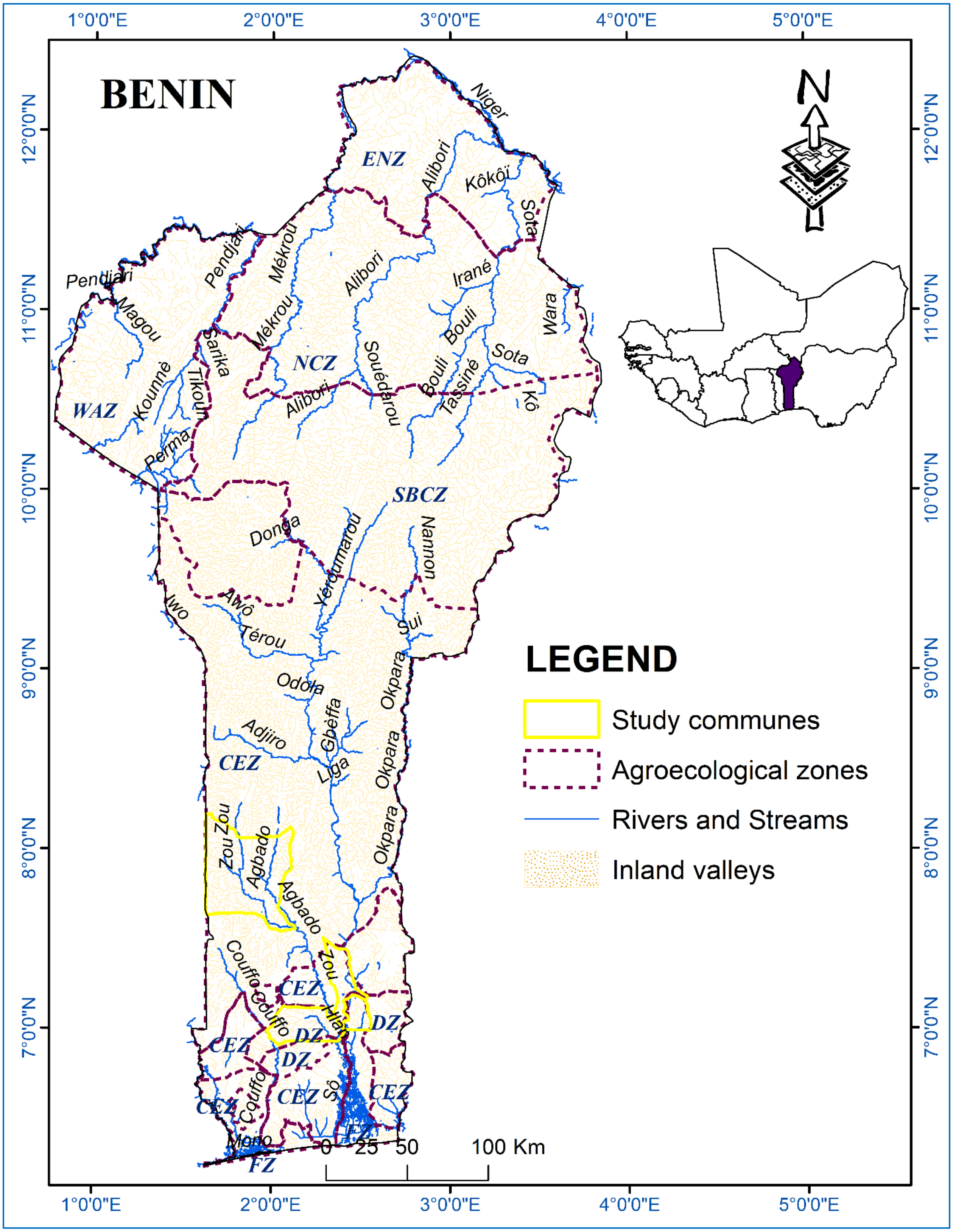

Figure 4. Map illustrating the agroecology areas and the hydrology distribution of Benin

❖ Hydrology

The hydrology of Benin is centered around four interconnected significant rivers that supply the available inland valleys. These primary rivers include the Ouémé, Zou, Okpara, and Couffo, along with other regional waterways such as the Volta and the Niger (Oussou et al., 2022). These rivers predominantly discharge into the Atlantic Ocean, with average flow rates measured at key stations: approximately 27.5 ± 24.6 cubic meters per second at the Atcherigbe station, 128.6 ± 87.1 cubic meters per second at the Pont Save station, and 30.7 ± 25.9 cubic meters per second at the Kaboua station.

The inland valleys in the study communes are primarily fed by the Zou and Ouémé rivers, with specific branches such as Agbado, Klou, Azokan, Bogui, and Hlan playing a significant role in water distribution. These valleys serve as critical resources for agricultural activities, ensuring water availability for smallholder farmers and other local uses.

3.1.3. Socio-economic aspects (Population density, socio-cultural groups, major activities)

Benin exhibits distinct socio-economic characteristics, particularly in terms of population density, socio-cultural diversity, and major economic activities. According to recent estimates from the General Population and Housing Census (RGPH 4), Benin, with a total area of 114,763 km², has approximately 10,008,749 inhabitants (INSAE, 2015). The population distribution is uneven across the country. Approximately 60% of the population resides in the southern region, primarily in the southern basin, which encompasses the departments of Atlantique, Couffo, Littoral, Mono, Ouémé, Plateau, and Zou. These areas include the main urban centres, such as Cotonou, the economic capital, and Porto-Novo, the political capital. In contrast, the northern part of the country, which includes the departments of Alibori, Atacora, Donga, and Borgou, accounts for approximately 33.9% of the population (Djagba, 2024).

Benin is a country rich in ethnic diversity, with over 40 distinct ethnic groups. Among the major groups are the Fon, who are predominant and concentrated in the south-central region around Abomey; the Yoruba or Edé-Yoruba, Holi, and Adja, present in the southeast and central areas; the Bariba and Fula, located in the northeast; the Betammaribe and Somba, found in the Atacora mountain range; and the Dendi, situated in the north-central region. This ethnic diversity is accompanied by linguistic and religious richness. French is the official language, but local languages such as Fon, Yoruba, and Bariba are widely spoken. Religious practices in the region include African traditional religions, Christianity, and Islam, reflecting a harmonious coexistence among diverse communities. In the communes considered for this research, the main identified ethnic groups are the Nago, Holi, Gbé-Adja, and Edé-Yoruba (Akodekou et al. 2025).

Benin's economy is primarily based on agriculture, which is the main economic activity and employs the majority of the population. In the study areas, agriculture is dominated by smallholder farmers who cultivate small plots of land, often using traditional methods. These farmers primarily focus on crops such as rice, maize, cassava, groundnuts, yams, soybeans, and cashew nuts (Djagba et al., 2018). Cotton, which is Benin's primary export crop, also plays a significant economic role. Additionally, the fishing sector contributes to livelihoods, particularly in coastal areas and around rivers and inland lakes.

Furthermore, informal trade plays a crucial role in the local economy, with markets such as Dantokpa in Cotonou integral to economic activity. Benin also serves as a regional trade corridor, facilitating the transit of goods to landlocked neighboring countries. Handicrafts, including textile production and artwork, as well as tourism centered on natural and cultural heritage, contribute to economic development.

3.2. Equipment

In the framework of this thesis, different materials, equipment and technological tools were mobilized to ensure data collection, processing and analysis. The details are outlined below:

- *Global Positioning System (GPS):* A GPS was used to record the geographic coordinates of the inland valleys during the initial phase and to confirm their presence or absence during the second survey phase.
- *TMS-45 cm Datalogger and Lolly.app*: The TMS-45 cm datalogger, paired with the Lolly.app application was used to record and manage soil moisture and temperature data from the sub-sub plots.
- *Rain Gauge*: A rain gauge was installed at each site to measure daily precipitation, which was crucial for analysing local climatic conditions.
- *Plot Identification Plates:* Identification plates were installed at each sub-subplot to facilitate easy identification of the treatments applied at each site.
- *Electronic Balances:* Electronic balances were used to accurately measure the quantities of fertilizer applied, the biomass harvested, and the grains produced.

- *Measuring Tapes*: Measuring tapes were used to measure the water depth in the piezometers installed within the experimental plots.
- *Adhesive Tape:* Adhesive tape was used to label and identify packaged samples, ensuring proper tracking and organization during storage and analysis.
- *Hoes and Machetes*: Hoes and machetes were used to delineate and prepare the experimental plots, including plots, sub-plots, and sub-sub-plots.
- *Buckets, Watering Cans, Barrels, and Sprayers*: These tools were utilized for irrigation, fertilizer application, and pesticide treatment during field experiments.
- *Scissors*: Scissors were used for harvesting biomass samples from the sub-sub plots.
- *Laboratory Oven:* A laboratory oven was used to dry biomass samples, allowing for the estimation of their moisture content and productivity.
- *Voice Recorder*: A voice recorder was used to document interviews with farmers and other stakeholders, facilitating qualitative data collection.
- *Geographic and Climatic Data*:
    - DIVA-GIS: Shapefiles of water bodies, administrative boundaries, and inland valleys were obtained from DIVA-GIS (www.diva-gis.org).
    - Africa Soil Information Service (AfSIS): Biophysical soil data were sourced from AfSIS (https://www.isric.org/projects/africa-soil-information-service-afsis).
    - Shuttle Radar Topography Mission (SRTM): Topographic data were downloaded from the SRTM platform (https://www.earthdata.nasa.gov/data/instruments/srtm).
    - WorldClim: Climatic data were obtained from WorldClim (https://www.worldclim.org/).
- *Mapping and Statistical Software:*
    - ArcGIS 10.1 and QGIS: These software tools were used to map the study areas and analyze the occurrence of droughts and floods.
    - R Software version 4.4.0 : The R statistical software was used to analyze all the collected data, including both quantitative and qualitative datasets.

3.3. Data

3.3.1. Secondary data from the literature

A search was conducted to identify scientific reviews focused on inland valleys in Benin. This process utilized research platforms such as Google Scholar and Web of Science, employing keywords including "inland valleys," "review," "lowlands," and "Benin."

A total of 218 publications were identified; however, only a limited number directly addressed the agricultural exploitation of inland valleys in West Africa or sub-Saharan Africa, with even fewer specifically targeting Benin. Among the relevant studies, the works of Dossou-Yovo et al. (2022); Rodenburg and Saito (2022); Djagba et al. (2019); Bado et al. (2018); Rodenburg et al. (2014); Rodenburg (2013) were particularly noteworthy.

These studies provided critical insights into the geographic distribution of inland valleys in Benin, the benefits derived from their use, the threats they face, and the agricultural practices and exploitation methods applied. This search of existing scientific reviews was a foundational resource for the present study.

3.3.2. Primary data: Field survey data based on point map distribution

In June 2022, an initial exploration using the snowball sampling method was conducted to identify key communes that utilize inland valleys extensively for agricultural purposes. The National Directorate of Lowlands served as the starting point for gathering information on communes with significant inland agricultural valleys. Recommendations obtained from this source led to the Territorial Agencies for Agricultural Development (ATDA), which directed the study toward the departments of Zou and Collines. The communes of Ouinhi, Zagnanado, Zogbodomey in Zou, and Savalou in Collines were identified as relevant to support objectives 1, 2, and 3. Subsequently, an inland valleys map was generated using QGIS software, which combined spatial analysis with a random point distribution method. This ensured a minimum distance of 5 km between points to maintain geographic representativeness and avoid spatial overlap. This approach identified 98 potential inland valleys.

In July 2022, a second phase of field surveys was conducted, following the georeferencing of 98 potential inland valleys, to verify and document those currently used for agricultural purposes. The coordinates of the identified points were verified to confirm the presence or absence of inland valleys, their agricultural exploitation, and their accessibility. This phase resulted in the selection of 68 inland valleys, distributed as follows: Savalou (22), Ouinhi (19), Zagnanado (18), and Zogbodomey (9). Additional data on the presence or absence of inland valleys, their usage, accessibility, and the different management approaches adopted were also collected to facilitate the achievement of objectives 1, 2, 3 and 4. Based on that, three water and land management approaches were identified:

- **Smart-valley**: In 2010, the Africa Rice Center introduced this approach in Benin, focusing on the Zou and Collines departments. It is a low-cost, participatory land and water management approach designed to improve water control in inland valleys. It focuses on simple, affordable interventions such as bunding, drainage, and leveling to enhance water control and productivity. The method follows a three-phase process: (1) site selection based on biophysical (soil, water availability, topography) and socio-economic (land tenure, market access) criteria; (2) participatory development, where farmers and technicians co-design water control infrastructure (drainage canals, bunded fields) following natural topography to optimize flow and retention; and (3) adaptive management, ensuring long-term maintenance and scalability. This smart-valley approach is now being expanded to other areas in Benin like Savalou, Ouinhi, Zagnanado, and Zogbodome.
- **Bund valley:** This refers to an inland valley where embankments or bunds have been constructed to control water flow and retain moisture in rice fields. Bunding helps conserve water, reduce water loss, and improve crop yields by creating a more controlled environment for rice cultivation. Bund valley has been utilized by farmers in IV in Benin since the 2000s (Djagba et al., 2018; Dossou-Yovo et al., 2022).
- **Undeveloped valley:** This approach involves utilizing inland valleys without implementing water management technologies. These valleys often lack infrastructure, such as bunds or drainage systems, and their agricultural potential remains underutilized due to uncontrolled water conditions. This approach is prevalent in many Inland valleys in Benin.

Based on these initial findings, four communes (Savalou, Zogbodome, Zagnanado, and Ouinhi) were selected, where all three Inland valley management approaches (smart valley, bund valley, and undeveloped valley) have been developed.

3.3.3. Primary data: Interview

A mixed quantitative-qualitative approach was adopted to collect smallholder farmers' perceptions of the ecosystem services of inland valleys, the determinants of these services, the threats to their sustainability, data on the occurrence of droughts and floods in inland valleys, and mitigation approaches. This approach involved conducting Focus Group Discussions (FGDs), followed by a quantitative survey targeting each smallholder farmer involved.

- *Farmers sampling*

Socio-economic data were collected at two levels: Focus Group Discussions (FGDs) and individual surveys. Two sessions were conducted per inland valley for the focus group discussions (FGDs), comprising 68 FGDs with men and 68 FGDs with women. Each FGD included 8 to 10 smallholder farmers. A total of 1,124 participants participated in the FGDs.

For the individual surveys, a sample of 50 participants per commune was initially selected during the pilot study to determine the proportion *p* of inland valley smallholder farmers with knowledge of inland valley management approaches, ecosystem services and experience of flooding and/or drought. The final sample size of smallholder farmers for each commune was determined using the following formula (Köhl et al., 2006)

$$n = \frac{1}{e^2} p(1-p) U^2_{1-\frac{\alpha}{2}} \qquad \text{(Equation 1)}$$

where n represents the total sample size, U is the value of the normal random variable (U = 1.96 for α = 0.05), and e represents the margin error, held to be 9%.

The proportions of inland valleys smallholder farmers with knowledge of inland valley management approaches, ecosystem services and experience of flooding and/or drought were 16, 10, 16, and 39% in Ouinhi, Zangnanado, Zogbodomey, and Savalou, respectively, corresponding to sample sizes of 64, 21, 64, and 149 respondents.

Regarding ecosystem services, the information collected during the FGDs through an open-ended mini-guide included the services provided by the different Inland valleys, their functioning, and the threats faced by each Inland valley. Based on the Millennium Ecosystem Assessment framework, the services recorded during the qualitative phase were identified and categorized into four groups: provisioning, regulating, supporting, and cultural. This facilitated the design of the questionnaire and the conduct of the quantitative phase. The list of ecosystem services and threats, summarized from the literature review and refined during the qualitative phase, was used to comprehensively design the quantitative questionnaire, facilitating data collection (Table S1). The questionnaire was first pretested with five to ten farmers per commune, and corrections were made before the quantitative data collection. The first part of the questionnaire focused on the socio-cultural characteristics of respondents, including gender, ethnicity, age, income, education level, religion, residency status, and main activity. The second and third parts focused on scoring the services or sub-services and identifying threats. Respondents were first asked to score the categories of services provided by each Inland valley (provisioning, regulating, supporting, and cultural) using a 5-point Likert scale (1 - very low, 2 - low, 3 - moderate, 4 - high, 5 - very high). They were further asked to use the same method to score the sub-services identified for each category during the qualitative phase and the threats. Regarding the climate data, the focus group discussions (FGDs) were related to farmers' experiences with flooding and drought and the mitigation measures that they commonly use. At the beginning of each FGD, key concepts, including climate hazard, flooding, and drought, were explained in local languages to ensure clear understanding. The FGDs were held near the inland valleys to facilitate their georeferencing. This phase was crucial for gathering foundational data on local knowledge of flooding and drought occurrences in inland valleys, and the mitigation practices used by farmers. It also contributed to the development of the interview questionnaire for the quantitative phase. Following its design, the questionnaire was first tested, reviewed, and used to collect data from the 298 selected smallholder farmers. At the beginning of each individual discussion, respondents were informed about the study context and provided verbal consent to participate. The data collected during the survey included five key points: farmers' experiences with drought and/or flooding, mitigation measures adopted, socio-economic characteristics, characteristics of the inland valleys' farms, and hydrology of the inland valleys (see Table 2).

Table 2. Description of the various parameters and variables considered.

Survey data			
Point	**Variable**	**Modalities**	**Data type**
Farmers' experience with drought/Flooding in their inland valley (IV) during the last 10 years	Occurrence of climate hazards (Drought and/or Flood)	Yes/No	Nominal
	Frequency	Every Year, 2-5 years, More than 5 years	Ordinal
	Frequency of entire crop harvest loss	Every Year, 2-5 years, More than 5 years	Ordinal
	Frequency of crop yield reduction	All Year, in 2-5 years, More than 5 years	Ordinal
	Inland valley size	Hectare	Numeric

Characteristics of Inland valley	Average width	Meter	Numeric
	Cross-sectional shape	Convex, concave and flat	Nominal
Hydrology of Inland valley	Water source	River, rain, spring, other	Nominal
	Flooding regime	Seasonal, Sporadic, Permanent	Nominal
	Flooding duration	Week	Numeric
	Emerging water table duration	Week	Numeric
	Drainage/irrigation infrastructure	1. No drainage, 2. Canal for drainage/irrigation	Ordinal
Socio-economic characteristics of Inland valley	Distance to road	Meter	Numeric
	Distance to market	Meter	Numeric
	Quality of road to market	No road, Dirt road, Asphalt road and Mixed-surface track	Nominal
	Land ownership	Individual, family, village, State	Nominal
	Origin of Inland valley users	Migrant, Native	Nominal
	Percentage of women in the Inland valley	Value	Numeric
	Exploitation mode	Individual, Collective, both	Nominal
	Source of seeds and inputs	In the village, < 25km, 25-50km and > 50km	Ordinal
	Support from extension services	Yes or No	Nominal
	Farmer's organization	Yes or No	Nominal
	Role of crop farming in production system	1. Main activity and 2. Secondary activity	Nominal
Mitigation measure adopted by farmers to drought or flooding occurring in Inland valley	drought-resistant varieties	Yes or No	Nominal
	Change in cultivation areas	Yes or No	Nominal
	Investment of irrigation facilities	Yes or No	Nominal
	change in cropping seasons	Yes or No	Nominal
	Organic farming	Yes or No	Nominal
	Managed rewilding	Yes or No	Nominal
	Agro-forestry	Yes or No	Nominal
	Land restoration	Yes or No	Nominal
	Wetlands restoration	Yes or No	Nominal
	Sediment trapping using plants	Yes or No	Nominal
	Crop	Cereals, Legumes, Perennials, Tubers, Vegetables	Nominal
	Variety	Local, Improved, Both	Nominal
	Soil fertility management	No fertiliser,organic fertilizer; mineral fertiliser, or both (mineral + organic fertilizers)	Nominal
	Bund	Yes or No	Nominal

3.3.4. Secondary data from online sources (objectives 2 and 3)

The secondary data obtained from online sources and used in this study primarily concern the climatic and biophysical data necessary to characterize climatic hazards and their associated predictors.

The biophysical and climatic data used in this study were the physical properties of the Inland valley, including soil particle size distribution (sand, clay, and silt content), soil organic carbon content, flow accumulation, and daily rainfall alongside minimum and maximum air temperature data from 1991 to 2021 (Table 3). The physical properties of the topsoil (30 cm) were derived from the Africa Soil Information Service (AfSIS) project database, which has a spatial resolution of 250 m (Hengl et al., 2017). A 30 m resolution Digital Elevation Model (DEM) was extracted from the Shuttle Radar Topography Mission (SRTM) website to derive flow accumulation, which refers to the volume of water flowing into an inland valley outlet and often serves as a proxy for water storage capacity (Dossou-Yovo et al., 2019). Daily temperature (minimum and maximum) and rainfall data, with a spatial resolution of 2.5 minutes, were retrieved from the WorldClim version 2.1 database for the period 1991 to 2021 (Fick & Hijmans, 2017). Daily data for minimum and maximum temperatures and rainfall were used to calculate the Standardized Precipitation Evapotranspiration Index (SPEI), a comprehensive climatic water balance index for assessing the occurrence and severity of drought and flooding (Vicente-Serrano et al., 2010).

Table 3. Climatic and biophysical data collected.

Point	**Variable**	**Unit**	**Data type**
Physical characteristics of Inland valley	Sand content	g/(100g (%))	Numeric
	Clay content	g/(100g (%))	Numeric
	Soil carbon content (SOC)	g/(100g (%))	Numeric
	Flow accumulation	Value	Numeric
Climate data from 1991 to 2021	Monthly minimum temperature	°C	Numeric
	Monthly maximum temperature	°C	Numeric
	Monthly rainfall	Mm	Numeric
	SPEI	Value	Numeric
	Flooding duration	Month	Numeric
	Flooding frequency	Month	Numeric

	Drought duration	Month	Numeric
	Drought frequency	Month	Numeric

3.3.5. Experiment setting and monitoring

To assess the impact of management approaches on the sustainability of inland valleys and agricultural productivity (objective 4), the experiment carried out is described as follows:

- *Experiment design*

The experimental system was established in the inland valley bottoms, utilizing a split-split-plot design with four replications per treatment over a two-year period (2022 and 2023). The factors studied included the inland valley water and land management approach (Smart-valleys and undeveloped inland valleys), the fertilization application (control plot without fertilization (F0), standard fertilization level based on the conventional farmer fertilization practice (F1), and fertilization level recommended by the RiceAdvice application (F2)), as well as the rice variety (IR841, Orylux6, and Nerica L19) (Table 1). The plot dimensions were 30 m × 18 m for the main plot, 15 m × 9 m for the first-level sub-plot, and 3 m × 5 m for each experimental unit.

The Smart-valleys system was implemented by experienced farmers with over 10 years of expertise at each site. The layout followed the water flow and the approach described by Dossou-Yovo et al. (2020), which they acquired during training in 2012. All plots were manually plowed and leveled, with residues removed before crop establishment.

Table 4. Fertilization application schedule and rates for rice varieties (IR 841, Nerica L19, and Orylux 6) under conventional farmer practices and RiceAdvice recommendations

Fertilization application	Type of fertilization	First application	Second application	Third application	Fourth application	N (kg/ha)	P (kg/ha)	K (kg/ha)
	F0: No fertilizer application							
IR 841, Nerica L19 and ORYLUX 6		0	0	0		0	0	0
F1 : Conventional farmer fertilization practice (kg/ha)								
IR 841, Nerica L19 and ORYLUX 6		Transplanting date	12-15 DAT	22-24 DAT	60-62 DAT			
	Urea	0	25	50	25	46	0	0
	NPK	200	0	0	0	28	15.70	29.88
	Total					74	15.70	29.88
F2 : RiceAdvice recommendations (kg/ha)								
IR 841		16-20 DAT	36-40 DAT	54-57 DAT				
	Urea	34.7	77.5	77.5		87.26	0	0
	NPK (g)	104.7				14.66	8.22	15.64
	Total					101.92	8.22	15.64
Nerica L19 and ORYLUX 6		14-18 DAT	27-32 DAT	38-40 DAT				
	Urea (g)	34.7	77.5	77.5		87.26	0	0
	NPK (g)	104.7				14.66	8.22	15.64
	Total					101.92	8.22	15.64

Figure 5. Illustration photo of the (a) smart valley and (b) undeveloped valley approaches implemented in the experiment

Before transplanting, rice seedlings were raised in a 40 m × 25 m² nursery, using 12–16 kg of seeds per variety. The seedlings were grown to a height of 5–10 cm. After land preparation (both developed and non-developed sites), rice seedlings were transplanted 21 days after establishment, with a spacing of 20 cm between rows and plants and two seedlings per hill (Figure S1).
Subsequently, three 3 × 3 piezometers were installed within each plot, each 1.5 m in length and 10 cm in diameter. These piezometers were perforated with 1 cm diameter holes at a depth of 80 cm and driven into the soil to a depth of 1 m. They were positioned in three locations:
downstream (three piezometers), midstream (three piezometers), and upstream (three piezometers).

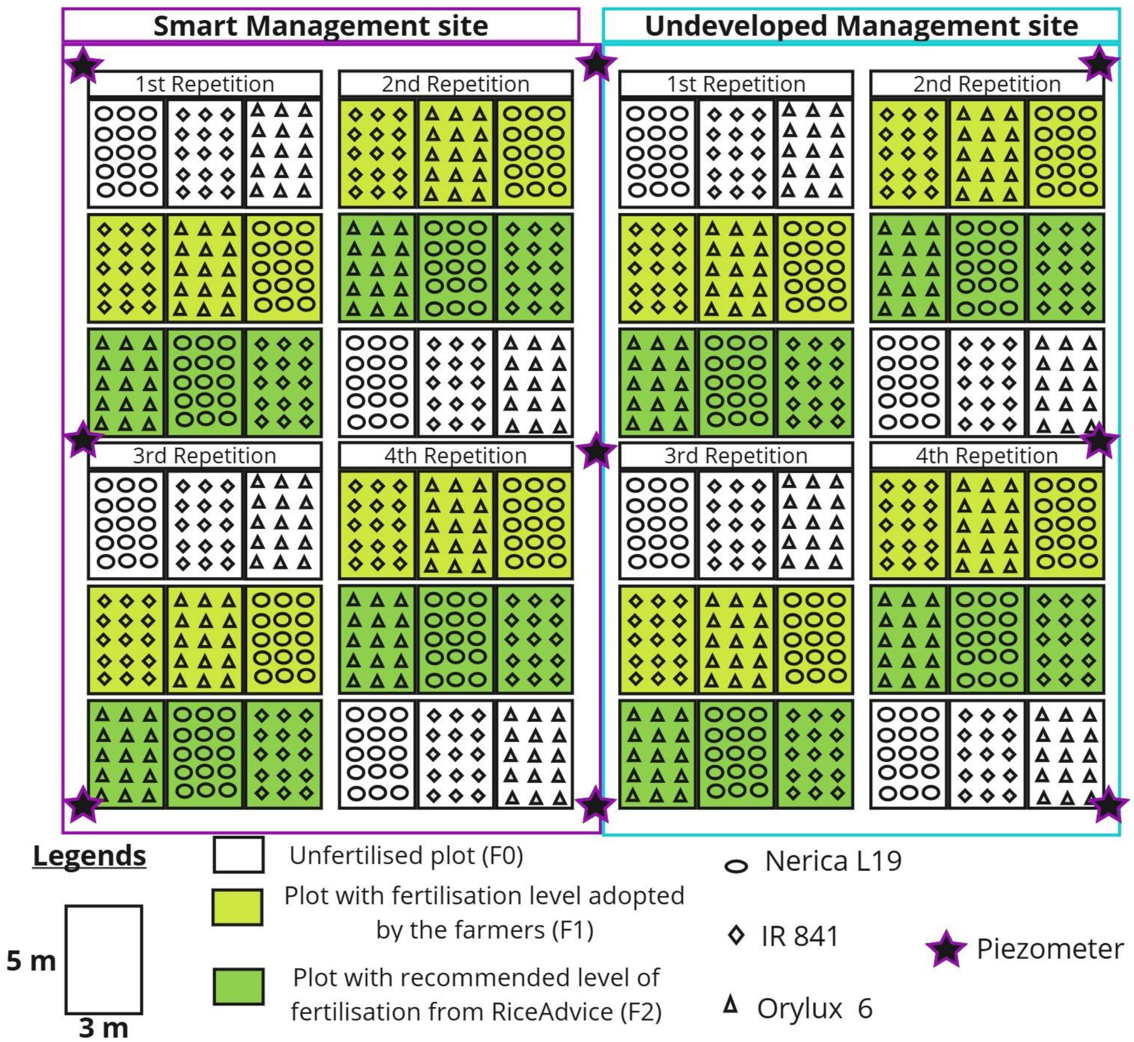

Figure 6. Experimental design illustration with distribution of involved factors

❖ *Soil sampling and analysis*

Prior to the establishment of the trials, a pedological characterisation was carried out at each of the two study sites (Ouinhi and Savalou) (Table 5). On every experimental plot, soil samples were collected at five locations, namely the four corners and the center of the plot, and at three distinct depths corresponding to the 0–15 cm, 15–30 cm, and 30–60 cm horizons. The samples taken from the same depth were then homogenized in order to obtain a representative composite sample for each horizon.

The composite samples thus obtained were air-dried, sieved, and subsequently analyzed to characterize the physical properties (clay, silt, and sand contents) and chemical attributes of the soil [pH (1:2.5 soil:water ratio), total organic carbon, total nitrogen, and available phosphorus (Bray-2 method)]. All analyses were conducted following the protocols described by Johnson et al. (2019).

Table 5. Physical and chemical properties of soils at the Savalou and Ouinhi experimental sites.

Property	Unit	Savalou			Ouinhi		
		0–15 cm	15–30 cm	30–60 cm	0–15 cm	15–30 cm	30–60 cm
Textural class	—	Sandy loam			Loam to sandy clay loam		
pH (H_2O)	—	5.80	5.96	5.86	5.15	5.18	5.04
Organic carbon	%	1.09	0.83	0.73	0.84	0.35	0.36
Total nitrogen	%	0.095	0.064	0.052	0.067	0.052	0.046
Clay	%	8.2	9.1	11.2	19.6	21.8	19.4
Silt	%	21.20	18.60	22.32	38.20	31.40	32.60
Sand	%	69.91	71.92	66.20	41.38	46.29	47.50
Available P (Bray-2)	mg/kg	19.54	15.02	13.09	15.09	6.34	6.49
Exchangeable K	mg/kg	46.80	36.08	34.13	35.10	19.50	30.23
Bulk density	g/cm³	0.96	1.10	1.12	1.13	1.21	1.52

❖ *Field observation and data collection*

During the experimental period, agronomic data and observations were made on all the experimental plots. Among these data, we have:

Biomass data collection: Every three weeks, 12 hills per plot (0.48 m²) were pulled, the roots were cut with scissors, and then the roots were washed and dried at 70°C in an oven for varying durations until a constant weight was achieved, following the methods described by Hussain et al. (2021). Finally, they were weighed with an electronic scale to measure dry biomass.

Number of days to anthesis: Days to 50% flowering were recorded for each subplot.

Yield: At maturity, 4 m² areas were harvested with a machete and threshed, and the weight of grain and straw was measured using an electronic balance. The grains were dried in the shade until 14% grain moisture content was obtained. Grain moisture was assessed by weight difference.

Nutrient analysis and nutrients uptake: The harvested grains were sent to the AfricaRice laboratory in Bouaké, Côte d'Ivoire, to analyze N, P, and K content. Then, nutrients uptake is calculated using the following equation:

$$Nutrient\ Uptake\ = Nutrient\ content\ \times Grain\ Yield \times 0.001 \text{ (Equation 2)}$$

With nutrient = N or P or K; Nutrient Uptake in kg/ha; Nutrient content in mg/kg, and Yield in t/ha.

Agronomic efficiency of nitrogen (AEN): The agronomic efficiency of nitrogen (AEN) measures the economic output generated from the input of a unit of nitrogen, serving as a key indicator to assess the optimal response of rice yield to nitrogen application across different management approaches and different fertilization levels and rice varieties. This metric helps evaluate how effectively nitrogen fertilization contributes to increasing grain yield under varying agricultural practices. It is calculated using the following equation:

$$AEN = \frac{G_f \quad -G_u}{Na} \qquad\qquad Equation\ 3$$

In this equation: AEN represents the agronomic efficiency of nitrogen (in kg kg^{-1}); Gf is the grain yield from the fertilized plot F1 and F2; Gu is the grain yield from the unfertilized plot (in kg ha^{-1}) F0; Na is the amount of nitrogen applied (in kg ha^{-1}) with F1 and F2.

Water monitoring: The field water conditions were observed visually in each sub-sub plot every three days and scored using a three-point scale (1: ponded water, 2: wet soil surface, 3: dry soil surface) between 7:00 AM and 8:00 AM, following Haefele et al., (2006). The soil moisture and temperature values were measured at the center of each sub-subplot with portable TMS-45 cm dataloggers at a depth of 0 – 30 cm between 7:00 AM and 8:00 AM. The groundwater table depth outside the experimental plots was monitored with a set of 3 × 3 piezometers (3 upstream, 3 middle, and 3 downstream), each placed 2 m from the main plots between 7:00 AM and 8:00 AM.

Rainfall data: Daily rainfall was recorded with the rain gauge installed in each field in each site during the two experiment years (Figure 7, 8).

Figure 7. Illustration photo of rainfall gauge installed in the experiment site

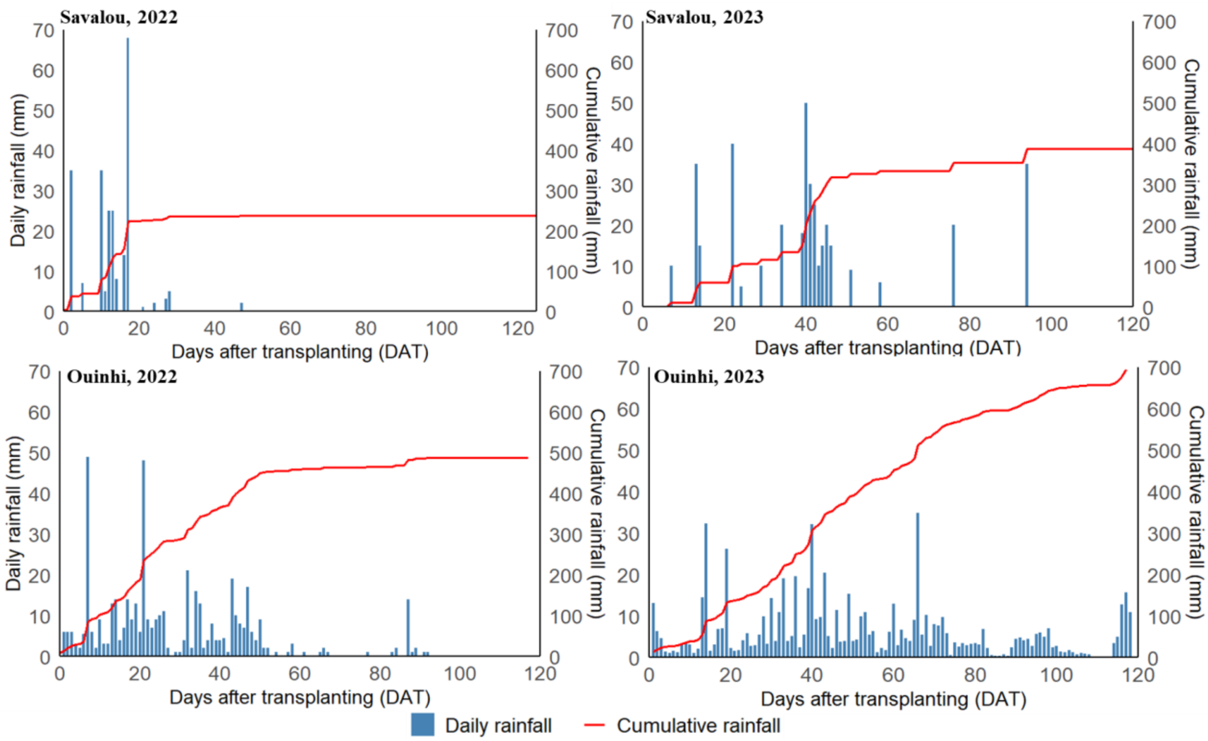

Figure 8. Distribution of Rainfall (mm) during the experimental period in Savalou (Central Benin) and Ouinhi (Southern Benin) for 2022 and 2023.

Rice seedlings (21 days old) were transplanted on 28/08/2022 in Savalou and 05/09/2022 in Ouinhi during the 2022 rainy season and on 22/08/2023 in Savalou and 24/07/2023 in Ouinhi during the 2023 rainy season. Each experimental season lasted approximately 120 days.

3.4. Data analysis

Statistical analyses were all conducted using the statistical software R (R Core Team, 2022). The ArcGIS 10.1 software was used to create maps and analyze the distribution of drought and flooding occurrences. The analyses were conducted in accordance with specific objectives.

3.4.1. State of ecosystem services provided by inland valleys in relation to management approaches.

The data collected during the qualitative phase by the smallholder farmers were transcribed and coded to derive information about the functioning of each management system, as well as the ecosystem services and threats. The quantitative data was analyzed using the relative importance index (RII), which analyzes the scores attributed to the various ES, sub-services, and threats (Gnansounou et al. 2022). To compute the RII, farmers were asked to indicate the importance of the categories of ES provided by their inland valleys based on a 5-point Likert scale (Equation 3). The categories of ES included in the study were provisioning, regulating, supporting, and cultural

ES. The sub-services refer to ecosystem services that fall within each broad category of ES. To compute the RII of each identified subservice, farmers were asked to indicate the importance of each sub-service based on a 5-point Likert scale (Equation 4).

$$RII_j = \frac{\sum_i^n W_{i,j}}{A \times N} \qquad \text{(Equation 4)}$$

In equation 2; ***Wi,j*** is the score given by respondent *i* to the ES category j (for the broad category), or the subservice j (for the subservices), ranging from 1 to 5; A is the highest score (5 in this study for the perception of each broad category or each subservice) and N stands for the total number of smallholder farmers involved in the study. The relative importance index (RII) ranges from 0 to 1. RII was also used to rank the threats to ES delivery using the same approach.

Given the ordered nature of the response variable with five levels ranging from "1: not important" to "5: extremely important," we performed a Seemingly Unrelated Regression model (Fiebig, 2001) to analyze the relationship for each category of ES. This approach allows us to capture the cumulative effects on each level of the ordered response variable while accounting for its inherent ordering (Gnansounou et al., 2022; Mensah et al., 2017). Spearman's correlation test was performed to analyze the relationship between ES and smallholder farmers' perceptions of it. The non-parametric Kruskal-Walli's test was used to evaluate the impacts of water management approaches (undeveloped-valley, bund-valley, and smart-valley) on the different ES and threats to Inland valley sustainability. This test compared the distributions of farmers' perceptions about the ES between the three types of water management approaches. Next, Dunn's post-hoc test with Bonferroni correction at $P < 0.05$ was used to make post-hoc comparisons and determine which pairs of approaches were significantly different. This test was used to compare the distributions of perceptions between groups defined by water management practices. Analyses were performed using R statistical software, version 4.2.2 (R Core Team 2022).

3.4.2. Vulnerability of inland valleys to climatic hazards and predictors of hazard occurrence.

The data analysis process consisted of two main steps: assessing the spatiotemporal variation in flooding and drought severities, and evaluating the predictors of flooding and drought occurrence in inland valleys.

- ❖ *Assessment of the spatiotemporal variation of flooding and drought severities*

The Standardized Precipitation Evapotranspiration Index (SPEI) on a 12-month scale was used to assess the temporal occurrence of flood and drought hazards, while the SPEI on a 3-month scale was used to assess the spatial distribution of the hazards over the period from 1991 to 2021, following the classification by Vicente-Serrano et al. (2010) (Table 6).

The SPEI enables the evaluation of monthly differences between precipitation and potential evapotranspiration (PET) across time scales ranging from one week to 48 months. PET was estimated using the Thornthwaite equation, calculated from monthly precipitation (P) values and average monthly temperatures. The water balance (D) was then evaluated according to Equation 4. This approach provides a robust measure of climatic water deficits or surpluses, capturing both short-term and long-term climatic variability that affects water availability. Thus, it facilitates a comprehensive assessment of drought and flood severity.

$D = P - PET$ (Equation 5)

The SPEI value is then determined as a standardised value of the probability P derived from the distribution function F(x) of the water balance D obtained on a 12-month timescale (for temporal trend analysis) and a 3-month timescale (for spatial analysis), following the classic approach as outlined by Abramowitz and Stegun (1968) :

$$\text{SPEI} = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3}$$ (Equation 6)

With $W = \sqrt{-2\ln(P)}$ for P≤ 0.5 and $W = \sqrt{-2\ln(1-P)}$ for P>0.5 (Equation 7)

P is the probability of exceeding a given D value, defined as P = 1-F(x), and C0 = 2.515517, C1 = 0.802853, C2 = 0.010328, d1 = 1.432788, d2 = 0.189269, and d3 = 0.001308.

To assess the temporal trend, years were classified according to their SPEI values on a 12-month scale, allowing us to distinguish between periods with varying moisture conditions. Following this classification, we applied the non-parametric Mann-Kendall test to detect any significant trends over the years by using the pyMannKendall package (Hussain and Mahmud, 2019). The Mann-Kendall test is particularly useful in this context, as it does not assume a specific data distribution, making it well-suited for detecting gradual changes in climate data over time. This approach helped us observe whether there is a consistent trend in drought or flood occurrences, providing insights into potential shifts in climate patterns in the region.

Table 6. Categories of dryness/wetness grade by the SPEI (Vicente-Serrano et al., 2010)

Categories	**SPEI Values**
Extreme dryness	< -2
Severe dryness	-1.99 to -1.5
Moderate dryness	-1.49 to -1.0
Near Normal	-0.99 to 0.99
Moderate wetness	1.0 to 1.49
Severe wetness	1.50 to 1.99
Extreme wetness	> 2

To assess the spatial distribution of flooding and drought events, we employed the Runs Theory developed by Yevjevich (1967), which is widely used in flooding and drought research (Achite et al., 2024). This theory considers events identical based on a predefined threshold, allowing for characterizing their onset, end, and frequency of occurrence. In our study, the threshold for drought periods was set as SPEI values below -1, and for humid periods (indicative of flood conditions), SPEI values were set at or above +1. Using this threshold, we evaluated the duration and frequency of these hazards, which allowed us to assess both the extent (from beginning to end) and the trend of these occurrences. The duration of an event was defined as the longest consecutive period (in months) reaching the set threshold for each hazard type ($\leq$ -1 for drought and $\geq$1 for flood). The hazard frequency (Fiv) was then calculated using the following formula:

$$F_{iv} = 100 \times \frac{n_{iv}}{N_{iv}} \qquad \text{(Equation 8)}$$

Here, n_{iv} represents the number of months reaching the event threshold within each inland valley iv, while the total number of months in the study period provides the basis for calculating event frequency.

Subsequently, the severity of drought and flooding was assessed through a hierarchical clustering analysis using Ward's method on key variables: drought duration, drought frequency, flooding duration, and flooding frequency. This approach allowed us to classify inland valleys into three hazard levels: high drought-prone, high flooding-prone, and drought-prone inland valleys. Standardizing the variables ensured comparability, a crucial step in climatic hazard assessments.
We used the Chi-Square Test of Independence to validate these classifications by comparing the derived hazard levels with farmers' perceptions of drought and flooding occurrences in their inland valleys.

- *Assessment of the determinants of flooding and drought occurrence in inland valleys*

The determinants of drought and flooding events were assessed using the Random Forest algorithm (Breiman, 2001), where event severity, determined through cluster analysis, was the dependent variable. The independent variables included the drainage of Inland valley, size, average width, duration of water table availability, flooding regime, fertility management practices, water source, cross-sectional shape of the Inland valley, flow accumulation, average rainfall, sand content, clay content annual average Standardized Precipitation Evapotranspiration Index, and soil organic carbon content.
Random Forest is a machine-learning method widely used for classification and regression, particularly suited for applications in climatology, such as analyzing drought and flooding events (Mohammed et al., 2022). This approach is advantageous when predictor variables are highly interdependent (Breiman, 2001). The algorithm constructs numerous decision trees, each trained on a random subset of data and predictors, using the Bagging technique with bootstrap sampling and random feature selection at each split node (Breiman, 2001). Two critical parameters guide the performance of Random forests: (1) the number of decision trees to construct (k) and (2) the number of variables used per split (m). According to Breiman (2001) and Dossou-Yovo et al. (2019), model accuracy improves as the number of trees increases and the number of split variables decreases. Based on model tuning, we randomly selected optimal values (k = 5 and m = 500) (see Figure S4).
We used the Mean Decrease Accuracy (MDA) metric to rank the contribution of each variable, which reflects the drop in classification accuracy when a variable is omitted. We used the partial dependence plots (Hastie et al., 2009) to visualize the relationships between the three top predictors

and the likelihood of drought and flooding occurrence as the Random Forest model predicted. In binary classification scenarios, the y-axis of these plots is represented on the logit scale, illustrating the relationship between occurrence probability and each predictor, with effects from other model variables averaged out (Hosmer Jr et al., 2013).

3.4.3. Mitigation strategies adopted by smallholder farmers to address climatic hazards.

The following approach was followed to evaluate the mitigation measures adopted in response to drought and flooding. First, we calculated the relative frequency of each mitigation measure and identified the most adopted measures. Next, we evaluated the frequency distribution of the number of mitigation measures adopted to understand which combinations of measures are most frequently implemented in response to flooding and drought. To explore potential relationships between the various mitigation measures, we conducted a Principal Component Analysis (PCA), which facilitated a deeper understanding of collective choices in response to drought and flooding hazards.

We employed a Poisson regression model to analyze the socioeconomic determinants of mitigation measures adopted by smallholder farmers to address flooding and drought. This model is well-suited for predicting dependent variables that represent count data(Qange et al., 2024). The dependent variable was the number of drought and flood mitigation measures used by farmers. The independent variables included socioeconomic characteristics, such as distance to infrastructure (roads and markets), road quality, type of land ownership, agricultural exploitation mode, user origin, proximity to input sources, access to extension services, membership in farmer organizations, and the role of crop farming in the production system. These variables were selected based on a literature review that identified their potential influence on the adoption of adaptation measures to climate shocks (Dossou-Yovo et al., 2019; Yegbemey et al., 2013).

The fitness and predictive performance of the models were assessed using the Pseudo R^2, log-likelihood, Akaike Information Criterion (AIC), and deviance (Cameron and Trivedi, 2013). The regression coefficients were interpreted using a statistical threshold of 10% of error.

3.4.4. Impact of management approaches on the sustainability of inland valleys and agricultural productivity

Following the data collection, statistical analyses, graphical representations, and model development were conducted using R statistical software version 4.2.2. Initially, the assumptions of normality and homoscedasticity of residuals were evaluated for each response variable. The Shapiro-Wilk test was employed to assess the normality of residuals, while the Breusch-Pagan test was used to detect potential heteroscedasticity.

Subsequently, an analysis of variance (ANOVA) was performed to examine the effects of the different treatments. To identify significant differences between mean values, the least significance difference (LSD) test was applied, with a significance threshold set at $p \leq 0.05$.

In addition, generalized linear models (GLMs) were used to model the relationship between explanatory factors (e.g., treatments, environmental variables) and response variables (e.g., yield, nutrient content).

CHAPTER 4. RESULTS AND DISCUSSIONS

4.1. Result
4.2. Discussion

4. Results and discussions

4.1. Result

4.1.1. State of ecosystem services provided by inland valleys in relation to management approaches.

- Characteristics of farm households and farmers' water management practices

The demographic and socio-economic characteristics of smallholder farmers and the impact of socio-economic characteristics on ecosystem services perception are presented in Table 7. Smallholder farmers of the study area are predominantly male (67%) and of Gbé-Adja ethnicity (90%). More than half of smallholder farmers are married and middle-aged (25 to 44), with average annual incomes (less than 830 USD for more than 79% of smallholder farmers). Most respondents are natives (90%), with 92% engaged in farming as their main activity. Regarding land management approaches, three management approaches were identified as follows: undeveloped valleys approach adopted by 50% of farmers, bund valleys approach adopted by 35%, and smart valleys adopted by 15% adopted the smart valleys management approach.

Table 7. Ecosystem services and the summary of respondents' narratives

	Sub-services	Summary of respondents' narratives
Provisioning		
	Provision of food	The Inland valley provides fruit, fish
	Provision of fresh water	The Inland valley provides water used for domestic drinking, irrigation, and livestock.
	Natural medicines and pharmaceuticals	Plants used as traditional medicines
	Provision of genetic resources	There are some rare animals found in the Inland valley
	Provision of fiber and domestic energies	The Inland valley provides timber for building and firewood
	Provision of ornamental resources	Collection of shells, flowers
	Clay, mineral, aggregate harvesting	Clay is extracted for brick-making and pots
	Waste disposal	Discharge of wastewater
Regulation		
	Flood hazard regulation	Regulation and storage of flood water, regulation of intense rainfall events
	Regulation of human diseases	Inland valley controls pest species such as mosquitoes

	Pest regulation	The Inland valley is a source of pests (for example rats thriving in dirty water systems)
	Local climate regulation	The Inland valley habitat structure provides shade for humans
	Pollination	Pollination of plants and crops by bees, butterflies, and wasps, is observed in the Inland valley
	Water regulation	Regulation of flows of surface water during high and low flows, regulation of recharge of groundwater, etc.
	Fire regulation	The wet condition of Inland valley provides physical barriers to the spread of fire
	Natural filter system	The Inland valley's water is fresh all the time
	Erosion regulation	The Inland valley vegetation provides protection from erosion for the soils
	Global climate regulation	The Inland valley contributes to the storage and/or sequestration of carbon
	Water purification	Inland valley contributes to the cleaning of water, improvement of water quality, deposition of silts, trapping of contaminants and pollutants, etc.
	Storm hazard regulation	Regulation of tidal or storm surges, regulation of extreme winds
	Air quality regulation	Removal of airborne particles from the exhaust of cars, chimneys of industry
	Noise and visual buffering	The presence of trees absorbs and buffers the impact of noise
Cultual and Culic		
	Educational and research	Use of the Inland valley by students, AfricaRice, and NGOs for education and research
	Spiritual and religious value	The Inland valley plays a role in local religious festivals
	Social relations	There is a presence of rice farming communities that have developed within and around the Inland valley
	Aesthetic value	Inland valley is part of a known area of natural beauty
	Cultural heritage	Some parts of the Inland valley have historical aspects
	Recreation and tourism	Inland valley previously served as a tourist site
	Inspirational value	There is a presence of local myths or stories relating to the wetland
Supporting		
	Habitat	Presence of locally important habitats and species, presence of species and habitats of conservation concern

Water recycling	The presence of wetland vegetation and open water results in evapotranspiration and local recycling of water
Nutrient cycling	In the Inland valley, there is a source of nutrients present from inputs from agricultural land
Primary production	Presence of primary producers such as plants, algae, etc.
Soil formation	Deposition of sediment, accumulation of organic matter, etc.

Source : Akodekou et al. (2026)

- **Ecosystem services provided by inland valleys**

Smallholder farmers gave high ranks to Inland valley provisioning ES (RII = 0.76) (Figure 9). Also, regulation (RII = 0.69) and support services (RII = 0.67) received high ranks by smallholder farmers. Nonetheless, cultural and cultic services (RII = 0.37) received relatively lower ranks by the smallholder farmers surveyed. Furthermore, Spearman's correlation test revealed a significant positive relationship between provisioning services and regulation services ($r=0.45$; $p<0.001$), and also between provisioning services and support services ($r=0.40$; $p<0.01$). In addition, cultural and provisioning services had significant and positive low relationships ($r=0.20$; $p<0.05$) (Figure S3).

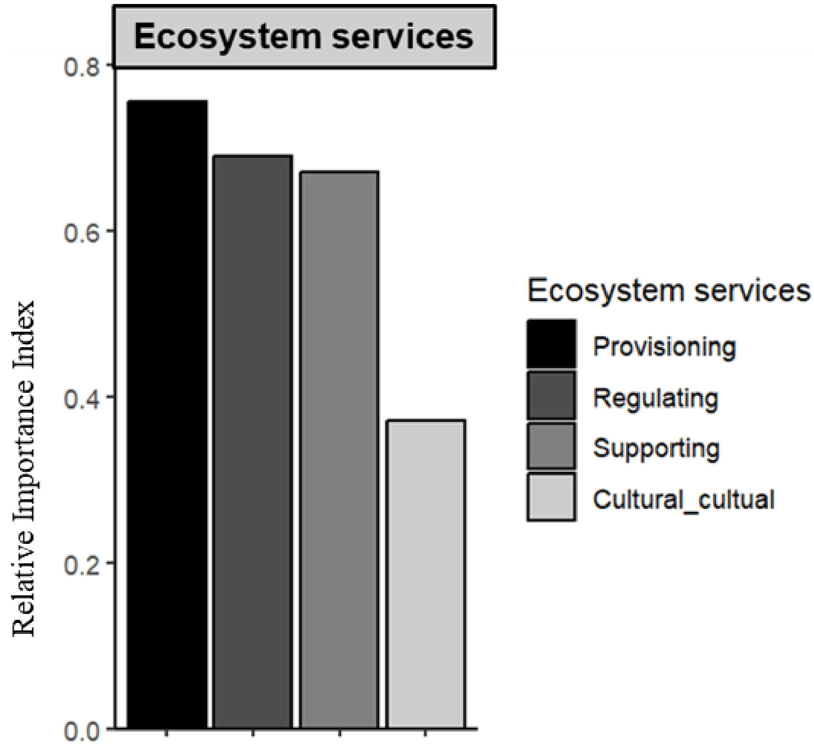

Figure 9. Ranking of the ecosystem services provided by Inland Valley.

Figure 10 shows the ranks of the subservices recorded in each category of ES. Smallholder farmers ranked provisioning services, particularly the provisioning of food and fresh water, higher, while flood hazards and human diseases received higher ranks among the regulating services. For the supporting services, smallholder farmers attributed high ranks to the role of Inland valley as a habitat for biodiversity conservation and their water-retention service. Education and research received high ranks for the cultural services by smallholder farmers (Figure 10).

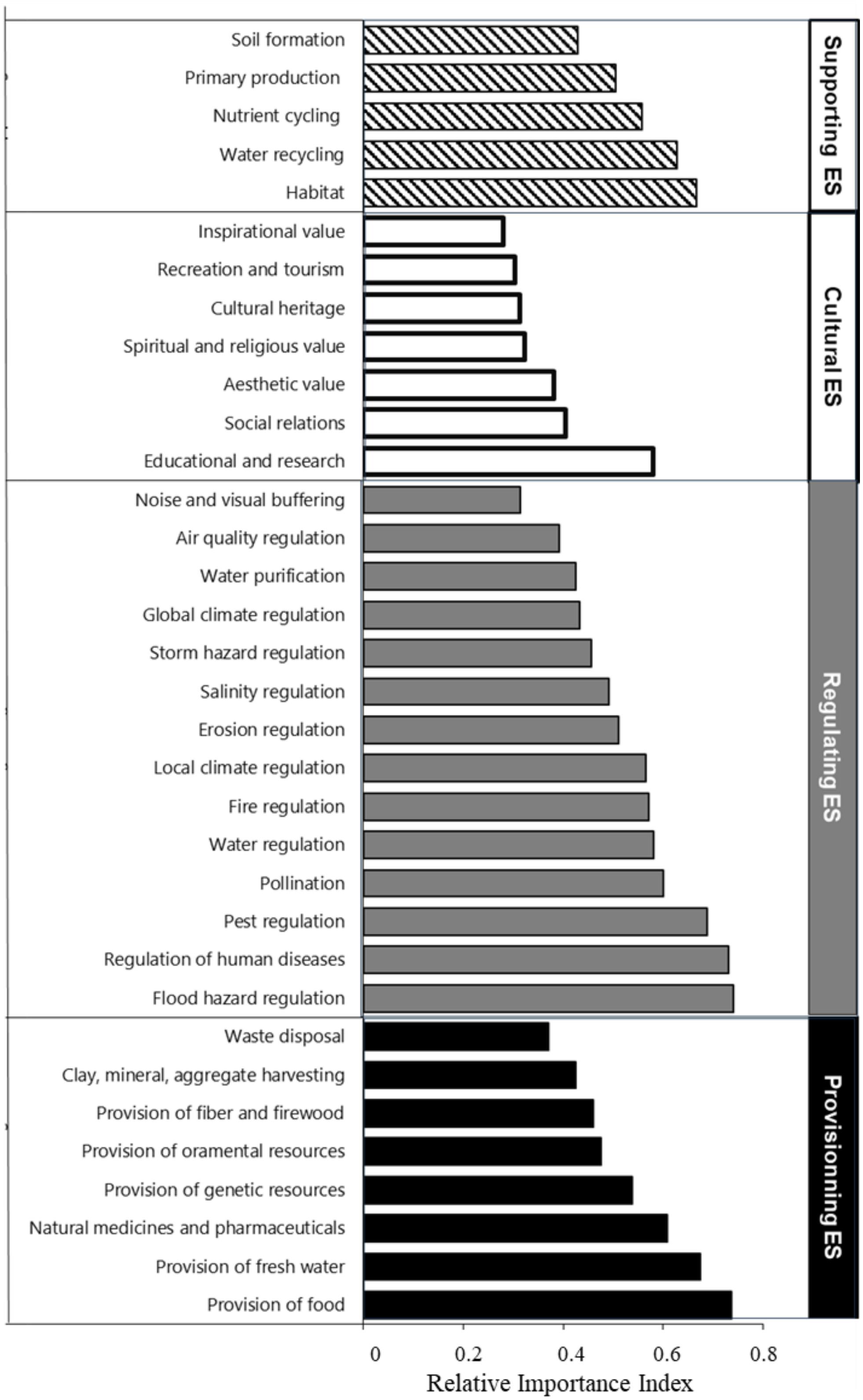

Figure 10. Comparative analysis, by service category of the relative importance of ecosystem services provided by Inland Valley.

- **Determinants of smallholder farmers perceptions of ecosystem services provided by inland valleys**

The Table 8 outlines the results of a statistical analysis examining how various socio-economic factors shape farmers' perceptions of ecosystem services (ES) across four categories: provisioning, supporting, regulating, and cultural. These perceptions' key factors include gender, age, education level, main occupation, and annual income. Males tend to place significantly less value on provisioning and regulating services than females. Age also plays a role, with individuals over 64 years old prioritizing cultural services more, while those between 25-44 years place greater importance on provisioning services. Higher education particularly at the tertiary level, is strongly linked to an increased appreciation for supporting services. Additionally, higher income positively correlates with the greater perceived value of provisioning, regulating, and cultural services. Traditional healers tend to significantly undervalue provisioning services. There are also notable regional variations, with farmers in Savalou showing a higher appreciation for cultural services, while those in Zangnanado demonstrate lower levels of appreciation.

Table 8. Seemingly Unrelated Regression Model results showing the determinants of farmers' perceptions of the Ecosystem Services (ES) provided by inland valleys. Standard errors are shown in brackets.

The determinants are the socioeconomic characteristics : Gender (male, female); Age (less than 25, 25 to 44, 45 to 64 and more than 64); Education level (Uneducated, primary, secondary and tertiary); Religion (Non-religious, Christian, Muslim, Traditional); Ethnicity (Ede-Yoruba, Gbe-adja, Holi and Nago); Annual income (less than 830 USD, 830 to 1660 USD and more than 1660 USD); Resident status (native and immigrant); Study communes (Ouinhi, Savalou, Zangnanado and Zogbodomey).

Characteristics	**Proportion in sample**	**Provisioning ES**	**Supporting ES**	**Regulating ES**	**Cultural ES**
	Estimate (Std_Err)	*Estimate (Std_Err)*	*Estimate (Std_Err)*	*Estimate (Std_Err)*	*Estimate (Std_Err)*
Intercept		4.06***(0.68)	3.63***(0.68)	3.43***(0.59)	0.65**(0.29)
		Gender (Female as reference level)			
Male	67	-0.32*(0.12)	-	-0.23*(0.10)	-0.14(0.10)
		Age (<25 years as reference level)			
25-44	53	0.37(0.25)	-0.26 (0.22)	-	-
45-64	35	0.36 (0.25)	-0.42(0.26)	-	0.23(0.12)
>64	7	0.15 (0.09)	-1.76 (0.91)	-	0.67*(0.30)
		Education (Primary as reference level)			
Uneducated	36	-	0.03 (0.31)	-	-

Secondary	19	-	0.77 (0.12)	-	0.33*(0.16)
Tertiary	2	-	0.91** (0.33)	-	-
Religion (Non religious as reference level)					
Christian	26	-	-1.53 (1.03)	-	-
Muslim	12	-	-0.34 (0.32)	-	-
Traditional	38	-	-	-	-
Ethnicity (Ede-Yoruba as reference level)					
Gbe_Aja	90	-0.22(0.14)		0.12 (0.06)	-0.46** (0.17)
Holi	1	-		-0.21 (0.12)	0.24 (0.19)
Nago	2	0.32(0.19)		0.43 (0.22)	-0.32 (0.16)
Annual income (< 830 USD as reference level)					
830-1660	12	0.38* (0.22)	-	0.11 (0.10)	0.70** (0.25)
>1660	9	0.53* (0.23)	-	0.56** (0.21)	0.63*(0.28)
Main activity (Agriculture as reference level)					
Traditional healing	1	-0.83*(0.42)	0.44 *(1.32)	-	-
Others	7	-0.44 (0.18)	-1.2* (0.54)	-	-
Resident status (Native as reference level)					
Immigrant	10	-	0.79 (0.43)	-	-
Study communes (Ouinhi as reference level)					
Savalou	50	-			0.27*(0.15)
Zangnanado	7	-			-0.19(0.09)
Zogbodomey	21	-			-

Note: ** Prob. < 0.05; ** Prob. < 0.01; *** Prob. < 0.001; 1 USD ≈ 600 FCFA ; Estimate (Std_Err) : Estimate (Standard Error)*

❖ **Threats to Inland Valleys Sustainability**

Based on smallholder farmers' perceptions, nine major threats undermined the sustainability of ES provided by Inland valley in the study area (Figure 11). The relative importance index indicates that high chemical pesticide use (RII = 0.72), flood and drought (RII = 0.64 and 0.62 respectively), and fire outbreaks (RII = 0.57) received the highest ranks as threats to the sustainability of Inland valley by smallholder farmers. Furthermore, flood management and drought also received relatively high ranks by smallholder farmers. (Figure 11).

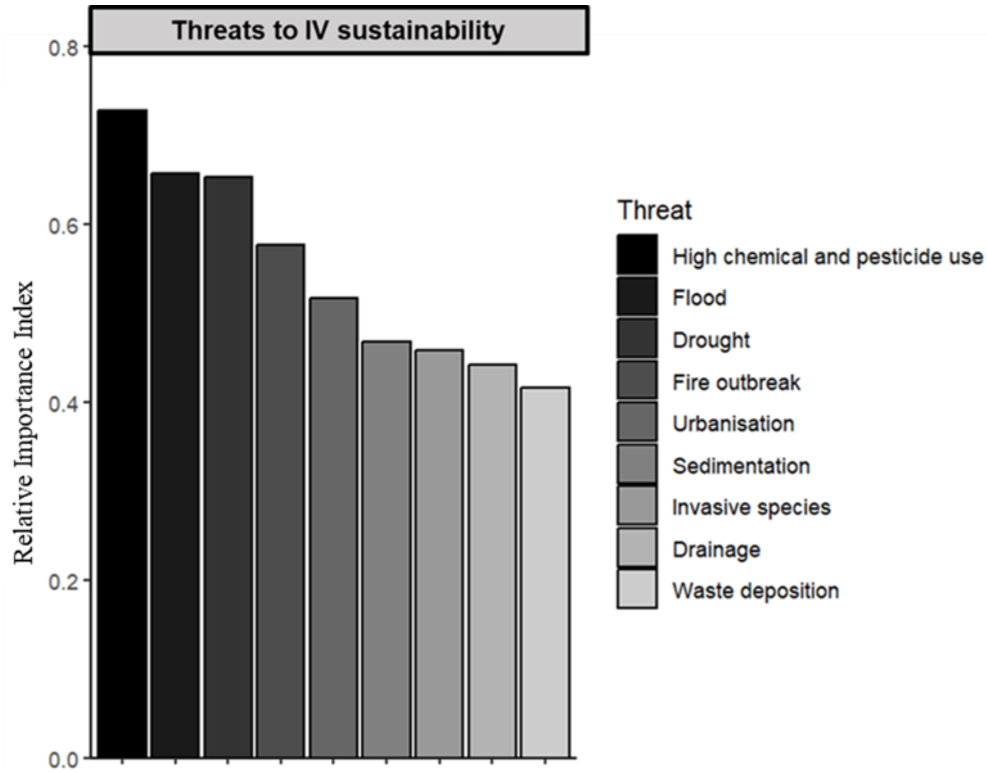

Figure 11. Threats perceived by smallholder farmers to the sustainability of Ecosystem Services provided by Inland Valley.

- **Impact of water management technologies on Inland Valley ecosystem services and threats to Inland Valleys sustainability.**

The ranks provided by farmers on the inland valleys ES differed significantly between water management technologies (Table 9). Among the provisioning ES, smart-valley outperformed the bund-valley and undeveloped-valley such as food, freshwater, and genetic resources. Among the regulating ES, smart-valley outperformed other forms of water management technology, particularly in terms of flood hazard, human disease, pollination, water, and fire regulation. Among the supporting ES, smart-valley outperformed the other water management technologies in terms of habitat conservation, water recycling, primary production, and soil formation. Nonetheless, most of the cultural services received lower ranks in smart-valley compared to bund-valley and undeveloped-valley.

Table 9. Analysis of ecosystem services provided by Inland Valley as a function of management approaches (Undeveloped-valley, Bund-valley and Smart-valley), according to the perceptions of smallholder farmers.

Sub-services	Undeveloped-valley		Bund-valley		Smart-valley		P-value
	Sum	RII	Sum	RII	Sum	RII	
Provisioning	**544**	**0.69[a]**	**322**	**0.76[b]**	**160**	**0.85[c]**	***p<0.001***
Provision of food	544	0.74	317	0,76	41	0.83	*p<0.001*
Provision of fresh water	456	0.58	322	0.63	160	0.72	*p<0.01*
natural medicines and pharmaceuticals	365	0.59	311	0,63	83	0.57	ns
Provision of genetic resources	239	0.56	188	0.43	118	0.71	*p<0.001*
Provision of fiber and firewood	243	0.48	189	0.41	52	0.55	ns
Provision of ornamental resources	93	0.39	209	0.54	11	0.31	ns
Clay, mineral, aggregate harvesting	98	0.35	195	0.48	23	0.38	*p<0.05*
Waste disposal	109	0.31	189	0.42	32	0.32	*p<0.001*
Regulation	**569**	**0.67[a]**	**329**	**0.68[a]**	**263**	**0.81[b]**	***p<0.001***
Flood hazard regulation	550	0.68	329	0.65	145	0.85	*p<0.001*
Regulation of human diseases	569	0.68	317	0.62	156	0.70	*p<0.001*
Pest regulation	540	0.67	276	0.55	143	0.65	*p<0.001*
Local climate regulation	370	0.66	229	0.46	65	0.65	*p<0.01*
Pollination	475	0.66	273	0.54	164	0.78	*p<0.001*
Water regulation	355	0.60	115	0.64	263	0.83	*P <0.05*
Fire regulation	353	0.58	257	0.51	97	0.67	ns
Salinity regulation	319	0.52	239	0.49	53	0.41	*p<0.05*
Erosion regulation	352	0.51	133	0.72	214	0.42	*p<0.01*
Global climate regulation	269	0.48	51	0.29	199	0.42	*p<0.05*
Water purification	329	0.47	196	0.40	63	0.36	*p<0.05*
Storm hazard regulation	199	0.46	195	0.44	44	0.49	ns
Air quality regulation	260	0.41	198	0.39	50	0.29	*p<0.05*
Noise and visual buffering	172	0.28	187	0.38	46	0.25	*p<0.001*
Cultual and Culic	**390**	**0.45[c]**	**236**	**0.37[b]**	**142**	**0.31[a]**	***p<0.01***
Educational and research	390	0.68	236	0.48	142	0.47	*p<0.001*
Spiritual and religious value	164	0.57	210	0.24	41	0.23	*p<0.01*

Social relations	249	0.43	190	0.40	47	0.29	*p<0.05*
Aesthetic value	228	0.37	201	0.43	48	0.34	*p<0.05*
Cultural heritage	171	0.31	107	0.24	33	0.21	*p<0.001*
Recreation and tourism	164	0.30	186	0.39	32	0.23	*p<0.01*
Inspirational value	192	0.30	188	0.37	42	0.22	ns
Supporting	516	0.64	269	0.66	234	0.68	*ns*
Habitat	516	0.60	269	0.53	147	0.70	*p<0.001*
Water recycling	469	0.52	142	0.73	234	0.68	*p<0.01*
Nutrient cycling	392	0.48	259	0.53	84	0.53	ns
Primary production	271	0.44	206	0.45	45	0.53	*p<0.05*
Soil formation	182	0.35	185	0.43	38	0.35	*p<0.01*

Note : a–c: Relative Importance Index values followed by different letters in rows are different at Bonferroni-adjusted significant level (post-hoc tests with Bonferroni's correction for multiple comparisons). P-value: P-value of the Kruskal-Wallis test value; RII: Relative Importance Index. ns: non-significant.

Table 9 shows the impact of management approaches on the threats to Inland valley sustainability perceived by smallholder farmers. The results of the analysis showed that the threats differ significantly between the different management approaches (see Table 10). High chemical fertilizer and pesticide use received higher ranks in bund-valley compared to smart-valley and undeveloped management Inland valley (Table 9). Drought and flooding received high ranks in undeveloped management Inland valley (RII = 0.67 and 0.61 respectively) compared to smart-IV (RII = 0.54 and 0.45) and bund management IV (RII = 0.59 and 0.57). In smart-IV, high chemical fertilizer and pesticide use, and sedimentation received high ranks.

Table 10. Distribution of threats to Inland Valley sustainability according to management approaches (Undeveloped-valley, Bund-valley and Smart-valley)

Threats to Inland valley sustainability	**Smart-valley**		**Bund-valley**		**Undeveloped-valley**		**P-value**
	Sum	*RII*	*Sum*	*RII*	*Sum*	*RII*	
High chemical fertilizer pesticide use	71	0.59^{a}	352	0.80^{b}	341	0.66^{a}	*P <0.001*
Sedimentation	53	0.56	210	0.48	227	0.44	*ns*
Drought	65	0.44^{a}	258	0.59^{ba}	347	0.67^{b}	*P <0.05*
Urbanization	60	0.40^{ba}	239	0.54^{b}	223	0.43^{ba}	*P <0.01*
Invasive species	54	0.35^{b}	233	0.53^{b}	194	0.37^{a}	*P <0.001*
Flood	54	0.35^{a}	250	0.57^{ba}	318	0.61^{b}	*P <0.05*

Fire outbreak	41	0.34[a]	298	0.68[c]	269	0.52[b]	*P <0.001*
Drainage	36	0.30[a]	216	0.49[b]	172	0.33[a]	*P <0.001*
Waste deposition	35	0.29[a]	155	0.35[b]	137	0.26[a]	*P <0.001*

Note : a–c: Relative Importance Index values followed by different letters in rows are different at Bonferroni-adjusted significant level (post-hoc tests with Bonferroni's correction for multiple comparisons). *P-value : P-value of the Kruskal Wallis test value; RII : Relative Importance Index.*

4.1.2. Vulnerability of inland valleys to climatic hazards and predictors of hazard occurrence.

- **Spatiotemporal patterns of flooding and drought severity in Benin inland valleys**

The temporal analysis of drought and flooding events revealed significant temporal variability across the inland valleys studied (Figure 12). Regarding drought, Zogbodomè recorded the highest proportion of dry years, with 16.13%, followed by Zangnanado with 12.90%, and both Savalou and Ouinhi with 9.68%. Specifically, the years 2001 and 2016 were characterized by extreme and moderate drought conditions consistently across all sites. Extreme dryness (SPEI < -1.5) was observed in 2001 at Zangnanado (SPEI = -1.74), Savalou (SPEI = -1.64), and Ouinhi (SPEI = -1.64). Zogbodomè experienced extreme dryness in both 2001 (SPEI = -1.64) and 2016 (SPEI = -1.52).

Regarding wetness conditions, the proportion of wet years was highest in Zogbodomè (16.13%), followed by Zangnanado (12.90%) and Savalou (12.90%), while Ouinhi recorded the lowest proportion at 9.68% over the study period (1991 to 2021). Extreme wet conditions (SPEI > 1.5) were observed in various years: 2008, 2009, and 2019 in Zangnanado; 1991 and 2019 in Savalou; 2008 and 2019 in Ouinhi; and 2008 in Zogbodomè.

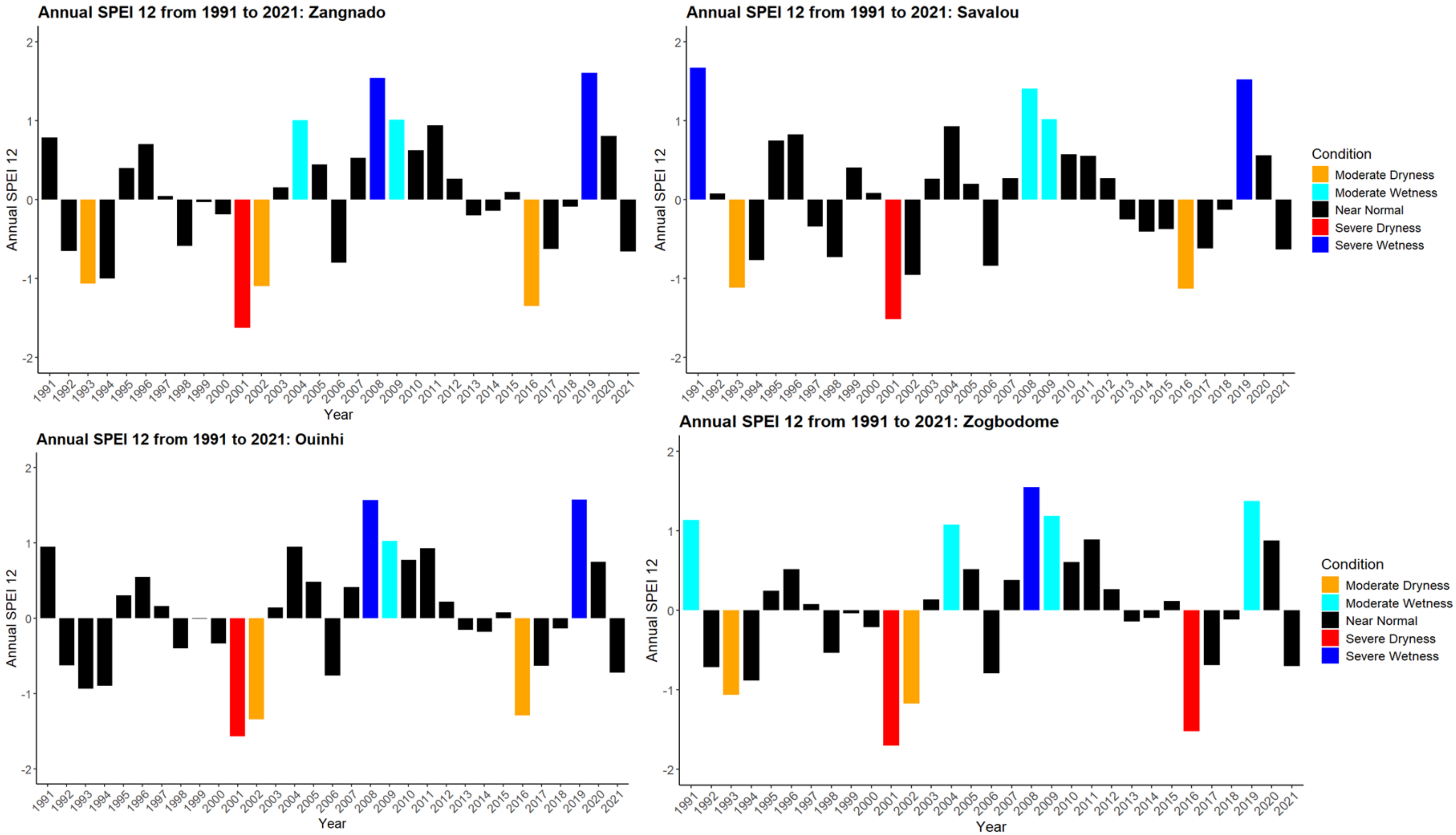

Figure 12. Temporal distribution of SPEI 12-month timescale across the Inland valleys communes.

The levels of dryness and wetness are classified using the Standardized Precipitation Evapotranspiration Index (SPEI) values as described in Table 2.

The spatial distribution of flooding (Figure 14) showed significant variability in flooding duration (FD) and frequency (FF) across different communes. Overall, the communes of Zou department (Ouinhi, Zangnanado and Zogbodomey) experienced prolonged and frequent flooding between 1991 and 2021, with flooding duration exceeding 5.9 months and flooding frequencies greater than 24% (Figure 13 illustrates a 2022 flooding event). In contrast, the commune of Savalou in the department of Collines experienced more moderate flooding conditions with flooding frequent between 19 and 30% and flooding duration shorter than 5.2 months. Besides, the flooding frequency was lower in the southern part and minimal in the northern part of the study area.

Figure 13. Photographic illustration of flooding occurrence in agricultural inland valleys in Zou department (Picture taken along inland valleys of Zougo, Ouinhi Commune In July 2022)
Source: Akodekou (2022)

Regarding drought distribution, spatial analysis indicated that the communes of Savalou and Zogbodomey faced very long and moderately frequent drought, with drought durations exceeding 7.7 months and drought frequencies greater than 28%. Meanwhile, Zangnanado experienced relatively drought conditions, with drought frequencies between 21 and 43% and durations between 4 and 8.3 months (Figure 14).

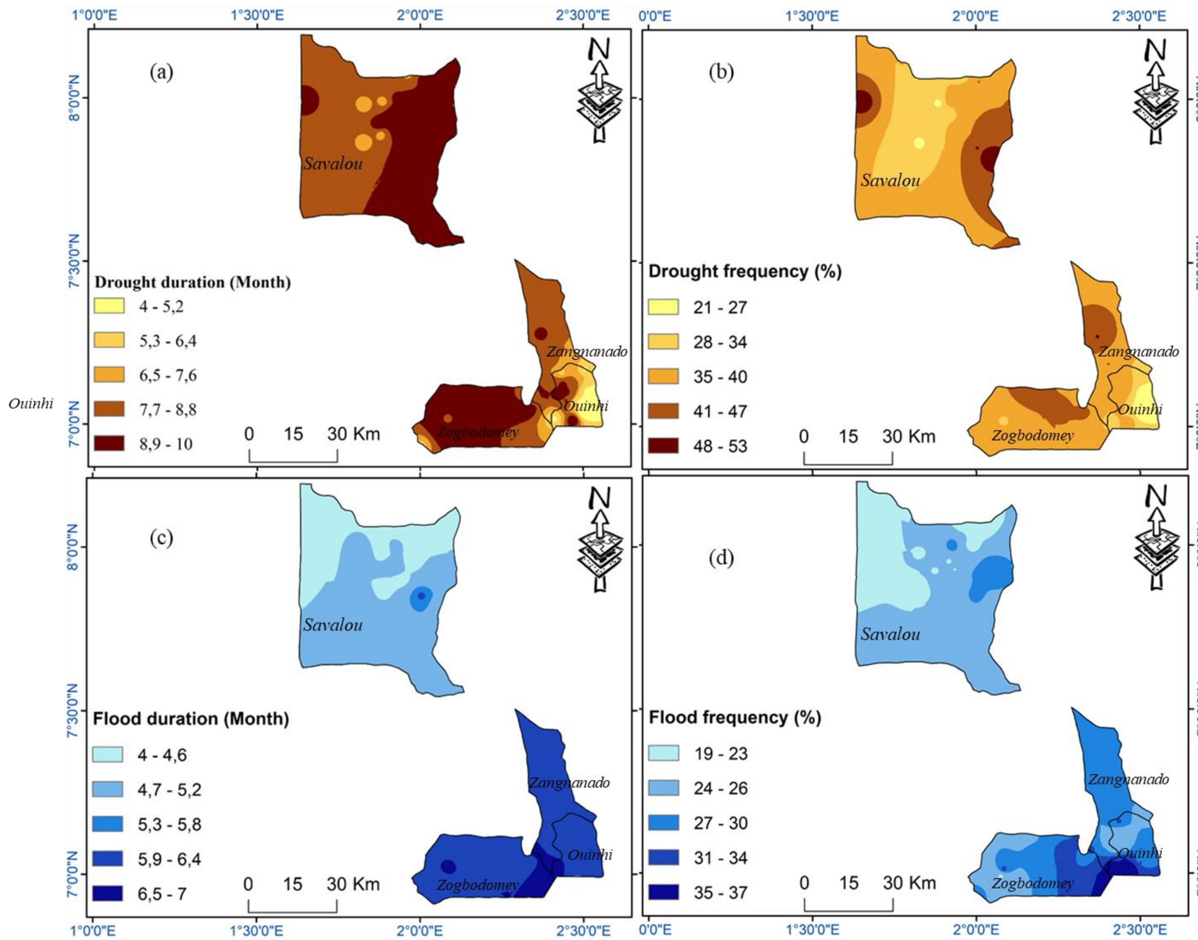

Figure 14. Spatial distribution of (a) drought frequency, (b) drought duration, (c) flooding frequency and (d) flooding duration in the study area from 1991 to 2021.

The clustering of Inland valleys, based on the frequency and duration of drought and flooding identified three distinct clusters of inland valleys (Figure S5 and Table 11), each characterized by specific drought and flooding patterns, along with corresponding severity levels. Cluster 1, encompassing 35% of the Inland valleys, is marked by an extended drought duration (averaging 9.13 months) and a high drought frequency (40%), which collectively defines it as being a highly drought-prone cluster. Conversely, Cluster 2, covering 30% of the Inland valleys experiences prolonged flooding durations (7 months) and the highest flooding frequency (33%), defining it as being highly flooding prone cluster. Cluster 3 accounts for the remaining 35% and exhibits moderate durations and frequencies of both drought and flooding events, defining it as moderately drought and flooding prone clusters.

Cross-validation with farmers' perceptions shows significant alignment across all clusters, with Chi^2 and p-values confirming the statistical relevance of these clusters (Table 10). This alignment between the cluster analysis and farmers' experience strengthens the validity of the approach used in this study for mapping exposure to drought and flooding.

Table 11. Characteristics of inland valleys clusters identified in the study area

	Cluster 1	**Cluster 2**	**Cluster 3**
Percentage of Inland valley (%)	35	30	35
Drought duration (Month)	9.13 ± 0.06	6.64 ± 0.25	7.02 ± 0.19
Drought frequency (%)	39.83 ± 0.40	30.58 ± 0.57	30.47 ± 0.58
Flooding duration (Month)	5.15 ± 0.06	7.00 ± 0.00	5.17 ± 0.07
Flooding frequency (%)	25.50 ± 0.27	33.24 ± 0.34	25.22 ± 0.33
Severity	Highly drought prone	Highly flooding prône	Moderately drought and flooding-prone
Cross-validation with farmers perceptions	Chi² = 11.36; P-value = 0.003	Chi² = 49.12; P-value = 2.15e-11	Chi² = 23.77; P-value = 0.000007

❖ **Determinants of flooding and drought occurrence**

The Mean Decrease in Accuracy (MDA) from the Random Forest model is summarized in Figure 15 for highly drought-prone Inland valleys, highly flooding-prone Inland valleys, and moderately drought and flooding-prone Inland valleys. The most significant variables influencing drought occurrence are soil organic carbon, SPEI, and sand content. In contrast, for flooding occurrence, the primary predictors include average annual rainfall, soil organic carbon, and SPEI. When examining the inland valley areas prone to flooding and drought, the key factors identified are average annual rainfall, SPEI, and soil organic carbon.

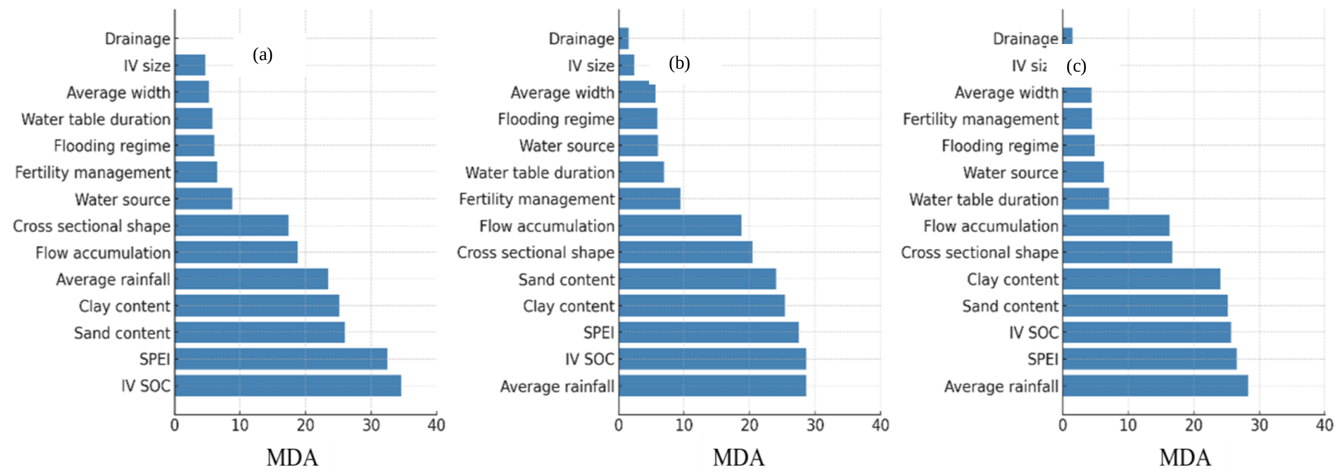

Figure 15. Variable importance contribution as measured by the Mean Decrease in Accuracy in (a) Highly drought, (b) Highly flooding, and (c) both drought and flooding-prone inland valleys.

SPEI: Standardized Precipitation Evapotranspiration Index; Clay content (g/(100g); IV SOC: Soil Organic Content (g/(100g); Sand content (g/(100g).

The Partial Dependence Plots (PDP) show how those key predictors influence the likelihood of a drought and flooding event (Figure 16).

In cases of drought (Figure 16.a), soil organic carbon content plays a complex role: the probability of drought initially decreases as carbon content increases up to around 1.5 but then rises beyond this level. For sand content, the likelihood of drought decreases with sand levels up to 40% but then climbs sharply beyond 60%, reaching an approximate probability of 0.38. Finally, the increase in the SPEI was associated with a decrease in the probability of drought. Regarding flooding occurrences (Figure 16.b), soil organic carbon content was positively linked to flooding probability, which increases sharply as organic carbon rises from 0 to 1.5, reaching a probability of around 0.5 before levelling off. Average annual rainfall also shows a positive effect: as rainfall rises above 86 mm, the probability of flooding increases exponentially by 0.11. Similarly, the SPEI index raises flooding probability as it moves from 0.0015 to 0.005, reflecting the impact of wet climate conditions on flooding vulnerability.

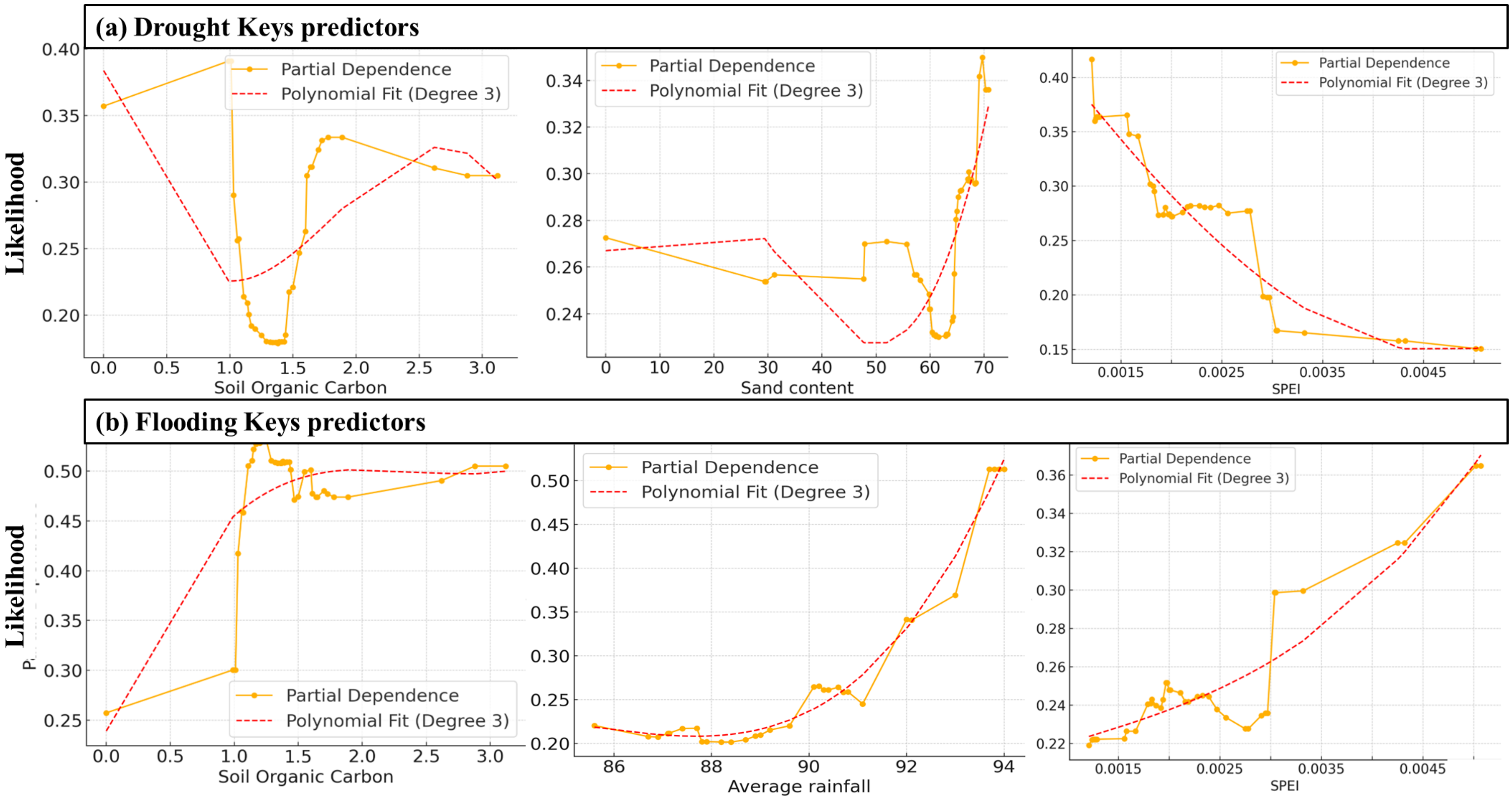

Figure 16. Partial dependence plots for the three key predictor variables selected from random forest predictions of the occurrence of (a) drought and (b) flooding.

4.1.3. Mitigation measures adopted by smallholder farmers and their determinants in face of climatic hazards

❖ **Mitigation measures adopted by smallholder farmers**

In response to increasing climatic drought and flooding hazards, smallholder farmers have adopted various mitigation measures, including adjusting cropping seasons, shifting cultivation to less exposed areas, and practicing agroforestry (planting *Eucalyptus torelianna* and *Acacia* species along the borders of inland valleys). Other strategies include using crop residues for moisture retention, adopting organic farming to reduce costs, and growing drought-resistant or flooding-adapted crop varieties. Farmers also employ irrigation systems, construct small bunds, and establish drainage channels to manage flooding. Some farmers consider wetland reconfiguration, while a few abandon herbaceous vegetation to reduce flooding impacts. The adoption rates of each measure in response to flooding and drought are illustrated in Figure 17. In response to flooding, most smallholder farmers opt to adjust the cropping season, change cultivation areas, and adopt agroforestry practices. To mitigate drought, the most frequently mentioned strategies include changing the cropping season, adopting organic farming practices, investing in irrigation infrastructure, and using drought-resistant crop varieties (Figure 17)

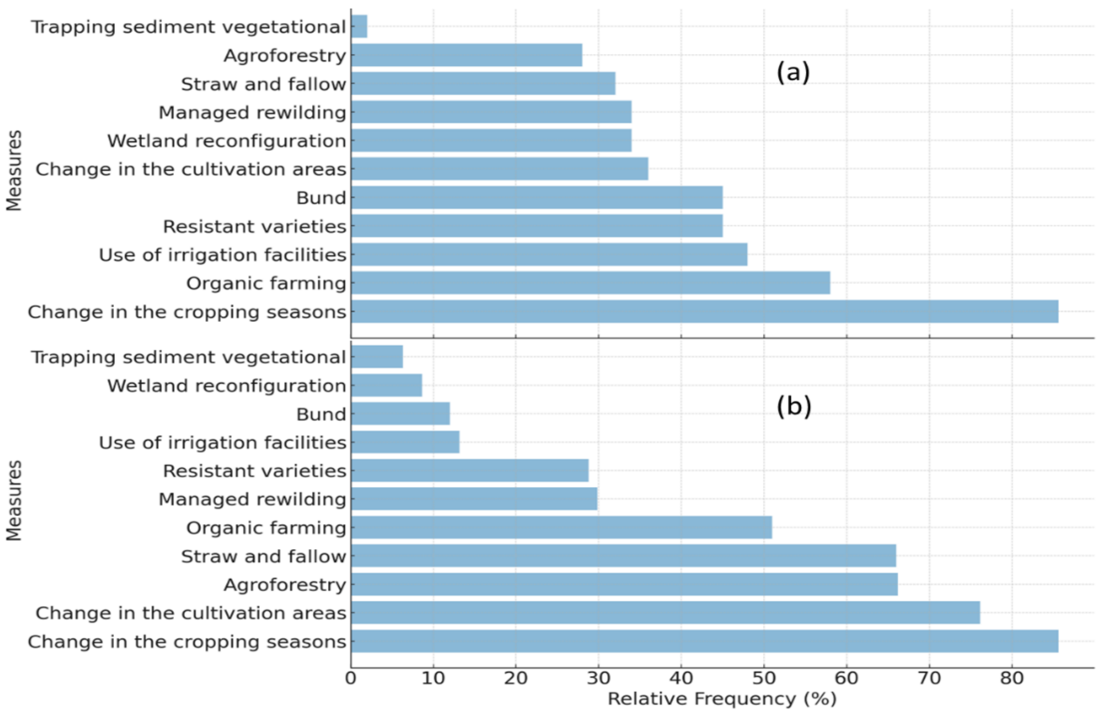

Figure 17. Relative importance of (a) drought and (b) flooding mitigation measures in the Inland valley studied

Additionally, the assessment of the frequency distribution of the number of mitigation measures generally combined by smallholder farmers in response to each hazard (Figure 18) reveals that smallholder farmers tend to combine between three and eight measures to cope with both flooding and droughts. Specifically, most smallholder farmers combine approximately six mitigation measures in response to flooding, whereas they predominantly combine four mitigation measures in response to drought.

The results of the principal component analysis (PCA) (Figure S6) reveal that the use of drought-resistant varieties, irrigation facilities, organic farming, and bund establishment exhibit strong associations and serve as major drought mitigation strategies, as indicated by their high loadings along the principal components. In addition to these four primary measures, there is a slightly weaker association with using sediment trapping approaches.

For flooding, mitigation strategies such as the construction of bunds, sediment trapping with vegetation, the use of flood-resistant crop varieties, irrigation facilities, wetlands reconfiguration and straw and fallow show good associations, indicating their significant roles as core strategies for flooding mitigation.

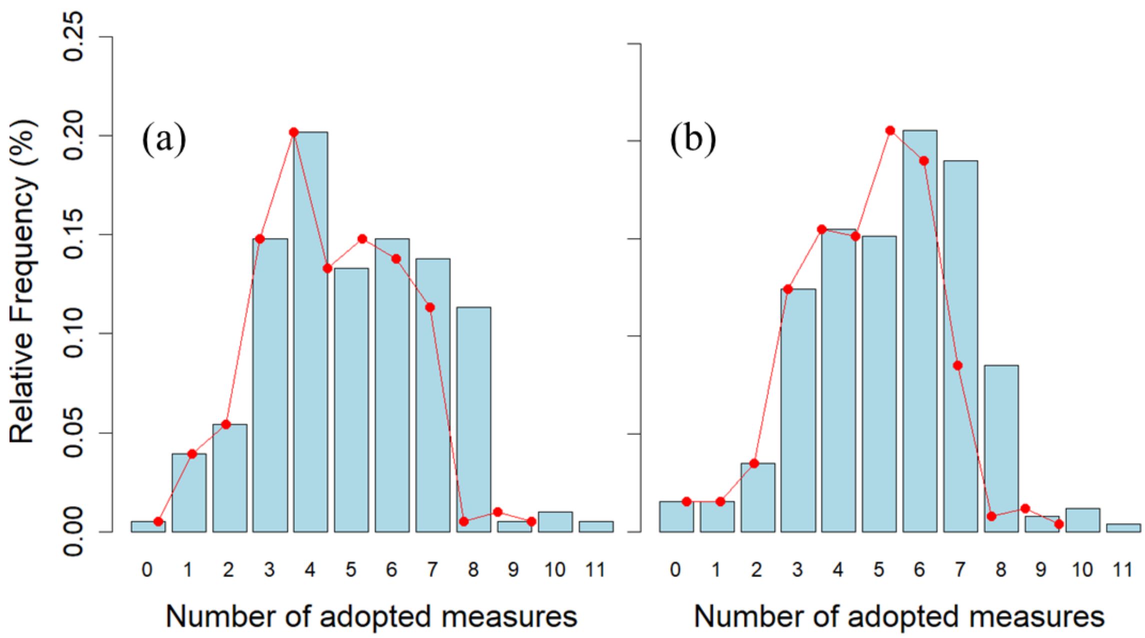

Figure 18. Relative frequency distribution of adopted number of mitigation measures for (a) Drought and (b) Flooding

❖ **Socio-economic determinants of mitigation strategies to drought and flooding**

The results of the Poisson regression model presented in Table 12 demonstrate how various socio-economic factors influence the number of mitigation measures adopted in response to flooding and drought.

The following factors emerged with regard to flooding mitigation measures. Land ownership was associated with an approximate 19.7% increase in the number of mitigation measures adopted (estimate = 0.18, p=0.02). Similarly, individual exploitation mode led to a substantial increase in the number of mitigation measures taken (estimate = 1.29, p=0.02). On the other hand, when the village collectively owns land, the number of adopted measures significantly decreases by 28.2% (estimate= -0.33, p=0.02). Additionally, obtaining support from extension services is associated with a 3% increase in the number of measures taken to mitigate flooding risks (estimate = 0.03, p=0.08).

The type of road leading to the market is particularly notable regarding drought mitigation measures. The findings indicate that areas accessible via asphalt roads or mixed-surface track (asphalt and dirt track) are associated with an increased number of mitigation measures. Specifically, the presence of mixed-surface track leads to an approximate 21% increase in measures taken (estimate = 0.19, p=0.05), while asphalt roads are associated with an increase of 31% (estimate = 0.27, p=0.05).

Moreover, as observed for flooding, village land ownership is linked to a 17% reduction in the number of measures adopted in response to droughts (estimate = -0.19, p=0.07) compared to familial land ownership.

Table 12. Poisson regression models on the socioeconomic determinants of farmers' decision to use a number of mitigation measures against (a) flooding and (b)drought occurring in their inland valleys.

	Flood	**Drought**
	Estimate (Std. Error)	*Estimate (Std. Error)*
Estimate	**0.55 (0.64)**	**1.12 (0.64)**
Distance to road	0.003 (0.01)	-0.002 (0.005)
Distance to market	0.002 (0.004)	-
Percentage of women in the Inland valley	0.01 (0.002)	-0.001 (0.002)
Road to the market: *Mixed-surface track*	0.05 (0.18)	**0.27 (0.14)***
Road to the market: *Dirt track*	0.03 (0.11)	0.17 (0.11)
Road to the market: *Asphalt Road*	0.04 (0.13)	**0.19 (0.13)***
Land ownership: *Individual owner*	**0.18 (0.12)****	-0.11 (0.08)
Land ownership: *State property*	-0.23 (0.28)	0.15 (0.24)
Land ownership: *Village property*	**-0.33 (0.14)****	**-0.19 (0.11)***

Origin of Inland valley users: *Native user*	0.01 (0.18)	0.09 (0.14)
Exploitation mode: *Individual user*	**1.29(0.58)****	0.54 (0.59)
Source of seeds and inputs: *In the village*	-0.07 (0.16)	**0.06 (0.15)***
Source of seeds and inputs: *<25 km from Inland valley*	-0.03 (0.16)	-0.06 (0.15)
Source of seeds and inputs: *>50 km from Inland valley*	-0.58 (0.45)	
Access to extension services	**0.03 (0.08)****	-0.01 (0.07)
Member of a farmer's organization	0.11 (0.07)	0.08 (0.06)
Role of crop farming in a production system: *Secondary Activity*	0.09 (0.39)	0.07 (0.18)
Distance to market (Km)		0.001 (0.004)
Model Evaluation Metrics	Pseudo R^2 = 0.92 Log-Likelihood = -380.01 AIC = 798.01 Deviance= -32.27	Pseudo R^2 = 0.93 Log-Likelihood = -241.23 AIC = 885.75 Deviance = -32.68

*AIC : Akaike Information Criterion ; Std. Error : Standard Errors ; IV : Inland valleys ; * Significant at 10% (p ≤ 0.1). ** Significant at 5% (p ≤ 0.05). *** Significant at 1% (p ≤ 0.01);*

The models included specified reference categories for categorical variables: 'No road' for road to the market, 'Familial' for land ownership, 'Migrant' for origin of IV users, 'Collective user' for exploitation mode, '25 to 50 Km' for the source of seeds and inputs, 'Main_activity' for the role of crop farming.

4.1.4. Impact of management approaches on the sustainability of inland valleys and agricultural productivity

❖ ***Soil moisture, temperature and hydric condition***

Soil moisture

The site ($p<0.001$), the management approaches adopted($p=0.02$), and the year ($p<0.001$) significantly influence soil moisture variation (Table 13). The sites of Ouinhi and Savalou recorded average soil moisture values of 43.85% and 34.00% in the volume of water, respectively (Table 14). Regarding the soil and water management approaches, the average moisture values were 40.66% for the Smart approach and 37.30% for the Undeveloped approach.

Analysis of the interactions between site and management ($p < 0.001$), site and fertilization level ($p < 0.001$), and management and fertilization level ($p < 0.001$) indicate significant effects on soil moisture across the experimental sites (Table 13). These results suggest that both site conditions and the applied management and fertilization strategies have a significant influence on soil moisture dynamics.

Table 13. P-value from the multinomial logistic regression model for soil dryness index and from the analysis of variance for soil moisture and soil temperature at 0 – 30 cm depth during the growing seasons (August-December 2022 and July-November 2023); nitrogen, phosphorus and potassium uptake (mg/kg) in harvested rice grains; rice grain yield for different water management, fertilizer application and rice varieties evaluated at two sites and for two years

Source of variation	Dryness *PR(>Chisq)*	Moisture *PR(>F)*	Temperature *PR(>F)*	N Uptake *PR(>F)*	P Uptake *PR(>F)*	K Uptake *PR(>F)*	Grain Yield *PR(>F)*	Anthesis *PR(>F)*
Site (S)	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.09	0.72	**0.02**
Management (M)	**<0.001**	0.92	0.10	**<0.001**	0.24	0.22	**<0.001**	**<0.001**
Fertilisation (F)	0.05	0.99	0.21	**0.002**	**<0.001**	**<0.001**	**0.003**	0.09
Variety (V)	**0.04**	0.99	0.99	**<0.001**	**0.02**	**0.03**	**<0.001**	**<0.001**
Year (Y)	**<0.001**	**<0.001**	**<0.001**	0.56	0.12	0.25	0.05	0.19
S x M	**<0.001**	**<0.001**	**0.03**	0.40	**0.04**	0.06	0.11	**<0.001**
S x F	0.60	**<0.001**	0.19	0.99	**<0.001**	0.29	0.92	0.07
M x F	0.62	**<0.001**	**0.03**	**<0.001**	**<0.001**	0.27	**<0.001**	0.64
S x V	**<0.001**	0.09	**<0.001**	**0.03**	0.32	0.20	**0.002**	**<0.001**
M x V	0.20	0.08	0.91	0.80	0.65	0.29	0.65	0.83
F x V	0.99	0.99	0.99	0.06	0.06	0.61	0.05	0.73
S x Y	**<0.001**	**<0.001**	**<0.001**	0.41	0.34	0.75	0.26	**<0.001**
M x Y	**<0.001**	**0.006**	**<0.001**	0.06	0.07	0.41	**<0.001**	0.50
F x Y	0.05	0.53	0.47	0.58	0.93	0.12	0.69	0.07
V x Y	**0.02**	0.99	0.69	0.35	0.26	0.72	**0.002**	0.11
S x M x F	-	**0.002**	0.59	0.54	0.51	0.57	0.76	0.10
S x M x V	-	**<0.001**	**0.003**	0.48	0.42	0.23	0.51	0.65
S x F x V	-	**<0.001**	0.15	0.48	0.42	0.51	0.33	0.92
M x F x V	0.33	0.52	0.90	0.69	0.44	0.63	0.49	0.98
S x M x Y	-	**<0.001**	**<0.001**	0.52	0.12	0.39	**0.04**	**<0.001**
S x F x Y	-	**0.02**	0.90	0.71	0.25	0.14	0.87	0.08
M x F x Y	0.79	0.56	0.92	0.72	0.89	**0.02**	0.85	0.56
S x V x Y	-	0.80	0.60	0.74	0.07	0.73	**0.002**	**<0.001**
M x V x Y	-	0.86	0.52	0.41	0.08	0.61	0.46	0.90
F x V x Y	-	**<0.001**	0.90	0.05	0.05	0.68	0.36	0.85

PR(>F): P value from the analysis of variance.

Table 14. Soil Moisture (%vol.) at 0-30 cm and Soil Temperature (°C) at 0-15 cm depth during the growing seasons (August-December 2022 and July-November 2023); Total Nitrogen, Phosphorus, and Potassium Uptake (kg/ha) and rice grain yield (t), across different treatments (Water management approaches, Fertilization application, and Rice Varieties).

	Moisture	Temperature	N Uptake	P Uptake	K Uptake	Grain Yield (t)	Days to Anthesis (number of day)
Site							
Site 1 : Ouinhi	43.85a	32.95a	214.17a	3.45a	8.40a	4.65a	69.8a
Site 2 : Savalou	34.00b	25.39b	178.20b	2.61bb	6.34a	4.60a	68.6a
LSD (main Site effect)	2.16	ns	17.36	0.27	2.37	0.25	1.47
Water management							
Smart-Valleys	40.66a	29.12a	226.22a	3.62a	9.25a	5.45a	68.0a
Undeveloped inland valley	37.30b	29.28b	166.14b	2.46a	5.49b	3.81b	70.5b
LSD (main Management effect)	12.34	ns	17.36	0.27	2.37	0.27	1.46
Fertilizer application							
No fertilizer (F0)	38.99a	29.19a	179.93b	2.89a	6.12a	4.32b	69.9a
Recommended fertilizer (F1)	39.16a	29.21a	204.34a	3.10a	7.57a	4.84a	69.1a
RiceAdvice recommendation (F2)	38.78a	29.20a	204.27a	3.10a	8.45a	4.71a	68.5a
LSD (main Fertilization effect)	20.05	ns	21.63	ns	ns	1.43	ns
Varieties							
Orylux 6	39.05a	29.10b	182.14b	2.81b	6.65ab	4.23c	61.5a
Nerica L19	38.65a	29.15b	192.83ab	3.06ab	5.91b	4.60b	69.8b
IR 841	26.24a	29.46a	213.58a	3.22a	9.55a	5.04a	76.3c
LSD (main Variety effect)	4.07	ns	21.26	0.33	2.91	0.30	1.09

Values followed by different letters (e.g., a, b, c) within the same column are significantly different at $p < 0.05$ *based on Tukey's HSD test LSD test.*

Figure 19 illustrates the evolution of soil moisture based on management approach and fertilization level, revealing that across both sites over the two-year period, soil moisture remains relatively high during the first 50 days after transplantation. However, after this initial period, a general downward trend in moisture is observed, with values falling below 20% across all sites by the end of the study period.

Furthermore, across both sites, the Smart management approaches combined with varying fertilization levels (SF2, SF1, SF0) as compared to the undeveloped approach showed an increase in soil moisture, highlighting the crucial role of the Smart approach in improving soil moisture management. These findings underscore the positive impact of this integrated management approach on moisture retention, suggesting its essential role in optimizing crop growth conditions.

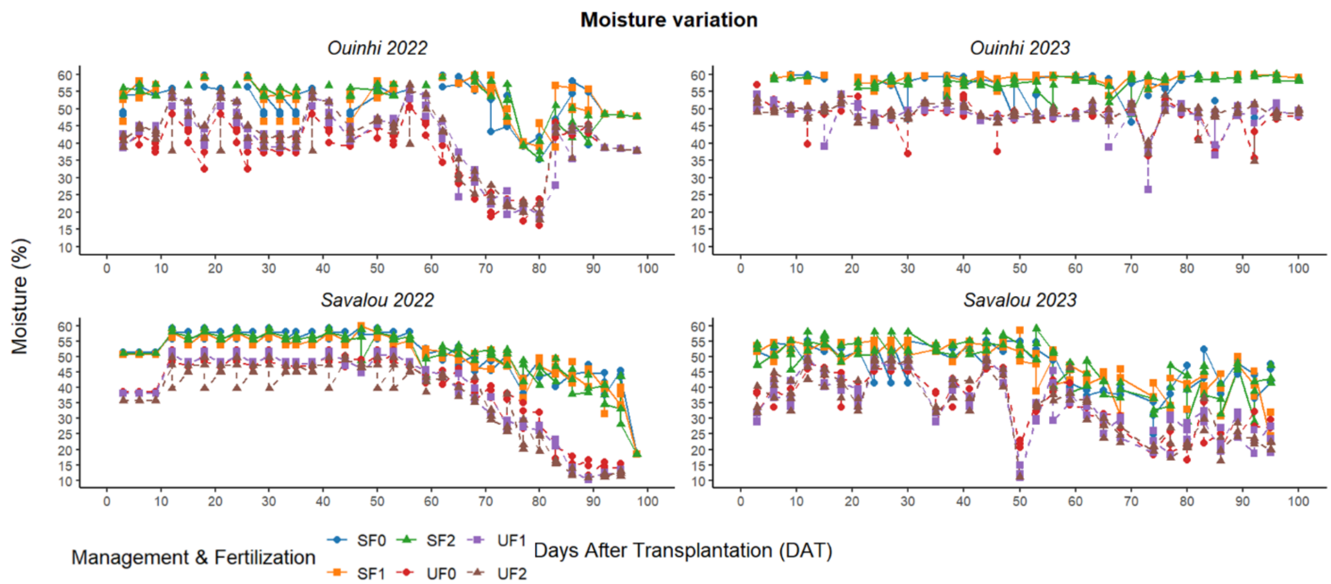

Figure 19. Effect of soil and water management approaches and fertilization level on soil moisture at two study sites (Ouinhi and Savalou) over two years of data collection (2022 and 2023).

<u>Soil temperature.</u>

Similarly, the variation in soil temperature is significantly influenced by the site and year (Table 2). The sites of Savalou and Ouinhi recorded average temperature values of approximately 32.95°C and 22.39°C, respectively (Table 12). In terms of soil and water management approaches, the average temperature values were approximately the same for both approaches (29.12 °C for the Smart approach and 29.28 °C for the Undeveloped approach) (Table 13).

The result of the analysis of the interactions between site and year ($p < 0.001$), management and year ($p < 0.001$), and site, management, and year ($p < 0.001$) indicate significant effects on soil temperature across the experimental sites (Table 12). These results indicate that the site and year conditions have a significant influence on soil temperature.

Figure 20, which shows the evolution of soil temperature based on management approach and fertilization level, reveals that the temperature remains below 37°C for the first site (Ouinhi) and below 30°C for the second site (Savalou) over the two-year period. Nevertheless, the temperature is relatively low in the smart approach compared to the undeveloped approach across both sites over the two-year period. These results highlight the positive impact of the Smart approach on soil temperature and, indirectly, its benefits for plant growth and development.

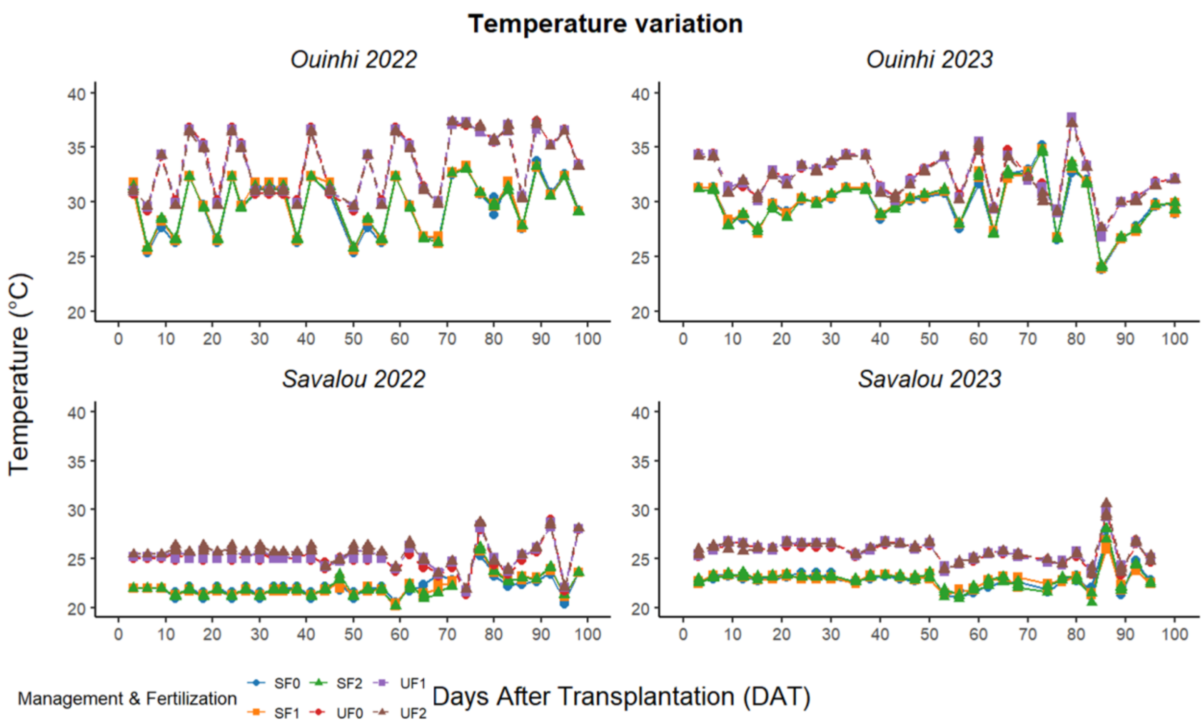

Figure 20. Effect of soil and water management approaches and fertilization level on soil temperature (0-30 cm) at two study sites (Ouinhi and Savalou) over two years of data collection (2022 and 2023).

Smart approach with no fertilization; SF1: Smart approach with the farmers' standard fertilization level; SF2: Smart approach with the fertilization recommended by RiceAdvice (F2); UF0: Undeveloped approach with no fertilization; UF1: Undeveloped approach with the farmers' standard fertilization level; UF2: Undeveloped approach with the fertilization recommended by RiceAdvice (F2).

Soil hydric condition

The hydric status is significantly influenced by the site ($p < 0.001$), management approach ($p < 0.001$), rice variety ($p = 0.04$), year ($p < 0.001$), as well as by the interactions between site and management ($p < 0.001$), site and variety ($p < 0.001$), site and year ($p < 0.001$), management and year ($p < 0.001$), and variety and year ($p = 0.02$) (see Table 12).

In Ouinhi in 2022, the smart approach demonstrated a high relative frequency of wet conditions for the IR841 variety (0.75) and Nerica L19 (0.50) starting from the initial days after transplanting (DAT), with a tendency to maintain these conditions until around 60 DAT (Figure 21). In contrast, the Undeveloped system exhibited a quicker transition to dry conditions, particularly for IR841 and Nerica L19 (0.75 dry conditions at 45-60 DAT). Wet conditions under the Undeveloped system were uncommon, with a relative frequency of 0.25 for IR841, primarily observed before 30 days after treatment (DAT) (Figure 21). In 2023, the smart management approach maintained predominantly stagnant water conditions for IR841 (0.75) and Nerica L19 (0.50) up to 60 DAT, slightly shifting towards wet conditions following this period. The undeveloped system displayed wet conditions during the production period.

In Savalou in 2022, the smart management approach favoured stagnant water conditions for IR841 (0.75), Nerica L19 (0.75), and Orylux 6 (0.75) up to 40 DAT, demonstrating remarkable stability during the early growth stages, followed by a transition primarily to wet conditions for the remainder of the production period (Figure 21). Dry periods of approximately 0.5 were also noted during the final days of production (DAT > 79). In contrast, the undeveloped management approach transitioned from wet to dry conditions after 79 DAT for all varieties. In 2023, the Smart system maintained 100% wet conditions for IR841, Nerica L19, and Orylux 6 (0.75) up to 79 DAT, with a slight reduction in wet conditions thereafter. The undeveloped management exhibited dry conditions following this period for all varieties. Under the undeveloped management, water conditions were wet (0.60) for all three varieties during the first 79 DAT, transitioning to dry periods thereafter.

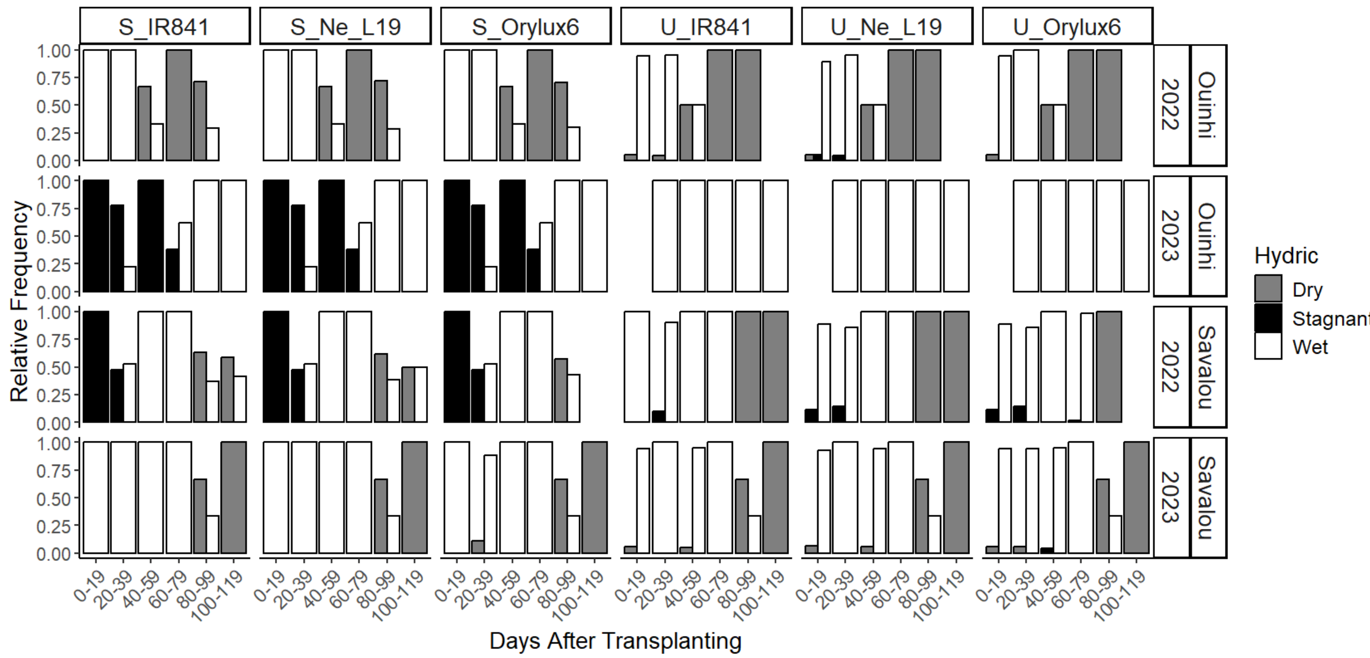

Figure 21. Effect of land and water management systems (S: Smart, U: Undeveloped) and rice varieties (Ne_L19: Nerica L19, Orylux 6, and IR841) on soil hydric conditions (wet, stagnant, and dry) at two study sites (Ouinhi and Savalou) over two experimental years (2022, 2023) as a function of days after transplanting.

<u>*Number of days to Anthesis*</u>

Days to anthesis varied significantly depending on the site ($p = 0.02$), rice variety, management approach ($p < 0.001$), and interactions among site and management ($p < 0.001$), site and variety ($p < 0.001$), site and year, as well as site, management, and year; and site, variety, and year ($p < 0.001$) (Table 12). Figure 23 illustrates that smart valley management consistently resulted in fewer days to anthesis compared to undeveloped valleys across both sites. Notably, in 2022 at the Ouinhi site, smart valleys showed a non-significantly higher day to anthesis. On average, the days to anthesis were 68 days for Smart Valleys and 70.5 days for undeveloped valleys. The average number of days to anthesis at the Savalou site is 68.6, compared to 69.8 for the Ouinhi site. Additionally, the average days to anthesis varied by variety: 61.5 days for Orylux 6, 69.8 days for Nerica L19, and 76.3 days for IR 841 (Table 13). Further analysis using a Poisson regression model revealed that rice plants typically reached anthesis in approximately 64 days under baseline conditions (Table 14). However, this timing was influenced by several factors. For example, plants in Savalou reached anthesis 11% faster (Est = -0.11, $p < 0.001$) than those in Ouinhi. Undeveloped management practices delayed anthesis by 4% compared to smart management. Fertiliser application did not significantly affect the timing, but the choice of rice variety did: IR 841 took 23% longer, and Nerica L19 took 14% longer compared to Orylux 6 (Table 14). These findings highlight the significance of site selection, management practices, and varietal choice in optimizing the timing of anthesis, a crucial factor in enhancing rice crop performance.

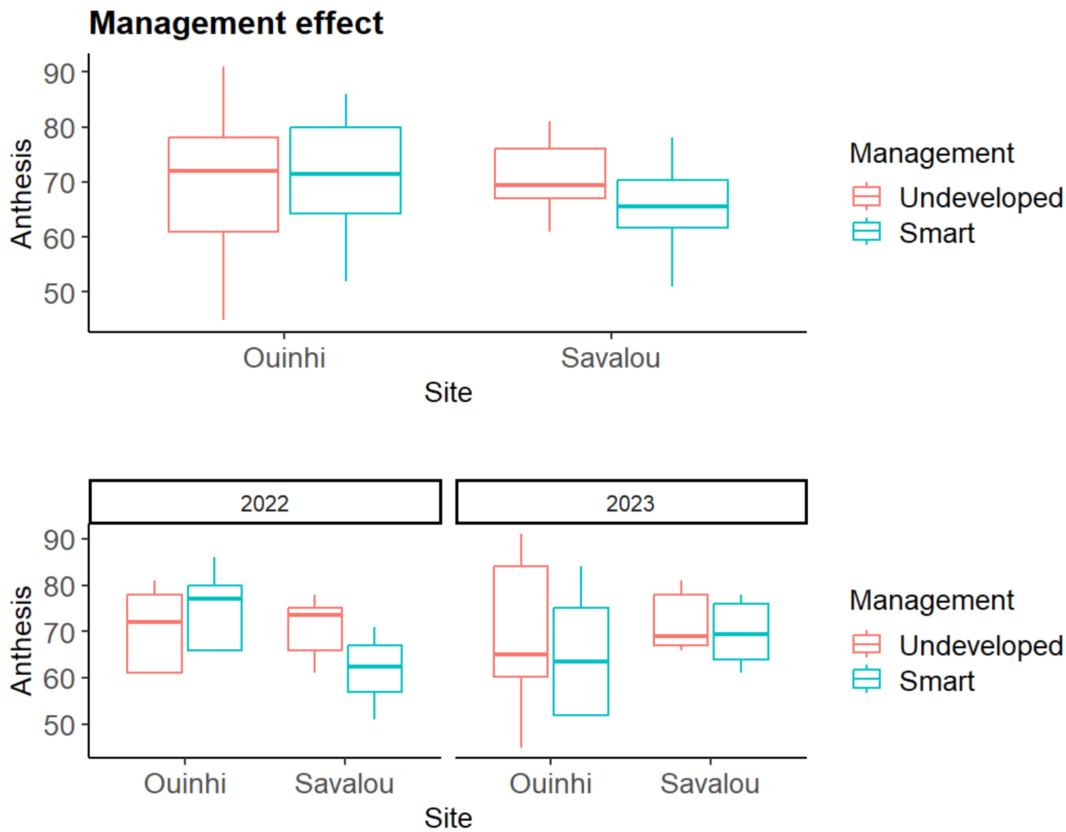

Figure 22. Impact of management approaches (Smart valley and Undeveloped valley) on days to Anthesis at Ouinhi and Savalou sites during 2022 and 2023

<u>*Rice grain yield productivity*</u>

Grain yield varies significantly depending on management practices ($p < 0.001$), fertilization level ($p = 0.003$), and rice variety ($p < 0.001$), as well as interactions between management and fertilization and between site and variety (Table 12). The average grain yield under the Smart approach is 5.45 t/ha, compared to 3.81 t/ha under the Undeveloped approach. The adoption of fertilization level F2 increases rice yield by 0.52 t/ha compared to no fertilization, while the adoption of F1 results in a yield increase of 0.32 t/ha relative to the zero-fertilization level. The average grain yields for the rice varieties Orylux 6, Nerica L19, and IR841 are 4.23 t/ha, 4.60 t/ha, and 5.04 t/ha, respectively (Table 13).

Figure 24 illustrates the effects of the same management approaches on grain yield for the three rice varieties. Across both sites, the Smart approach with recommended fertilization (SF2) achieved the highest grain yields, with increases of up to 30% compared to the Undeveloped approach without fertilization (UF0) at each site. For example, for the IR841 variety, the yield under SF2 was 5.2 t/ha, compared to approximately 3.0 t/ha under UF0 at Savalou. The Smart approach with standard farmer fertilization (SF1) also demonstrated higher yields than the Undeveloped approach, although slightly lower than SF2. In contrast, the Undeveloped approach with recommended fertilization (UF2) showed lower yields than SF2.

These results highlight the variations in grain yield based on management practices, fertilization levels, and rice varieties, as well as the interactions between these factors.

Furthermore, the generalised linear model reveals that the undeveloped management system significantly reduced yield by -0.37 t/ha ($p < 0.001$). Fertilization levels F1 and F2 showed slight but significant increases in yield, with increments of 0.04 t/ha and 0.06 t/ha, respectively ($p < 0.05$). Additionally, the IR 841 and Nerica L19 varieties demonstrated significant yield improvements, with increases of 0.17 t/ha ($p < 0.001$) and 0.08 t/ha ($p < 0.05$), respectively (Table 14).

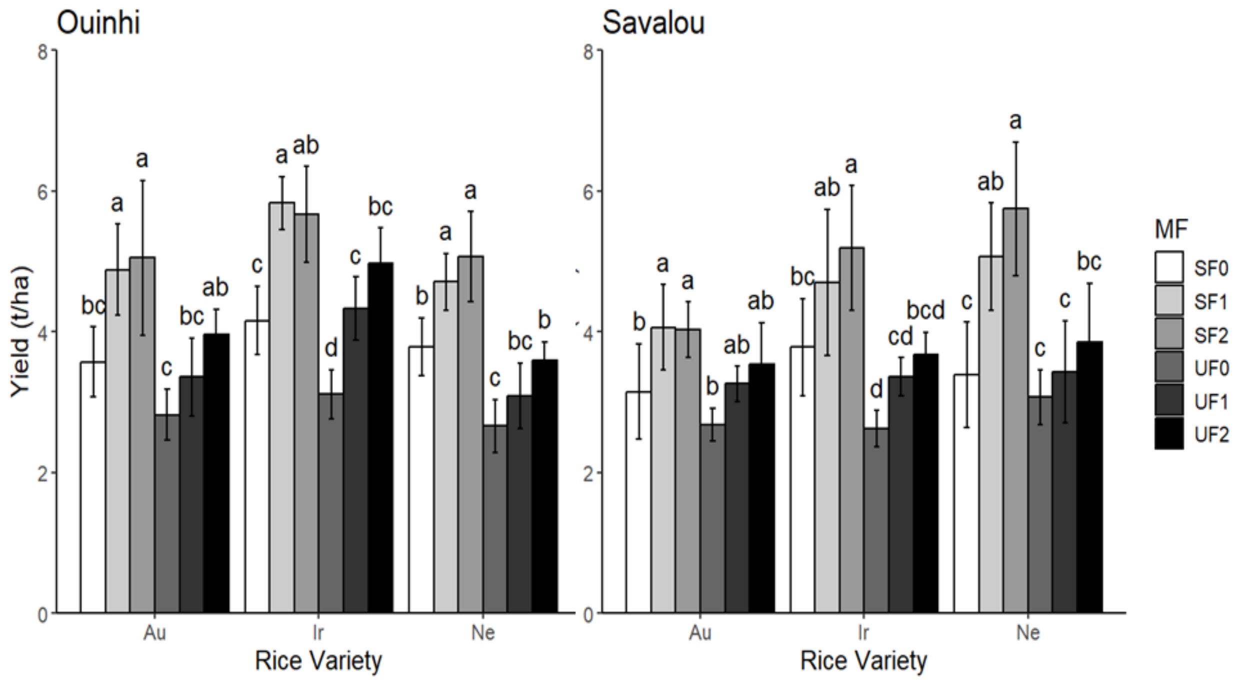

Figure 23. Effects of two soil and water management approaches combined with three fertilization levels on grain yield of three rice varieties (Orylux 6 - Au, IR841 - Ir, Nerica L19 - Ne) at the experimental sites of Savalou and Ouinhi.

SF0: Smart approach with no fertilization; SF1: Smart approach with the farmers' standard fertilization level; SF2: Smart approach with the fertilization recommended by RiceAdvice (F2); UF0: Undeveloped approach with no fertilization; UF1: Undeveloped approach with the farmers' standard fertilization level; UF2: Undeveloped approach with the fertilization recommended by RiceAdvice (F2).

❖ Nutrient uptake of grains and Agronomic efficiency of nitrogen

<u>*Nutrient uptake in rice grains*</u>

Nitrogen uptake in rice grain is significantly influenced by site ($p < 0.001$), management practices ($p < 0.001$), fertilization levels ($p = 0.02$), rice variety ($p < 0.001$) and interactions such as fertilization × management ($p < 0.001$) and site and variety ($p = 0.03$) (Table 2).

The nitrogen uptake is higher at the Ouinhi site (214.17 kg/ha) than at the Savalou site (178.20 Kg/ha), with the smart approach yielding a higher nitrogen uptake (226.22 Kg/ha) than the undeveloped approach (166.14 Kg/ha). Fertilization levels F2 and F1 show the highest nitrogen uptake compared to F0 application (Table 3). Among rice varieties, IR841 exhibits the highest nitrogen uptake (213.58 Kg/ha).

Figure 24a illustrates the effect of the interaction between water management approach and fertilization level on nitrogen (N) uptake in rice varieties. Analysis reveals that the Smart Valley approach, when combined with different fertilization levels, results in significantly higher N uptake concentrations than the Undeveloped Valley approach under the same fertilization conditions. Furthermore, no significant variation in N uptake capacity was observed among the different combinations of the Undeveloped Valley approach and fertilization levels. Notably, the highest N uptake concentration was recorded with the combination of fertilization level F2 and the Smart Valley approach.

Figure 24b demonstrates the interaction effect between site and rice variety on N uptake variation. The results indicate that, across all site-variety interactions, the Ouinhi site consistently exhibited the highest N uptake values. Overall, combining the Ouinhi site with the IR 841 variety yielded the highest recorded N uptake, highlighting the significant influence of site-specific conditions on nitrogen assimilation in rice.

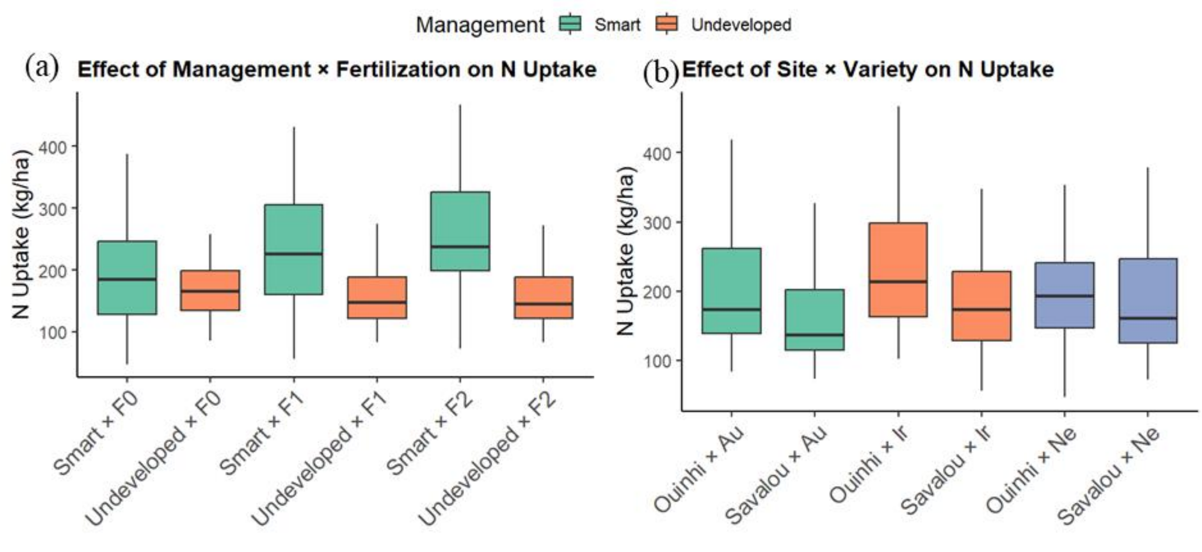

Figure 24. (a)Effect of the interaction between water management approach and fertilization level; and (b) the interaction between site and rice variety on N uptake.

Similarly, phosphorus uptake is significantly affected by site ($p < 0.001$), by fertilization ($p<0.001$), by variety ($p=0.02$) and by interactions like site × fertilization, management × fertilization ($p <0.001$) and management × Site ($p<0.001$). Phosphorus uptake is greater at Ouinhi (3.45 Kg/ha) than at Savalou (2.61 kg/ha). Furthermore, Phosphorus uptake exhibits the highest value with IR841 (3.22 Kg/ha).

Figure 25a illustrates the effects of water management and fertilization interactions on phosphorus (P) uptake in rice cultivation. The analysis reveals that the Smart management approach consistently yields higher P uptake across all fertilization levels (F0–F3) compared to the Undeveloped system (F0–F2). Notably, the combination of Smart management with fertilization level F2 results in the highest P uptake among all treatments, highlighting its agronomic efficiency. Figure 25b demonstrates the interaction between site and fertilization on P uptake. The results show that the Ouinhi site consistently achieves the highest P uptake across all fertilization levels (F0–F2) compared to the Savalou site. Furthermore, the Ouinhi site with fertilization level F2 produces the highest recorded P uptake, emphasizing the site-specific benefits of optimal fertilization.

Figure 25c examines the interaction between site and water management approach on P uptake. The results indicate that the Ouinhi site combined with the Smart approach yields the highest P uptake, followed by the Savalou site paired with the Smart system. This suggests that while water management plays a crucial role, site characteristics also significantly influence phosphorus assimilation in rice.

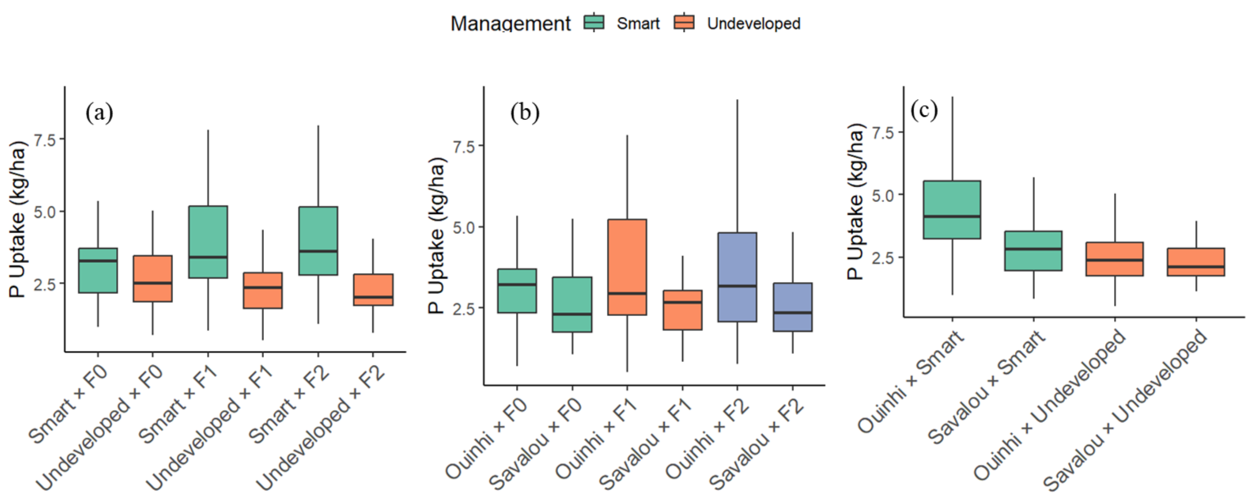

Figure 25. Effect of (a) water management and fertilization level, (b) site and fertilization, and (c) site and water management on P uptake of rice varieties.

Potassium uptake is influenced by fertilization ($p < 0.001$), variety ($p= 0.03$) and interactions such as management × fertilization × year ($p = 0.02$). Potassium uptake varies significantly among rice varieties; Orylux 6 has the highest potassium uptake (1919.63 mg/kg), followed by IR841 (1569.02 mg/kg) and Nerica L19 (1292.77 mg/kg).

Figure 26 shows that in both years (2022 and 2023), the smart approach recorded the highest K uptake value at each fertilization level. In particular, in 2022, the smart valley approach combined with the F2 fertilization level achieved the highest K uptake value, while in 2023, the smart valley approach combined with both the F2 and F1 fertilization levels recorded the highest K uptake values.

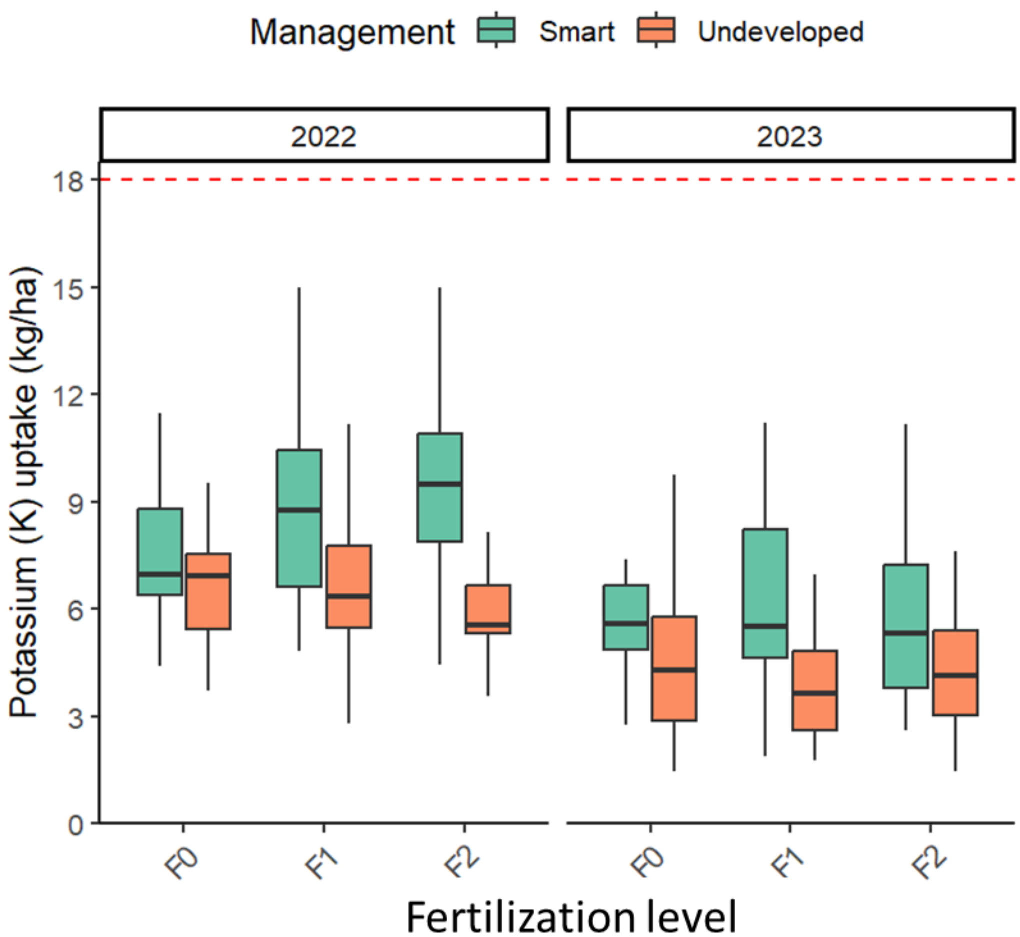

Figure 26. Effect of the interaction of water management, fertilization level and year on Potassium uptake

<u>*Agronomic efficiency of nitrogen*</u>

Figure 27 illustrates the agronomic efficiency of nitrogen for two nitrogen fertilization levels (F1 and F2) applied to three rice varieties under two soil and water management approaches at the Ouinhi and Savalou sites.

At the Ouinhi site, the Smart approach with the F2 fertilization level (SF2) shows significantly higher agronomic efficiency for the IR841 variety (Ir) compared to the Undeveloped approach without fertilization (UF0). For instance, the agronomic efficiency of SF2 for IR841 is approximately 20% greater than that of UF0. Similarly, for Orylux6, SF2 improves agronomic efficiency by 15% compared to UF0. In contrast, the Undeveloped approach with recommended fertilization (UF2) exhibits lower values than SF2, although still higher than UF0, highlighting the importance of integrated soil and water management.

At the Savalou site, similar trends are observed, with the Smart approach (SF2) achieving the highest agronomic efficiency values across all varieties. For example, the agronomic efficiency for Nerica L19 under SF2 is approximately 25% higher than under UF0 (Table 13). However, the differences between the Smart and Undeveloped approaches are less pronounced at Savalou compared to Ouinhi, likely due to site-specific pedoclimatic conditions.

Figure 25 illustrates that the Smart valleys approach, combined with optimized fertilization (F2), significantly enhances nitrogen agronomic efficiency compared to the Undeveloped approach, particularly for the IR841 and Orylux 6 varieties. These findings underscore the vital role of integrated resource management in improving nitrogen use efficiency in rice production.

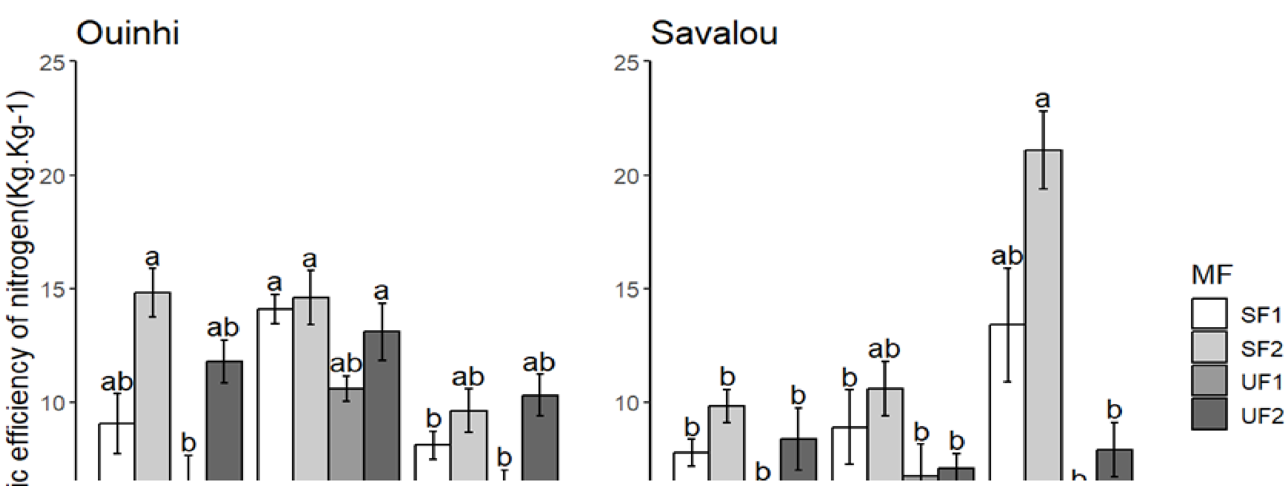

Figure 27. Agronomic efficiency of two nitrogen levels (116 kg. ha-1 for F1 and 147.6 kg.ha-1 for F2 for the IR841 variety (Ir), and 114.1 kg.ha-1 for F2 for the Orylux6 (Au) and Nerica L19 (Ne) varieties) under two soil and water management approaches (Smart (S) and Undeveloped (U)) at the experimental sites of Savalou and Ouinhi. Means with the same lowercase letter across treatments within each figure are not significantly different at p ≤ 0.05 according to the least significant difference test. The error bars represent the standard error.

4.2. Discussion

4.2.1. State of ecosystem services provided by inland valleys in relation to management approaches.

- **Characteristics of the farm households and farmers' water management practices**

Smallholder farmer population is dominated by low-income men, who predominantly did not use any water management practice in their inland valleys. Indeed, in the Inland Valley exploited in Benin, women have limited access to land resources, which could justify their low representation among smallholder farmers in the study area. This situation regarding women's rights to land was reported by Rodenburg et al. (2014), who also found that women farmers are predominantly confronted with land tenure issues. This situation reduces their ability to adopt some developed-valley approach (smart-valley and bund-valley), given their fear of having their land taken away at any time. This social disparity should be taken into account when designing agricultural development policies and projects. Furthermore, the low incomes observed among the majority of smallholder farmers could be justified by the low level of economic diversification observed in these areas. Indeed, the majority of these farmers are almost dependent on Inland valley for farming and meeting their daily needs. While the smart-valley approach enhanced water control, it was still not widely adopted by farmers. Only 15% of the farmers surveyed adopted the smart-valley approach, which could be explained by factors such as land tenure rights, strengthening farmers' capacity, availability of power tiller for land preparation and fertilizer, and higher paddy market price as reported in previous studies (Arouna and Akpa, 2019; Dossou-Yovo et al., 2022).

Further, gender, age, education level, main activity, and annual income influenced the importance attributed to ES. For several authors, the socio-economic characteristics of respondents, such as age, income, gender, and activity, are determinants of the value placed on ES (Githiora-Murimi et al. 2022; Gnansounou et al. 2022; Mathys et al. 2023). According to Liu et al. (2024), the capacities available to farmers determine their well-being and directly influence their degree of ES perception. Specifically, women attached greater importance to provisioning services. This result aligns with the observation made by Githiora-Murimi et al. (2022) who highlight a difference between the degree of importance given by women. This difference could be justified by the different roles played by women and men in agricultural practices and the collection of products (water, food) in these ecosystems. The results also highlight the influence of smallholder farmers' income on the importance attached to ES. Indeed, smallholder farmers often depend on products obtained from these ecosystems to supplement their income, and this could influence the importance attached to this service. According to Yapi et al. (2023), low and middle-income rural populations depend essentially on natural resources and ecosystem goods and services to support their families.

- **Ecosystem services and their importance**

Understanding the perceived importance placed on ecosystem services by smallholder farmers is essential for enhancing their well-being and livelihoods. This study revealed that provisioning and regulating services are overall perceived as more important to smallholder farmers than supporting and cultural services. This is consistent with observations in previous studies that investigated the perceptions of ecosystem services (Alemayehu et al., 2022; Gnansounou et al., 2022; Mensah et al., 2017; Rodenburg et al., 2014). According to Mensah et al. (2017), rural populations value-provisioning services probably because of their closer connections to these ecosystems, as they represent tangible and marketable benefits derived from nature. In the context of this study, this importance could also be justified by smallholder farmers' dependence on Inland valley for the development of their daily activities. Indeed, Inland valley are the last resort for smallholder farmers in this changing climatic context, for more resilient agricultural production. According to several authors, Inland valleys are potential agricultural ecosystems for smallholder farmers and are considered to be the food baskets of Africa (Djagba et al., 2019; Dossou-Yovo et al., 2017; Rodenburg et al., 2014).

Findings from this study also showed that provisioning, regulation, and supporting services are more important for smallholder farmers adopting smart-valley approaches compared to other management approaches, including bund-valley and undeveloped-valley. These results support the intended objective of implementing these approaches and align with the observations of many authors (Arouna & Akpa, 2019; Rodenburg et al., 2014). The Smart Valley approach was originally initiated to increase agricultural yields and the incomes of smallholder farmers (Djagba et al., 2018; Dossou-Yovo & Futakuchi, 2023). This interest in provisioning services by smallholder farmers adopting the smart-valley approach could be justified by the increased agricultural yields they derive from Inland valley when the approach is adopted. Smallholder farmers also emphasized the benefits of this approach for food and water. According to Arouna and Akpa (2019), adopting the smart-valley approach increases rice yields by 0.9 t/ha and income by 267 USD/ha. However, the high importance attributed to the regulation ES reveals people's awareness on the water and flood management capacities of these Inland valley and the adopted approaches. However, for the majority of smallholder farmers who adopted the smart-valley approach, regulating services were important, due to their ability to regulate water flow. Regulation services are largely part of the objectives set when developing the smart-valley approach, in that they ensure, according to several authors, proper water management (AfricaRice, 2015; Djagba et al., 2019). In addition, the relatively high importance given to provisioning services in bund-valley as compared to the undeveloped-valley can be linked to the easiness of smallholder farmers to obtain water from this Inland valley, given the water pipe structures being developed. According to (Senthilkumar et al., 2018), ridging or leveling techniques are some of the key procedures adopted by smallholder farmers in Tanzania to increase their agricultural yields. In contrast, cultural services received higher ranks in undeveloped-valley. This observation highlights the interest of these zones for scientific research and the conservation of endogenous divinities. This observation is in line with several authors who highlight the neglect of cultural ES during Inland valley development management measures (Bouwma et al., 2018; Eastwood et al., 2016; Hornung et al., 2019). For Hornung et al. (2019), the low consideration of cultural services by development approaches constitutes a weakness in inland valley development. Moreover, the presence of deities at these sites could also be a reason for their non-development for agricultural purposes. According to Gnansounou et al. (2024), the presence of deities in certain ecosystems is also a means of mitigating anthropic pressure on them, conserving biodiversity, and stimulating research interest.

- ❖ **Perceived threats to Inland valley sustainability**

The threats to the sustainability of Inland valley identified are diverse and vary according to management approaches. Mainly, the study highlights the use of chemical pesticides, mineral fertilizers, hydrological constraints including drought and flood, and sedimentation as the major threats to Inland valley sustainability. High chemical and pesticide use highlighted by smallholder farmers has been the subject of several research studies which have reported the negative impact of high inorganic fertilizer and pesticide use in Inland valley, calling for greater awareness of appropriate fertilizer use in these environments (Haefele et al., 2022; Rodenburg & Saito, 2022; Senthilkumar, 2022). Given that, these Inland valley are congested for agricultural production (rice in our case) the excessive and uncontrolled use of fertilizers constitutes a threat that impoverishes the soil and leads to soil toxicity (Rodenburg & Saito, 2022). Smallholder farmers' ardent desire to increase agricultural yields may justify the use of high chemical fertilizers, which threaten the sustainability of this ecosystem. (Asai et al., 2021) have shown that the application of inorganic fertilizers such as nitrogen in these Inland valleys should take into account the soil fertility status and the crop demand, to avoid the risk of overuse and subsequent degradation of provisioning, regulating and supporting services. Excessive use of inorganic fertilizers not only reduces the quality of agricultural soil, but also pollutes water resources used by the local community and dependent biological resources. According to the Ramsar Convention (2016) and other authors, these freshwater wetlands are highly vulnerable to the runoff of chemical pollutants and pesticides, which impact the biological life present (Canning et al., 2023; Rodenburg & Saito, 2022; Ramsar, 2016). Smallholder farmers adopting the undeveloped-valley approach have predominantly reported the imminent threats posed by hydrological constraints, specifically seasonal variability in rainfall, which sometimes leads to inland valleys drying up or flooding unexpectedly. This observation is not surprising, given that water channeling and regulation infrastructures are almost non-existent on un-developed Inland valleys. Thus, in this changing climatic context, these sites are vulnerable to frequent drying out or flooding. According to (Bonou et al., (2018), these environments have experienced several flooding occurrences during the last years, including four major ones over the past two decades, which have resulted in significant agricultural losses for smallholder farmers. In 2008, most of the Inland valley of sub sub-Saharan Africa were affected by drought that caused farmers to lose almost 29% of their agricultural production (Dossou-Yovo et al., 2019). This demonstrates the considerable impact of drought and flooding in these areas, and particularly in the undeveloped Inland valley. In contrast to the other approaches, at the smart-valley sites, some smallholder farmers reported a threat from sedimentation caused by the collapse of dykes. This threat could be due to the low level of regular maintenance carried out on these systems. However, the clogging up of valley bottoms due to the dykes created is a potential threat to the sustainability of this habitat of interest. Furthermore, previous studies reported that agriculture in the Inland valley is the origin of clogging of the valleys with sediments, pollution by nitrates, phosphates and pesticides, and should be considered (Djagba et al., 2019; Mengistie et al., 2017). It was noted the ranks of the cultural ES were relatively lower in Smart-Valley compared to other water management technologies, which implies that the design and implementation of the smart-valley approach need to account for the cultural ES provided by inland valleys.

4.2.2. Vulnerability of inland valleys to climatic hazards and predictors of hazard occurrence.

❖ **Spatio-temporal trends of drought and flooding in inland valleys**

The temporal analysis of drought occurrence, based on SPEI values, revealed that the years 2001 and 2016 were marked by extreme drought conditions across all sites studied. These findings are consistent with observations made by (Henchiri et al., (2020) and; Kasei et al., (2010), who noted that 2001, 2002, and 2016 were particularly dry years in West Africa. Specifically, Kasei et al. (2010) reported that the 2001 drought had a relatively high impact. In contrast, the years 2008, 2009, and 2019 were characterized by significantly wetter conditions, as documented in previous studies, primarily due to the heavy rainfall observed during these periods (Badou et al., 2021; Dossoumou et al., 2023). Dossoumou et al. (2023) classified these years among those that experienced extreme flooding, affecting over 57% of the country's communes. These flooding occurrences had significant repercussions, severely limiting agricultural production systems in the inland valleys, leading to the displacement of numerous agricultural producers and an increase in the vulnerability of rural communities (Bonou et al., 2024; Danvi et al., 2018). Spatial analysis indicated that the inland valleys of southern Benin (Ouinhi, Zogbodomey, and Zangnanado) are more exposed to flooding hazards, while those in the central regions (Savalou) are more vulnerable to drought, suggesting that geographical and climatic factors play a key role in the occurrence and severity of drought and flooding as previously reported by Mansour (2024). Similarly, Hounkpè et al. (2022)) showed that areas in the Zou region, characterized by high precipitation, are particularly susceptible to flooding. This increased flooding vulnerability in the Zou department contrasts with the less humid conditions in central regions such as Savalou. Moreover, the rising flooding hazards in southern Benin may also be attributed to the proximity of these areas to the sea, as suggested Dossou-Yovo et al. (2019) and Mohino et al. (2011). These findings underscore the urgent need to develop targeted strategies, such as enhancing water management infrastructure and raising community awareness in flood-prone southern regions while improving water management approaches and promoting resilient agricultural practices in drought-prone central areas.

❖ **Determinants of flooding and drought occurrence**

The study findings emphasize that three key parameters: soil organic carbon (SOC), SPEI and sand content are critical in determining drought occurrence and severity. These results align with previous studies (Wang et al., 2024; Beillouin et al. 2023; Page et al., 2022; Dossou-Yovo et al., 2019) . Soil organic carbon plays a crucial role in regulating soil response during drought events (Wang et al., 2024; Page et al., 2022; Dossou-Yovo et al., 2019). In general, soils with higher SOC content have better water retention capacity, which can mitigate the occurrence and severity of drought (Beillouin et al., 2023). Additionally, low SOC content exacerbates the effects of drought by reducing soil water retention capacity and accelerating organic matter decomposition upon rewetting, which could explain the relatively high likelihood of drought occurrence when soil organic carbon is low.

The soil sand content is another key factor affecting drought occurrence in Inland valley. Soils with high sand content exhibit low water retention capacity and high percolation and are more prone to drought. This observation is consistent with findings from Fenner and Freeman, (2020) and Yu et al. (2023), who reported that sandy soils are more prone to drought due to their coarse structure and limited water-holding capacity (Yu et al. (2023).

Research by Dal Monte et al. (2024) highlights the importance of the SPEI in capturing the interplay between precipitation deficits and increased evapotranspiration rates, which are critical components in the onset of drought. When considering flooding event, precipitation, SPEI and soil texture were identified as key factors. The SPEI integrates evapotranspiration, temperature, and water balance, making it an ideal indicator for explaining flooding trends, particularly when compared to precipitation data alone (Dal Monte et al., (2024). An increase in the SPEI indicates a wetter climate, reflecting a surplus of water in the region, which can lead to flooding, particularly in areas with poor drainage like inland valleys. Conversely, lower SPEI values signal drier conditions and reduced flooding risk, which may contribute to explaining the positive relationship between an increase in the SPEI index and the likelihood of flooding occurrence and severity.

4.2.3. Mitigation measures adopted by smallholder farmers and their determinants in face of climatic hazards

- **Mitigation measures used by farmers to respond to flooding and drought**

The results indicate that smallholder farmers adopt specific measures based on the type of climatic hazards they face. In response to flooding, they often modify cropping seasons and cultivation zones, whereas for drought, they lean toward irrigation practices and drought-resistant crop varieties. These practices have been widely documented in previous studies emphasizing smallholder farmers' reliance on these approaches due to socio-economic constraints, such as limited financial resources (Alemayehu et al., 2022; Dossou-Yovo et al., 2019; Gezie, 2019).

Although farmers adjust their cropping seasons by planting following early rains during drought or immediately after flooding, many report substantial yield losses due to limited knowledge of an effective agricultural calendar and effective flood-resistant variety. Research by (Lakitan et al., 2018) in Indonesia highlights that well-informed wetland farmers adjust their cultivation periods to avoid peak flooding or intense drought seasons. However, the successful implementation of this approach may require access to updated climate hazard predictions and localized cropping calendars.

The use of crop varieties tailored to specific climatic hazards (case of drought) has emerged as a significant strategy for mitigating the effects of drought. Dossou-Yovo et al. (2019) report that smallholder farmers in the Sudan-Sahel zone adopt short-duration, drought-resistant varieties in response to drought conditions. Similarly, in West Africa, in the absence of flood-resistant varieties, farmers turn to short-duration crops. Although significant progress has been made in developing flood-resistant rice varieties by institutions like AfricaRice, their accessibility to farmers remains limited, requiring their large-scale dissemination.

The study further reveals that some smallholder farmers adopt multiple mitigation measures, ranging from three to eight strategies, to address drought or flooding hazards. These integrated approaches include the use of drought-resistant crop varieties, irrigation infrastructure, and conservation techniques such as sediment trapping and bund construction and play a central role in enhancing farmers' capacity to mitigate climatic hazards, even with limited resources like previously reported in (Below et al., 2010; Cherinet et al., 2022).

Effective water management through irrigation and drainage systems, coupled with the use of resistant crop varieties, ensures a steady water supply and maintains agricultural productivity during periods of hydrological stress. These measures are essential for sustaining crop yields and securing food production in the face of climatic challenges.

- **Drivers of Smallholder Farmers' Adoption of Multiple Measures to mitigate Drought and Flooding**

Adopting multiple mitigation measures against droughts and flooding is primarily driven by factors such as access to input markets, land ownership, and access to extension services. These observations are consistent with the findings of Dossou-Yovo et al., (2019); Tambo (2016); Yegbemey et al., (2013), who recognize the influence of these factors on adopting climate risk mitigation technologies.

A crucial element in this dynamic is the central role of road accessibility. Resilience practices significantly increase when the inland valleys are connected by paved or mixed-surface tracks. Improved road infrastructure not only facilitates the acquisition of essential agricultural inputs, such as drought-resistant seeds and irrigation equipment but also contributes to the overall well-being of smallholder farmers by enhancing mobility and the exchange of goods and services. Djagba et al., (2019) demonstrate that appropriate road infrastructure in rural areas facilitates market access, thereby strengthening farmers' ability to procure necessary inputs and sell their products, which is vital for investing in adopting drought and flooding mitigation strategies.

Furthermore, land ownership is a determining factor for investment in developing drought and flooding mitigation measures, with more measures developed by individual landowners. Yegbemey et al. (2013) emphasize that secure land tenure is essential for smallholders to invest in adopting drought mitigation measures. The lack of support from extension services is a major constraint, limiting the effective implementation of appropriate mitigation measures. Tambo (2016) highlights the crucial role of external institutions, such as non-governmental organizations (NGOs), in strengthening smallholders' technical and material capacities by promoting proven risk mitigation approaches.

In summary, securing individual land tenure and improving transportation infrastructure are essential levers for enhancing the adoption of drought and flooding mitigation measures in inland valleys.

4.2.4. Impact of management approaches on the sustainability of inland valleys and agricultural productivity

The hydrological and water conditions of the Ouinhi and Savalou sites play a crucial role in agricultural productivity and the sustainability of inland valleys, as these agroecosystems primarily depend on water sources and climatic conditions (Rodenburg, 2013; Rodenburg et al., 2014). Djagba et al. (2018) emphasize that inland valleys are of significant interest for rice production due to their capacity to retain water and maintain high soil moisture. However, this potential is contingent upon water supply from nearby sources or precipitation. Ouinhi, with cumulative precipitation ranging from 500 to 700 mm during the production period, exhibits a soil moisture content of 43%, while Savalou, receiving only 300 to 400 mm of precipitation, has a relative soil moisture of 34%. This disparity is primarily due to the geographical context of these sites, with Ouinhi located within the Guinean climatic zone and benefiting from the water supply of the Ouémé River, unlike Savalou, which is in a low-precipitation zone (Lokossou, 2021). This difference underscores the direct impact of precipitation on soil water availability, a crucial factor for crop growth and the sustainability of agroecosystems, particularly in rain-fed agricultural systems. In contrast, areas with lower precipitation, such as Savalou, require specific interventions to improve water retention and ensure sustainable productivity.

Dossou-Yovo et al. (2017) have noted that the diversity of inland valleys in West Africa presents opportunities for agricultural development, but these opportunities are highly dependent on local hydrological conditions. Water management practices, such as rainwater harvesting and supplementary irrigation, have been extensively explored to maximize the utilization of precipitation (Dossou-Yovo et al., 2022). However, the interannual variability of precipitation is often overlooked, even though it can be significant in tropical regions. Long-term studies are needed to assess the resilience of agricultural systems to climate change, as suggested by Dossou-Yovo et al. (2019) and Cooper et al. (2008).

When compared to the Undeveloped approach, the Smart Valley approach to soil and water management showed a significant improvement in hydric conditions, with soil moisture approximately 8.62% higher (Arouna and Akpa, 2019 and AfricaRice, 2015). This approach, which integrates sustainable resource management practices, has proven to be an effective adaptation strategy for climate change in rice production in West Africa. These practices, including water conservation and nutrient management, help to maximize water use efficiency and enhance agricultural yields, consistent with Saito et al. (2021), who observed a yield increase of 1.6 t/ha to 3.1 t/ha due to improved water management practices. Moreover, Giller et al. (2015) demonstrated that integrated management systems, such as the Smart approach, reduce soil temperature, enhancing plant growth conditions. These findings align with (Dossou-Yovo et al., 2022), who indicated that sustainable agricultural practices improve the resilience of agroecosystems to climate change.

The improvement of hydrological and water conditions directly affected rice yields, with the Smart approach yielding 35.42% higher than the Undeveloped approach. This result supports Rodenburg et al. (2014), who noted that properly managed inland valleys can serve as a critical food basket for Africa. Furthermore, the optimization of fertilization, particularly at levels F2 (recommended by the RiceAdvice digital application) and F1 (adopted by smallholder farmers), resulted in yield increases of 13.65% and 8.40%, respectively, compared to the control (absence of fertilization). These results highlight the significance of technological advancements that offer farmers tailored recommendations tailored to local conditions. Dobermann et al. (2002) demonstrated that fertilization based on crop-specific needs enhances nutrient use efficiency and yields, a point also highlighted by Dossou-Yovo et al. (2023), who emphasized the importance of fertilization optimization in low-input agricultural systems.

Despite these benefits, the adoption of fertilization technologies remains limited among smallholder farmers due to socio-economic factors such as lack of infrastructure, low digital literacy, and limited access to technology, as Amoussouhoui et al. (2024) reported. Combining the Smart approach with optimized fertilization levels significantly improves rice yields and optimizes water use. This observation is consistent with the research by (Asai et al., 2021; Vanlauwe et al., 2010), who noted that the impact of fertilization may be constrained by water stress. Additionally, Ibrahim et al. (2021) highlighted that nutrient management optimization can generate yield gains ranging from 0.4 to 2.9 tons per hectare, which is crucial for enhancing agricultural productivity.

Finally, the study revealed that among the rice varieties tested, IR841 recorded the highest yield, followed by Nerica L19 and Orylux 6. These results align with those of Aliou et al. (2014), who found that the IR841 variety responded positively to the applied treatments in terms of grain yield compared to the Nerica varieties. Rice varieties, such as IR841, are better suited to water and thermal stress conditions due to their increased drought tolerance and water-use efficiency. Nerica L19, an interspecific variety, also performs well but is slightly less productive than IR841, likely due to its sensitivity to temperature fluctuations, as reported by Saito et al. (2014). Furthermore, the yield achieved by the IR841 variety may be attributed to its long-standing cultivation by smallholder farmers, who have adapted it over time to local conditions. Dossou-Yovo and

Futakuchi (2023) reported that using varieties suited to local conditions is crucial for maximizing yields.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion
5.2. Recommendations

5. Conclusion and recommendations

5.1. Conclusion

This doctoral study has developed pathways for the conservation, sustainable management, and optimization of ecosystem services in inland valleys, addressing both climatic hazards and anthropogenic pressures. The findings highlight several key insights that contribute to a deeper understanding of the challenges and opportunities in these ecosystems.

First, the study underscores the critical importance of ecosystem services provided by inland valleys, particularly provisioning, regulating, and supporting services, which were ranked higher than cultural services by farmers. Water management technologies, such as Smart-valley systems, demonstrated a significant positive impact on these services. Developed systems outperformed non-developed valleys, particularly in hydrological management, drought mitigation, and flood reduction. Smallholder farmers perceived non-developed systems (inland valley) as more effective in addressing drought (RII = 0.67) and flood risks (RII = 0.61) compared to Smart-valley (RII = 0.54 and 0.45) and bund management systems (RII = 0.59 and 0.57). Furthermore, perceptions of ecosystem services varied based on gender, age, education level, primary occupation, and annual income, with women placing greater emphasis on provisioning services.

Second, the study highlights the high vulnerability of inland valleys to climatic hazards, with significant spatial and temporal variations in the occurrence and severity of droughts and floods. Southern valleys were found to be more frequently vulnerable to floods, while central valleys were more susceptible to droughts. This spatial differentiation underscores the need for region-specific adaptation strategies to address these climatic challenges effectively.

Third, the adaptation strategies adopted by smallholder farmers, such as adjusting cropping seasons, using resilient crop varieties, agroforestry, organic farming, and irrigation, were influenced by access to markets, extension services, and land ownership. These findings emphasize the importance of socio-economic factors in shaping farmers' responses to climatic and environmental pressures.

Finally, the experimental study demonstrated the effectiveness of integrated management practices, such as the Smart-valley approach, in improving soil hydric and thermal conditions, optimizing water use and fertilization, and increasing rice yields, particularly in water-stressed regions. Precision fertilization tailored to local conditions, as recommended by RiceAdvice, further enhanced grain yields. The IR841 rice variety achieved the highest yield, exceeding 5 tons per hectare under the Smart-valley approach, showcasing the potential of these technologies to improve agricultural productivity sustainably.

5.2. Recommendations

The findings of this study should serve as a foundation for communication, extension activities, policy briefs, and conceptual notes on resilience actions, sustainable management, and low-impact development of inland valleys. However, further in-depth research is needed to update precise fertilization formulas tailored to smallholder farmers in localized inland valley contexts, aiming to improve yields while minimizing chemical pollution.

The study recommends the following actions:

- *Integration of Cultural Services in Smart-Valley Systems:* Cultural ecosystem services should be incorporated into the design and implementation of Smart-valley systems to preserve the overall balance of ecosystem services. This approach will help maintain cultural values, community identity, and social cohesion while enhancing ecological and economic benefits.
- *Development of targeted strategies for inland valley sustainability*: Targeted strategies should be developed to reduce reliance on chemical fertilizers and improve water management techniques to mitigate the effects of droughts and floods. These interventions should be adapted to the socio-economic profiles of farmers, with consideration for gender-based preferences. Strategies could leverage technological approaches, such as the RiceAdvice application.
- *Strengthening climate hazard monitoring systems:* Robust monitoring systems for droughts and floods in inland valleys are essential to enable rapid and effective responses. These systems should be based on key predictors such as the SPEI index, soil organic carbon, and average annual rainfall.
- *Promotion of sustainable agricultural practices:* Sustainable agricultural practices, including agroforestry, organic farming, and the use of stress-tolerant rice varieties like IR841, should be promoted and supported through public policies. Access to extension services and markets should be improved to facilitate the adoption of these practices.
- *Future research on integrating traditional knowledge:* Future research should explore the integration of traditional ecological knowledge with modern water management technologies to enhance the resilience of inland valleys. Long-term studies on the impacts

of Smart-valley systems on biodiversity, soil health, and water quality are also needed to inform sustainable agricultural practices.

REFERENCES

Abramowitz, M., Stegun, I.A., 1968. Handbook of mathematical functions with formulas, graphs, and mathematical tables. US Government printing office.

Achite, M., Katipoğlu, O.M., Jehanzaib, M., Kartal, V., Mansour, H., 2024. Understanding run theory for evaluating hydrologic drought in the Wadi Mina Basin (Algeria): A historical analysis. Theor Appl Climatol 1–16.

AfricaRice, 2015a. SMART-IV technical report 2009-2014.

AfricaRice, 2015b. SMART-IV technical report 2009-2014.

Akodekou, A. D**.,** Dossou-Yovo, E. R., Salako, K. V., Gnansounou, S. C., Diarra, S. T., Nehren, U., & Kakaï, R. G., 2025. Drought and flood hazards in inland valleys of Benin: severities, adaptation strategies and associated factors across the Sudano-Guinean and Guinean zones. International Journal of Disaster Risk Reduction, 105953.

Alemayehu, A., Bewket, W., 2017. Smallholder farmers' coping and adaptation strategies to climate change and variability in the central highlands of Ethiopia. Local Environ 22, 825–839.

Alemayehu, T., Assogba, G.M., Gabbert, S., Giller, K.E., Hammond, J., Arouna, A., Dossou-Yovo, E.R., van de Ven, G.W.J., 2022. Farming Systems, Food Security and Farmers' Awareness of Ecosystem Services in Inland Valleys: A Study From Côte d'Ivoire and Ghana. Front Sustain Food Syst 6, 892818.

Aliou, S., Denis, G.K., Ibouraïman, B., Romain, H.S., Valentin, K.M., 2014. Effet de l'urée et du NPK 15-15-15 perlés et super granulés sur la productivité des variétés de riz IR841 et NERICA-L14 en zone de bas-fond au Sud-Bénin. J Appl Biosci 77, 6575–6589.

Amoussouhoui, R., Arouna, A., Cerjak, M., Yergo, W.G., Banout, J., 2024. Analyzing Farmers' Behavior in the Adoption of Paid Digital Extension Service: Experimental Evidence of Rice Advice in Nigeria. Hum Ecol 1–12.

Andriesse, W., 1985. Wetlands in sub-Saharan Africa, area and distribution. The Wetlands and Rice in Sub-Saharan Africa.

Arouna, A., Akpa, A.K.A., 2019a. Water management technology for adaptation to climate change in rice production: Evidence of smart-valley approach in West Africa. Sustainable Solutions for Food Security: Combating Climate Change by Adaptation 211–227.

Arouna, A., Akpa, A.K.A., 2019b. Water management technology for adaptation to climate change in rice production: Evidence of smart-valley approach in West Africa. Sustainable Solutions for Food Security: Combating Climate Change by Adaptation 211–227.

Arouna, A., Akpa, A.K.A., Adegbola, P.Y., 2017. Impact de la technologie smart-valley pour l'amenagement des basfonds sur le revenu et le rendement des petits producteurs de riz au Benin. Cahiers du CBRST 12, 47–66.

Arsenovic, D., 2024. Population of the World.

Asai, H., Saito, K., Kawamura, K., 2021a. Application of a Bayesian approach to quantify the impact of nitrogen fertilizer on upland rice yield in sub-Saharan Africa. Field Crops Res 272, 108284.

Asai, H., Saito, K., Kawamura, K., 2021b. Application of a Bayesian approach to quantify the impact of nitrogen fertilizer on upland rice yield in sub-Saharan Africa. Field Crops Res 272, 108284.

Asselen, S. van, Verburg, P.H., Vermaat, J.E., Janse, J.H., 2013a. Drivers of wetland conversion: a global meta-analysis. PLoS One 8, e81292.

Asselen, S. van, Verburg, P.H., Vermaat, J.E., Janse, J.H., 2013b. Drivers of wetland conversion: a global meta-analysis. PLoS One 8, e81292.

Bachmair, S., Kohn, I., Stahl, K., 2015. Exploring the link between drought indicators and impacts. Natural Hazards and Earth System Sciences 15, 1381–1397.

Bado, V.B., Djaman, K., Mel, V.C., 2018. Developing fertilizer recommendations for rice in Sub-Saharan Africa, achievements and opportunities. Paddy and Water Environment 16, 571–586.

Badou, D.F., Adango, A., Hounkpè, J., Bossa, A., Yira, Y., Biao, E.I., Adounkpè, J., Alamou, E., Sintondji, L.O.C., Afouda, A.A., 2021. Heavy rainfall frequency analysis in the Benin section of the Niger and Volta Rivers basins: is the Gumbel's distribution a one-size-fits-all model? Proceedings of the International Association of Hydrological Sciences 384, 187–194.

Baki, C.B., Wellens, J., Traoré, F., Palé, S., Djaby, B., Bambara, A., Thao, N.T.T., Hié, M., Tychon, B., 2022. Assessment of Hydro-Agricultural Infrastructures in Burkina Faso by Using Multiple Correspondence Analysis Approach. Sustainability 14, 13303.

Beillouin, D., Corbeels, M., Demenois, J., Berre, D., Boyer, A., Fallot, A., Feder, F., Cardinael, R., 2023. A global meta-analysis of soil organic carbon in the Anthropocene. Nat Commun 14, 3700.

Belem, M., Saqalli, M., 2017. Development of an integrated generic model for multi-scale assessment of the impacts of agro-ecosystems on major ecosystem services in West Africa. J Environ Manage 202, 117–125.

Below, T., Artner, A., Siebert, R., Sieber, S., 2010. Micro-level practices to adapt to climate change for African small-scale farmers: A review of selected literature.

Bonou, A., Egah, J., Aihounton, G.B.D., 2024a. Impact of floods on rice production in West Africa: Micro-evidence from Benin. Sustainable Environment 10, 2356396.

Bonou, A., Egah, J., Aihounton, G.B.D., 2024b. Impact of floods on rice production in West Africa: Micro-evidence from Benin. Sustainable Environment 10, 2356396.

Bonou, A., Wünscher, T., Adégbidi, A.A., Diaw, A., 2018. Impact of floods on farmers' livelihoods in the semi-arid zone of Benin. Strategies for building resilience against climate and ecosystem changes in sub-Saharan Africa 59–77.

Bouwma, I., Schleyer, C., Primmer, E., Winkler, K.J., Berry, P., Young, J., Carmen, E., Špulerová, J., Bezák, P., Preda, E., 2018. Adoption of the ecosystem services concept in EU policies. Ecosyst Serv 29, 213–222.

Breiman, L., 2001. Random forests. Mach Learn 45, 5–32.

Cabell, J.F., Oelofse, M., 2012. An indicator framework for assessing agroecosystem resilience. Ecology and Society 17.

Cameron, A.C., Trivedi, P.K., 2013. Regression analysis of count data. Cambridge university press.

Canning, A.D., Smart, J.C.R., Dyke, J., Curwen, G., Hasan, S., Waltham, N.J., 2023. Constructed Wetlands Suitability for Sugarcane Profitability, Freshwater Biodiversity and Ecosystem Services. Environ Manage 71, 304–320.

Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Díaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M., 2009. Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. Proceedings of the National Academy of Sciences 106, 1305–1312.

Change, I.P.O.C., 2007. Climate change 2007: The physical science basis. Agenda 6, 333.

Cherinet, A., Tadesse, C., Abebe, T., 2022. Drought and flood extreme events and management strategies in Ethiopia. J Geogr Nat Disast 12, 587–2167.

Christie, M., Martín-López, B., Church, A., Siwicka, E., Szymonczyk, P., Mena Sauterel, J., 2019. Understanding the diversity of values of "Nature's contributions to people": insights from the IPBES Assessment of Europe and Central Asia. Sustain Sci 14, 1267–1282.

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? Agric Ecosyst Environ 126, 24–35.

Coulibaly, T., Islam, M., Managi, S., 2020. The impacts of climate change and natural disasters on agriculture in African countries. Econ Disaster Clim Chang 4, 347–364.

Dal Monte, T., Alessandri, A., Cherchi, A., Gaetani, M., 2024. Assessing the predictability of Euro-Mediterranean droughts through seasonal forecasts. Copernicus Meetings.

Danvi, A., Giertz, S., Zwart, S.J., Diekkrüger, B., 2018a. Rice intensification in a changing environment: Impact on water availability in inland valley landscapes in Benin. Water (Switzerland) 10. https://doi.org/10.3390/w10010074

Danvi, A., Giertz, S., Zwart, S.J., Diekkrüger, B., 2018b. Rice intensification in a changing environment: Impact on water availability in inland valley landscapes in Benin. Water (Basel) 10, 74.

Dar, S.A., Bhat, S.U., Rashid, I., Dar, S.A., 2020. Current status of Wetlands in Srinagar City: threats, management strategies, and future perspectives. Front Environ Sci 7: 199.

Datta, S., Sinha, D., Chaudhary, V., Kar, S., Singh, A., 2022. Water pollution of wetlands: a global threat to inland, wetland, and aquatic phytodiversity, in: Handbook of Research on Monitoring and Evaluating the Ecological Health of Wetlands. IGI Global, pp. 27–50.

Defoer, T., Dugué, M.J., Loosvelt, M., Worou, S., 2017. Smart-valleys: Trainer-facilitator's manual. AfricaRice, Abidjan, Côte d'Ivoire.

Dixon, A., Wood, A., Hailu, A., 2021. Wetlands in Ethiopia: lessons from 20 years of research, policy and practice. Wetlands 41, 20.

Djagba, J.F., 2024. Assessment of Inland Valley Agroecosystems Potential for Rice Production Development in Benin using Spatial Analysis.

Djagba, J.F., Sintondji, L.O., Kouyaté, A.M., Baggie, I., Agbahungba, G., Hamadoun, A., Zwart, S.J., 2018a. Predictors determining the potential of inland valleys for rice production development in West Africa. Applied geography 96, 86–97.

Djagba, J.F., Sintondji, L.O., Kouyaté, A.M., Baggie, I., Agbahungba, G., Hamadoun, A., Zwart, S.J., 2018b. Predictors determining the potential of inland valleys for rice production development in West Africa. Applied geography 96, 86–97.

Djagba, J.F., Sintondji, L.O., Kouyaté, A.M., Baggie, I., Agbahungba, G., Hamadoun, A., Zwart, S.J., 2018c. Predictors determining the potential of inland valleys for rice production development in West Africa. Applied geography 96, 86–97.

Djagba, J.F., Zwart, S.J., Houssou, C.S., Tenté, B.H.A., Kiepe, P., 2019a. Ecological sustainability and environmental risks of agricultural intensification in inland valleys in Benin. Environ Dev Sustain 21, 1869–1890.

Djagba, J.F., Zwart, S.J., Houssou, C.S., Tenté, B.H.A., Kiepe, P., 2019b. Ecological sustainability and environmental risks of agricultural intensification in inland valleys in Benin. Environ Dev Sustain 21, 1869–1890.

Dossoumou, N.I.P., Gnazou, M.D.T., Villamor, G.B., Agbossou, E.K., Thiam, S., Wagner, S., Idrissou, M., 2023. Comparing households' perception of flood hazard with historical climate and hydrological data in the Lower Mono River catchment (West Africa), Benin and Togo. PLOS Climate 2, e0000123.

Dossou-Yovo, E.R., Baggie, I., Djagba, J.F., Zwart, S.J., 2017a. Diversity of inland valleys and opportunities for agricultural development in Sierra Leone. PLoS One 12, e0180059.

Dossou-Yovo, E.R., Baggie, I., Djagba, J.F., Zwart, S.J., 2017b. Diversity of inland valleys and opportunities for agricultural development in Sierra Leone. PLoS One 12, e0180059.

Dossou-Yovo, E.R., Baggie, I., Djagba, J.F., Zwart, S.J., 2017c. Diversity of inland valleys and opportunities for agricultural development in Sierra Leone. PLoS One 12, e0180059.

Dossou-Yovo, E.R., Devkota, K.P., Akpoti, K., Danvi, A., Duku, C., Zwart, S.J., 2022a. Thirty years of water management research for rice in sub-Saharan Africa: Achievement and perspectives. Field Crops Res 283, 108548.

Dossou-Yovo, E.R., Devkota, K.P., Akpoti, K., Danvi, A., Duku, C., Zwart, S.J., 2022b. Thirty years of water management research for rice in sub-Saharan Africa: Achievement and perspectives. Field Crops Res 283, 108548. https://doi.org/10.1016/J.FCR.2022.108548

Dossou-Yovo, E.R., Devkota, K.P., Akpoti, K., Danvi, A., Duku, C., Zwart, S.J., 2022c. Thirty years of water management research for rice in sub-Saharan Africa: Achievement and perspectives. Field Crops Res 283, 108548.

Dossou-Yovo, E.R., Futakuchi, K., 2023a. Smart-Valleys toolkit: An e-learning tool for the sustainable use of inland valleys for agricultural development and biodiversity and ecosystem services preservation.

Dossou-Yovo, E.R., Futakuchi, K., 2023b. Smart-Valleys toolkit: An e-learning tool for the sustainable use of inland valleys for agricultural development and biodiversity and ecosystem services preservation.

Dossou-Yovo, E.R., Kouadio, S.A.K., Saito, K., 2023. Effects of mid-season drainage on iron toxicity, rice yield, and water productivity in irrigated systems in the derived savannah agroecological zone of West Africa. Field Crops Res 296, 108901.

Dossou-Yovo, E.R., Kouyaté, A.M., Sawadogo, T., Ouédraogo, I., Bakare, O.S., Zwart, S.J., 2018. A geospatial database of drought occurrence in inland valleys in Mali, Burkina Faso and Nigeria. Data Brief 19, 2008–2014.

Dossou-Yovo, E.R., Zwart, S.J., Kouyaté, A., Ouédraogo, I., Bakare, O., 2019a. Predictors of drought in inland valley landscapes and enabling factors for rice farmers' mitigation measures in the Sudan-sahel zone. Sustainability (Switzerland) 11. https://doi.org/10.3390/su11010079

Dossou-Yovo, E.R., Zwart, S.J., Kouyaté, A., Ouédraogo, I., Bakare, O., 2019b. Predictors of drought in inland valley landscapes and enabling factors for rice farmers' mitigation measures in the Sudan-sahel zone. Sustainability (Switzerland) 11. https://doi.org/10.3390/su11010079

Eastwood, A., Brooker, R., Irvine, R.J., Artz, R.R.E., Norton, L.R., Bullock, J.M., Ross, L., Fielding, D., Ramsay, S., Roberts, J., 2016. Does nature conservation enhance ecosystem services delivery? Ecosyst Serv 17, 152–162.

FAO, IFAD, UNICEF, W. and W., 2017. The State of Food Security and Nutrition in the World 2024, The State of Food Security and Nutrition in the World 2024. https://doi.org/10.4060/cd1254en

Felipe-Lucia, M.R., Comín, F.A., 2015. Ecosystem services-biodiversity relationships depend on land use type in floodplain agroecosystems. Land use policy 46, 201–210. https://doi.org/10.1016/j.landusepol.2015.02.003

Fenner, N., Freeman, C., 2020. Woody litter protects peat carbon stocks during drought. Nat Clim Chang 10, 363–369.

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International journal of climatology 37, 4302–4315.

Fiebig, D.G., 2001. Seemingly unrelated regression. A companion to theoretical econometrics 101–121.

Gezie, M., 2019. Farmer's response to climate change and variability in Ethiopia: A review. Cogent Food Agric 5, 1613770.

Giertz, S., Steup, G., Schönbrodt, S., 2012. Use and constraints on the use of inland valley ecosystems in central Benin: results from an inland valley survey. Erdkunde 239–253.

Githiora-Murimi, Y.W., Owuor, M.A., Abila, R., Olago, D., Oriaso, S., 2022a. Integrating stakeholder preferences into ecosystem services mapping in Yala wetland, Kenya. Ecosystems and People 18, 146–163.

Githiora-Murimi, Y.W., Owuor, M.A., Abila, R., Olago, D., Oriaso, S., 2022b. Integrating stakeholder preferences into ecosystem services mapping in Yala wetland, Kenya. Ecosystems and People 18, 146–163.

Gnansounou, S.C., Salako, K.V., Sagoe, A.A., Mattah, P.A.D., Aheto, D.W., Glèlè Kakaï, R., 2022a. Mangrove ecosystem services, associated threats and implications for wellbeing in the

Mono Transboundary Biosphere Reserve (Togo-Benin), West-Africa. Sustainability 14, 2438.

Gnansounou, S.C., Salako, K.V., Sagoe, A.A., Mattah, P.A.D., Aheto, D.W., Glèlè Kakaï, R., 2022b. Mangrove ecosystem services, associated threats and implications for wellbeing in the Mono Transboundary Biosphere Reserve (Togo-Benin), West-Africa. Sustainability 14, 2438.

Gnansounou, S.C., Salako, K.V., Visée, C., Dahdouh-Guebas, F., Kakaï, R.G., Kestemont, P., Henry, S., 2024. The role of local deities and traditional beliefs in promoting the sustainable use of mangrove ecosystems. For Policy Econ 160, 103145.

Gnansounou, S.C., Toyi, M., Salako, K.V., Ahossou, D.O., Akpona, T.J.D., Gbedomon, R.C., Assogbadjo, A.E., Kakaï, R.G., 2021. Local uses of mangroves and perceived impacts of their degradation in Grand-Popo municipality, a hotspot of mangroves in Benin, West Africa. Trees, Forests and People 4, 100080.

Gumma, M., Thenkabail, P.S., Fujii, H., Namara, R., 2009. Spatial models for selecting the most suitable areas of rice cultivation in the Inland Valley Wetlands of Ghana using remote sensing and geographic information systems. J Appl Remote Sens 3, 33537.

Haefele, S.M., Thomas, C.L., Saito, K., 2022. Long-term fertility experiments for irrigated rice in the West African Sahel: effect on macro-and micronutrient concentrations in plant and soil. Field Crops Res 275, 108357.

Hastie, T., Tibshirani, R., Friedman, J.H., Friedman, J.H., 2009. The elements of statistical learning: data mining, inference, and prediction. Springer.

Henchiri, M., Liu, Q., Essifi, B., Javed, T., Zhang, S., Bai, Y., Zhang, J., 2020. Spatio-temporal patterns of drought and impact on vegetation in North and West Africa based on multi-satellite data. Remote Sens (Basel) 12, 3869.

Hornung, L.K., Podschun, S.A., Pusch, M., 2019. Linking ecosystem services and measures in river and floodplain management. Ecosystems and People 15, 214–231.

Hosmer Jr, D.W., Lemeshow, S., Sturdivant, R.X., 2013. Applied logistic regression. John Wiley & Sons.

Houètchégnon, T., Gbèmavo, D.S.J.C., Ouinsavi, C.A.I.N., Sokpon, N., 2015. Structural Characterization of Prosopis africana Populations (Guill., Perrott., and Rich.) Taub in Benin. International Journal of Forestry Research 2015, 101373.

Hounkpè, J., Badou, D.F., Ahouansou, D.M.M., Totin, E., Sintondji, L.O.C., 2022. Assessing observed and projected flood vulnerability under climate change using multi-modeling statistical approaches in the Ouémé River Basin, Benin (West Africa). Reg Environ Change 22, 112.

Hussain, M., Mahmud, I., 2019. pyMannKendall: a python package for non parametric Mann Kendall family of trend tests. J Open Source Softw 4, 1556.

Hussain, N., Ahmed, M., Duangpan, S., Hussain, T., Taweekun, J., 2021. Potential impacts of water stress on rice biomass composition and feedstock availability for bioenergy production. Sustainability 13, 10449.

Hutchison, J., Spalding, M., zu Ermgassen, P., 2014. The role of mangroves in fisheries enhancement. The Nature Conservancy and Wetlands International 54, 434.

Ibrahim, A., Saito, K., Bado, V.B., Wopereis, M.C.S., 2021. Thirty years of agronomy research for development in irrigated rice-based cropping systems in the West African Sahel: Achievements and perspectives. Field Crops Res 266, 108149.

Ishfaq, M., Farooq, M., Zulfiqar, U., Hussain, S., Akbar, N., Nawaz, A., Anjum, S.A., 2020. Alternate wetting and drying: A water-saving and ecofriendly rice production system. Agric Water Manag 241, 106363.

Johnson, J. M., Vandamme, E., Senthilkumar, K., Sila, A., Shepherd, K. D., & Saito, K., 2019. Near-infrared, mid-infrared or combined diffuse reflectance spectroscopy for assessing soil fertility in rice fields in sub-Saharan Africa. Geoderma, 354, 113840.

Kasei, R., Diekkrüger, B., Leemhuis, C., 2010a. Drought frequency in the Volta basin of West Africa. Sustain Sci 5, 89–97.

Kasei, R., Diekkrüger, B., Leemhuis, C., 2010b. Drought frequency in the Volta basin of West Africa. Sustain Sci 5, 89–97.

Köhl, M., Magnussen, S., Marchetti, M., 2006. Sampling methods, remote sensing and GIS multiresource forest inventory. Springer.

Lakitan, B., Hadi, B., Herlinda, S., Siaga, E., Widuri, L.I., Kartika, K., Lindiana, L., Yunindyawati, Y., Meihana, M., 2018. Recognizing farmers' practices and constraints for intensifying rice production at Riparian Wetlands in Indonesia. NJAS-Wageningen Journal of Life Sciences 85, 10–20.

Lau, J.D., Hicks, C.C., Gurney, G.G., Cinner, J.E., 2019. What matters to whom and why? Understanding the importance of coastal ecosystem services in developing coastal communities. Ecosyst Serv 35, 219–230.

Lechowska, E., 2018. What determines flood risk perception? A review of factors of flood risk perception and relations between its basic elements. Natural Hazards 94, 1341–1366.

Lee, A.R., Koo, D., Kim, I.K., Lee, E., Kim, H.H., Yoo, S., Kim, J.-H., Choi, E.K., Lee, H.-Y., 2023. Identifying facilitators of and barriers to the adoption of dynamic consent in digital health ecosystems: a scoping review. BMC Med Ethics 24, 107.

Liu, D., Chen, H., Geng, T., Shi, Q., Chen, W., 2024. The impact of individual capabilities on the access to ecosystem services: a case study from the Loess Plateau, China. Environmental Science and Pollution Research 29, 10443–10455. https://doi.org/10.1007/s11356-021-16486-7

Lokonon, B.O.K., 2017. Farmers ' Vulnerability to Climate Shocks : Insights from the Niger Basin of Farmers ' Vulnerability to Climate Shocks : Insights from the Niger Basin of Benin Boris Odilon Kounagbè Lokonon.

Mandishona, E., Knight, J., 2022. Inland wetlands in Africa: A review of their typologies and ecosystem services. Progress in Physical Geography: Earth and Environment 46, 547–565.

Mansour, S., 2024. Geospatial modelling of drought patterns in Oman: GIS-based and machine learning approach. Model Earth Syst Environ 1–21.

Markantonis, V., Farinosi, F., Dondeynaz, C., Ameztoy, I., Pastori, M., Marletta, L., Ali, A., Carmona Moreno, C., 2018. Assessing floods and droughts in the Mékrou River basin (West Africa): a combined household survey and climatic trends analysis approach. Natural Hazards and Earth System Sciences 18, 1279–1296.

Martín-López, B., Felipe-Lucia, M.R., Bennett, E.M., Norström, A., Peterson, G., Plieninger, T., Hicks, C.C., Turkelboom, F., García-Llorente, M., Jacobs, S., 2019. A novel telecoupling framework to assess social relations across spatial scales for ecosystem services research. J Environ Manage 241, 251–263.

Mathys, A.S., Van Vianen, J., Rowland, D., Narulita, S., Palomo, I., Pascual, U., Sutherland, I.J., Ahammad, R., Sunderland, T., 2023. Participatory mapping of ecosystem services across a gradient of agricultural intensification in West Kalimantan, Indonesia. Ecosystems and People 19, 2174685.

Mbereko, A., Chimbari, M.J., Mukamuri, B.B., 2007. An analysis of institutions associated with wetlands use, access and management in communal areas of Zimbabwe: A case study of Zungwi vlei, Zvishavane. Physics and Chemistry of the Earth, Parts A/B/C 32, 1291–1299.

Mengistie, B.T., Mol, A.P.J., Oosterveer, P., 2017. Pesticide use practices among smallholder vegetable farmers in Ethiopian Central Rift Valley. Environ Dev Sustain 19, 301–324.

Mensah, S., Veldtman, R., Assogbadjo, A.E., Ham, C., Kakaï, R.G., Seifert, T., 2017. Ecosystem service importance and use vary with socio-environmental factors: A study from household-surveys in local communities of South Africa. Ecosyst Serv 23, 1–8.

Mohammed, S., Elbeltagi, A., Bashir, B., Alsafadi, K., Alsilibe, F., Alsalman, A., Zeraatpisheh, M., Széles, A., Harsányi, E., 2022. A comparative analysis of data mining techniques for agricultural and hydrological drought prediction in the eastern Mediterranean. Comput Electron Agric 197, 106925.

Mohino, E., Janicot, S., Bader, J., 2011. Sahel rainfall and decadal to multi-decadal sea surface temperature variability. Clim Dyn 37, 419–440.

Montcho, M., Assani, A.S., de Dieu Ainamon, J., Aboh, A.B., Olounladé, P.A., Sinsin, B., 2025. Agroecological mapping of livestock feed resources for sustain productivity and climate resilience in Benin (West Africa). Discover Sustainability 6, 33.

Oussou, F.E., Ndehedehe, C.E., Oloukoi, J., Yalo, N., Boukari, M., Diaw, A.T., 2022. Characterization of the hydro-geological regime of fractured aquifers in Benin (West-Africa) using multi-satellites and models. J Hydrol Reg Stud 39, 100987.

Overå, R., 2011. Modernisation narratives and small-scale fisheries in Ghana and Zambia, in: Forum for Development Studies. Taylor & Francis, pp. 321–343.

Owuor, M.A., Mulwa, R., Otieno, P., Icely, J., Newton, A., 2019. Valuing mangrove biodiversity and ecosystem services: A deliberative choice experiment in Mida Creek, Kenya. Ecosyst Serv 40, 101040.

Page, S., Mishra, S., Agus, F., Anshari, G., Dargie, G., Evers, S., Jauhiainen, J., Jaya, A., Jovani-Sancho, A.J., Laurén, A., 2022a. Anthropogenic impacts on lowland tropical peatland biogeochemistry. Nat Rev Earth Environ 3, 426–443.

Page, S., Mishra, S., Agus, F., Anshari, G., Dargie, G., Evers, S., Jauhiainen, J., Jaya, A., Jovani-Sancho, A.J., Laurén, A., 2022b. Anthropogenic impacts on lowland tropical peatland biogeochemistry. Nat Rev Earth Environ 3, 426–443.

Partey, S.T., Zougmoré, R.B., Ouédraogo, M., Campbell, B.M., 2018. Developing climate-smart agriculture to face climate variability in West Africa: Challenges and lessons learnt. J Clean Prod 187, 285–295.

Qange, S., Mdoda, L., Mditshwa, A., 2024. Modeling drivers of postharvest losses among smallholder vegetable farmers in eThekwini Metropolitan: an examination of a zero-inflated Poisson (ZIP) approach. Cogent Food Agric 10, 2383316.

Reid, W. V, Mooney, H.A., Cropper, A., Capistrano, D., Carpenter, S.R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A.K., Hassan, R., 2005. Ecosystems and human well-being-Synthesis: A report of the Millennium Ecosystem Assessment. Island Press.

Reyes-Arroyo, N., Camacho-Valdez, V., Saenz-Arroyo, A., Infante-Mata, D., 2021. Socio-cultural analysis of ecosystem services provided by mangroves in La Encrucijada Biosphere Reserve, southeastern Mexico. Local Environ 26, 86–109.

Rodenburg, J., 2013. Inland valleys: Africa's future food baskets., in: Realizing Africa's Rice Promise. CABI Wallingford UK, pp. 276–293.

Rodenburg, J., Saito, K., 2022a. Towards sustainable productivity enhancement of rice-based farming systems in sub-Saharan Africa. Field Crops Res 287, 108670.

Rodenburg, J., Saito, K., 2022b. Towards sustainable productivity enhancement of rice-based farming systems in sub-Saharan Africa. Field Crops Res 287, 108670.

Rodenburg, J., Zwart, S.J., Kiepe, P., Narteh, L.T., Dogbe, W., Wopereis, M.C.S., 2014a. Sustainable rice production in African inland valleys: seizing regional potentials through local approaches. Agric Syst 123, 1–11.

Rodenburg, J., Zwart, S.J., Kiepe, P., Narteh, L.T., Dogbe, W., Wopereis, M.C.S., 2014b. Sustainable rice production in African inland valleys: seizing regional potentials through local approaches. Agric Syst 123, 1–11.

Saito, K., Vandamme, E., Johnson, J.-M., Tanaka, A., Senthilkumar, K., Dieng, I., Akakpo, C., Gbaguidi, F., Segda, Z., Bassoro, I., 2019. Yield-limiting macronutrients for rice in sub-Saharan Africa. Geoderma 338, 546–554.

Sayer, J., Cassman, K.G., 2013. Agricultural innovation to protect the environment. Proceedings of the National Academy of Sciences 110, 8345–8348.

Scholte, S.S.K., Van Teeffelen, A.J.A., Verburg, P.H., 2015. Integrating socio-cultural perspectives into ecosystem service valuation: A review of concepts and methods. Ecological economics 114, 67–78.

Secrétariat de la Convention de Ramsar, 2016. Introduction à la Convention Sur les Zones Humides, Manuels Ramsar 5ª Édition.

Senthilkumar, K., 2022. Closing rice yield gaps in Africa requires integration of good agricultural practices. Field Crops Res 285, 108591.

Senthilkumar, K., Tesha, B.J., Mghase, J., Rodenburg, J., 2018. Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. Paddy and Water Environment 16, 749–766.

Sinsin, C.B.L., Salako, K.V., Fandohan, A.B., Kouassi, K.E., Sinsin, B.A., Glèlè Kakaï, R., 2022. Potential climate change induced modifications in mangrove ecosystems: a case study in Benin, West Africa. Environ Dev Sustain 24, 4901–4917.

Sinsin, C.B.L., Salako, K.V., Fandohan, A.B., Kouassi, K.E., Sinsin, B.A., Glèlè Kakaï, R., 2021. Potential climate change induced modifications in mangrove ecosystems: a case study in Benin, West Africa. Environ Dev Sustain 1–17.

Tambo, J.A., 2016. Adaptation and resilience to climate change and variability in north-east Ghana. International Journal of Disaster Risk Reduction 17, 85–94.

Team, R.C., 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Totin, E., Stroosnijder, L., Agbossou, E., 2013. Mulching upland rice for efficient water management: A collaborative approach in Benin. Agric Water Manag 125, 71–80.

Van Oort, P.A.J., Zwart, S.J., 2018. Impacts of climate change on rice production in Africa and causes of simulated yield changes. Glob Chang Biol 24, 1029–1045.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric 39, 17–24.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23, 1696–1718.

Wang, Y., Wang, G., Sun, J., Song, C., Lin, S., Sun, S., Hu, Z., Wang, X., Sun, X., 2024. The impact of extreme precipitation on water use efficiency along vertical vegetation belts in Hengduan Mountain during 2001 and 2020. Science of The Total Environment 173638.

Ward, R.D., Friess, D.A., Day, R.H., MacKenzie, R.A., 2016. Impacts of climate change on mangrove ecosystems: a region by region overview. Ecosystem Health and Sustainability 2, e01211.

Windmeijer, P.N., Andriesse, W., 1993. Inland valleys in West Africa: an agro-ecological characterization of rice-growing environments. ILRI.

Worou, O.N., Gaiser, T., Saito, K., Goldbach, H., Ewert, F., 2013. Spatial and temporal variation in yield of rainfed lowland rice in inland valley as affected by fertilizer application and bunding in North-West Benin. Agric Water Manag 126, 119–124.

Worou, O.N., Gaiser, T., Saito, K., Goldbach, H., Ewert, F., 2012. Simulation of soil water dynamics and rice crop growth as affected by bunding and fertilizer application in inland valley systems of West Africa. Agric Ecosyst Environ 162, 24–35.

Yapi, T.S., Shackleton, C.M., Le Maitre, D.C., Dziba, L.E., 2023. Local peoples' knowledge and perceptions of Australian wattle (Acacia) species invasion, ecosystem services and disservices in grassland landscapes, South Africa. Ecosystems and People 19, 2177495.

Yegbemey, R.N., Yabi, J.A., Tovignan, S.D., Gantoli, G., Kokoye, S.E.H., 2013a. Farmers' decisions to adapt to climate change under various property rights: A case study of maize farming in northern Benin (West Africa). Land use policy 34, 168–175.

Yegbemey, R.N., Yabi, J.A., Tovignan, S.D., Gantoli, G., Kokoye, S.E.H., 2013b. Farmers' decisions to adapt to climate change under various property rights: A case study of maize farming in northern Benin (West Africa). Land use policy 34, 168–175.

Yevjevich, V.M., 1967. An objective approach to definitions and investigations of continental hydrologic droughts. Colorado State University Fort Collins, CO, USA.

Yu, M., Zhang, J., Wei, L., Wang, G., Dong, W., Liu, X., 2023. Impact of soil textures on agricultural drought evolution and field capacity estimation in humid regions. J Hydrol (Amst) 626, 130257.

ZANVO, M.G.S., BARIMA, Y.S.S., SALAKO, K.V., KOUA, K.A.N., KOLAWOLE, M.A., ASSOGBADJO, A.E., GLÈLÈ KAKAÏ, R., 2022. Mapping spatio-temporal changes in mangroves cover and projection in 2050 of their future state in Benin. Bois & Forets Des Tropiques 350, 29–42. https://doi.org/10.19182/bft2021.350.a36828

Zhang, M., Wang, J., 2022. Global flood disaster research graph analysis based on literature mining. Applied Sciences 12, 3066.

ANNEXES

Annex 1. Supplementary figures

Annex 2. Scientific publications

Annex 3. List of conferences and workshops attended during the thesis.

Annex 4. Data collection files

Annex 1. Supplementary figures

Figure S1. Installation of the experimental system at the Savalou experimental site

Figure S 3. Illustration photo of rice seeds: (a) IR841, (b) Nerica L19, (c) Orylux 6.

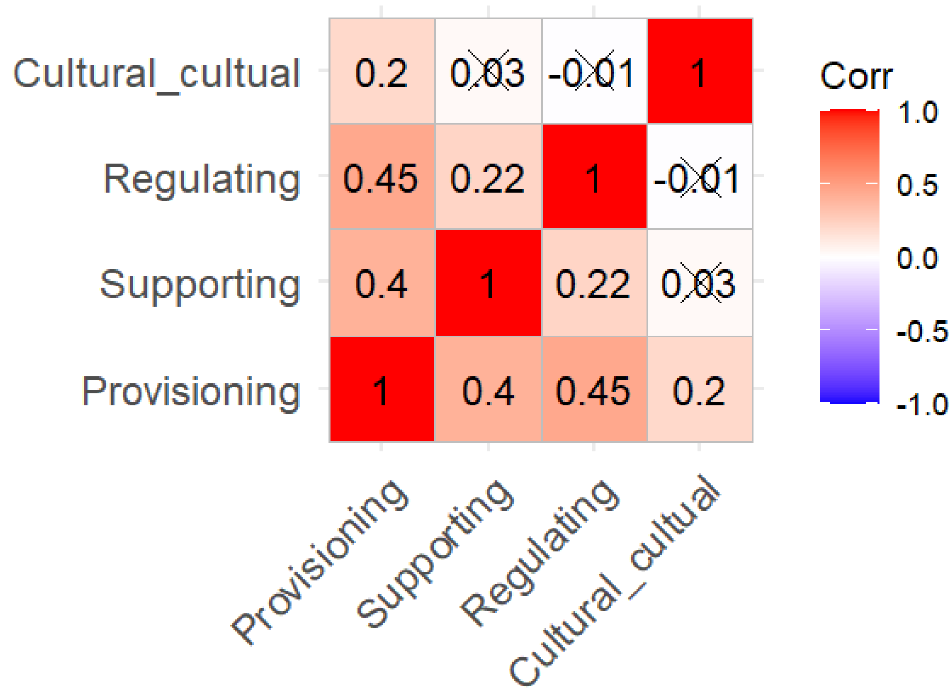

Figure S 3. Correlation matrix between perceived ES with a significance level of 0.05

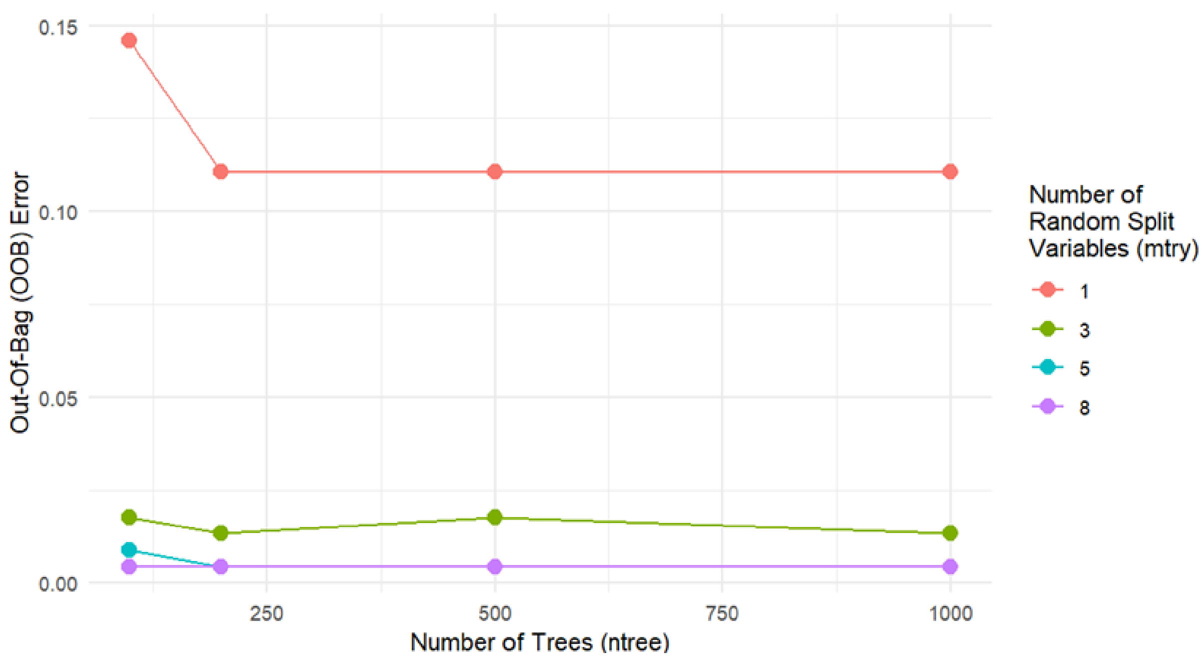

Figure S4. Effects of number of trees (k) and random split variables (m) on Out-Of-Bag (OOB) error

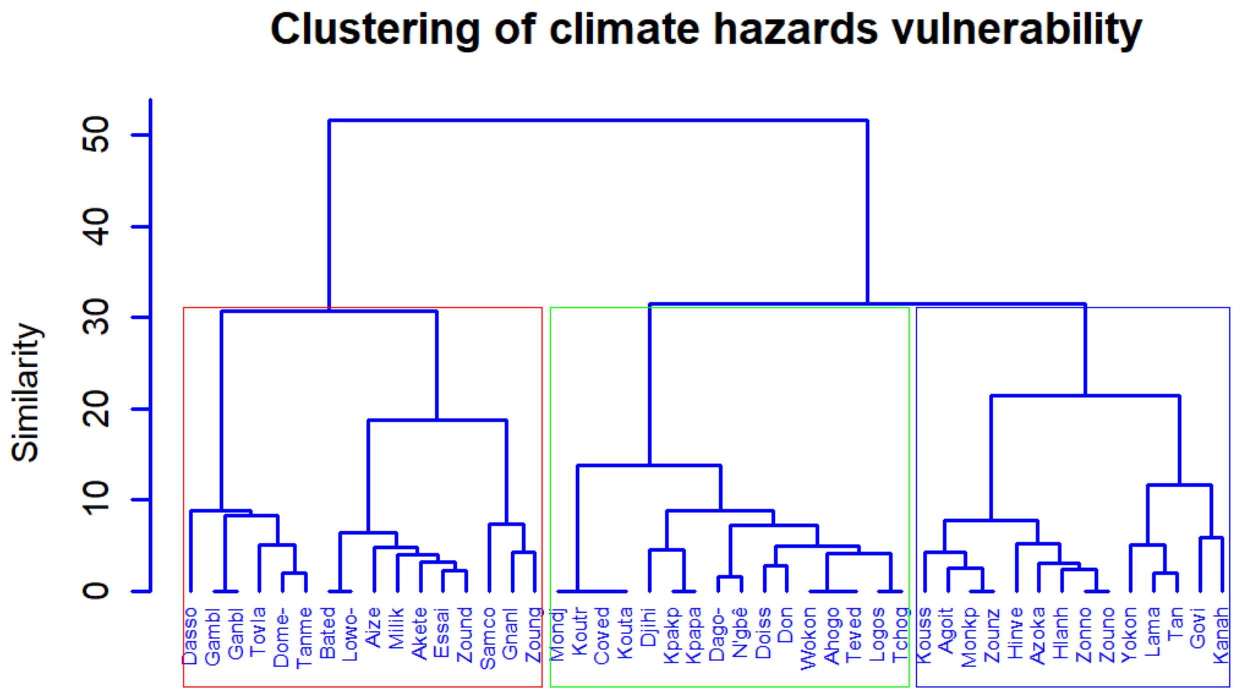

Figure S5. Hierarchical clustering dendrogram for locations with similar climate hazards based on the climate hazard duration, and frequency.

Govi=Govi, Miliki = Milik, Lowo-zoungo = Lowo_, Monkpa=Monkp, Mondji=Mondj, Daga-doho = Daga_, Lama= Lama, Koutago= Kouta, N_Gbehan=N_Gbe, Zoungo= Zoung, Doissa_Hounoukon = Doïss, Kpakpassa=Kpakp, Essaignon=Essai, Akété = Akete Batêdji = Bated, Tchogodo = Tchog, Logossovidji= Logos, Azokangoudo = Azoka, Koutago = Kouta, Covedji = Coved, Gnaly = Gnaly, Zoungo = Zoung, Ganblanou= Ganbl, Workou =Worko, Ahogo = Ahogo, Tanmedji= Tanm, Aize = Aize, Dome-go = Dome_, Samcodji = Samco, Dasso = Dasso, Zounon= Zouno, Hinvedo = Hinve, Koussoukpa= Kouss, Tovlame = Tovla, Djihizide = Djihi, Hlanhonou = Hlanh, Yokon= Yokon, Agoita = Agoit, Tanmedji = Tanme, Tevedji= Teved, Don= Don, Kanahoun = Kanah.

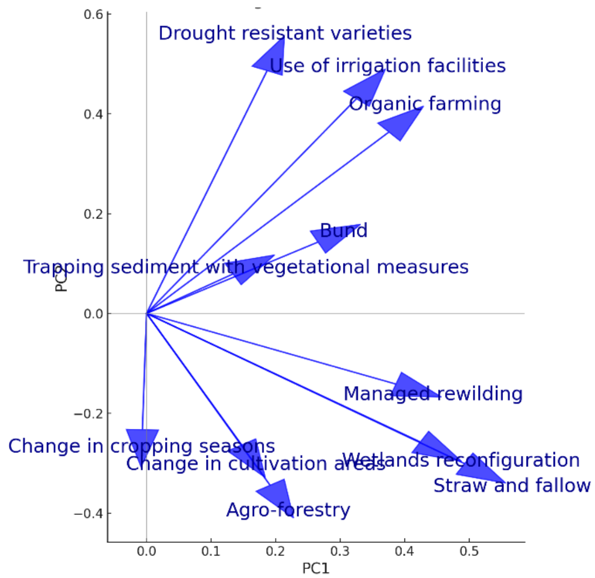

Figure S6. Principal Component Analysis of Flooding (in green) and Drought drought (in blue) mitigation measures.

Annex 2. Scientific publications

Scientific publications from the thesis work

Akodékou, D. A., Dossou-Yovo, E. R., Salako, K. V., Diarra, S., Nehren, U., & Glèlè Kakaï, R. (2024, September). Smart-Valleys' Effects on Inland Valleys Ecosystem Services: Farmer Insights in West Africa's Sudano-Guinean Zones. In Conference on International Research on Food Security.

Akodékou, D. A., Dossou-Yovo, E. R., Salako, K. V., Diarra, S., Nehren, U., & Glèlè Kakaï, R. G. (2025). Assessment of smallholder farmers' mitigation strategies to climatic hazards in the inland valleys of Central Benin: The case of drought and flood. In W. Leal Filho et al. (Eds.), Climate Change, Food Security, and Land Management. Springer Nature. https://doi.org/10.1007/978-3-031-71164-0_73

Akodekou, A. D., Dossou-Yovo, E. R., Salako, K. V., Gnansounou, S. C., Diarra, S. T., Nehren, U., & Kakaï, R. G. (2025). Drought and flood hazards in inland valleys of Benin: severities, adaptation strategies and associated factors across the Sudano-Guinean and Guinean zones. International Journal of Disaster Risk Reduction, 105953.

Scientific reports from the thesis work

Akodekou, A. D., & Dossou-Yovo, E. R. (2025). Smart-Valleys: a locally led adaptation solution that enhanced rice yield and nutrient uptake in inland valleys of Benin, West Africa. Activity report, Climate Action Science Program. AfricaRice (CGIAR). https://hdl.handle.net/10568/180381

Dossou-Yovo, E. R., Djagba, J., Kone, P., & **Akodekou, A. D.** (2025). Smart-Valleys: A locally led innovation enhancing rice yields, farmer incomes and climate resilience in West African inland valleys. Activity report, Climate Action Science Program. AfricaRice (CGIAR). https://hdl.handle.net/10568/180648

Dossou-Yovo, E. R., **Akodekou, A. D.,** & Futakuchi, K. (2025). Two Decades of Smart-Valleys Research: Insights, Knowledge Gaps, and Future Directions for Locally Led Adaptation in Africa's Inland Valley Food Systems. Activity report, Climate Action Science Program. AfricaRice (CGIAR). https://hdl.handle.net/10568/180646

Akodekou, A. D., & Dossou-Yovo, E. R. (2025). Drought and flooding prediction in inland valleys and determinants of farmers' mitigation measures across the Sudano-Guinean and Guinean zones. Activity report, Climate Action Science Program. AfricaRice (CGIAR). https://hdl.handle.net/10568/180612

Akodekou, A. D., & Dossou-Yovo, E. R. (2025). Smart-Valleys: a locally led adaptation solution that enhanced inland valleys ecosystem services in Benin. Activity report, Climate Action Science Program. AfricaRice (CGIAR). https://hdl.handle.net/10568/180378

Other scientific publications not derived from the thesis work

Valère, S. K., Hospice, D. G., Constant, G. S., Serge, Z. M., **David, A. A.,** & Romain, G. K. (2025). Wetlands of Benin (West Africa) Biodiversity, Livelihoods, and Conservation. Wetlands of Tropical and Subtropical Asia and Africa: Biodiversity, Livelihoods and Conservation, 161-185.

Gnansounou, S. C., **Akodékou, A. D.,** Salako, K. V., Houndjinou, E., Apithy, E., & Glèlè Kakaï, R. (2025). From the table to the mill: a socio-cultural valuation of the dynamics in mangrove oyster exploitation in Togo Republic using qualitative methods. *Maritime Studies*, *24*(3), 41.

Annex 3. List of conferences and workshops attended during the thesis.

Seminars, symposiums and conferences

(1) 20/09/2024 – 26/09/2024 University of Banjul,

The Gambia Symposium on climate change, land use and land management in Africa

Presentation on flooding and drought risk management approaches in inland valleys of Benin *Organized by the Research and Transfer Centre "Sustainable Development and Climate Change Management" of the University of Applied Sciences Hamburg (Germany), the University of The Gambia and the WASCAL Competence Centre, as part of the BMBF-funded "RECC-LUM" project (feasibility study on climate change, land use management and renewable energy in The Gambia)*. Link https://www.recclum.wascal.org/

(2) 10/09/2024 – 13/09/2024 University of Natural Resources and Life Sciences, Vienna (BOKU), Austria

Annual Interdisciplinary Conference on Tropical and Subtropical Agricultural Research, Natural Resource Management and Rural Development (Tropentag)

Presentation on the state of Benin's inland valleys: Sustainability of ecosystem services and management of threats. Link https://www.tropentag.de/

(3) 04/05/2023 – 06/05/2023 Laboratoire d'Etudes et de Recherches Forestières (LERF), University of Parakou, Benin

Scientific seminar on natural resource management

Presentation on the theme: Smallholder farmers' perceptions of ecosystem services, contributions to well-being and threats in inland valleys: A study in the Sudano-Guinean region of Benin.

Workshops

(1) 24/01/2024 – 26/01/2024 Laboratoire de Biomathématiques et d'Estimations Forestières, Faculty of Agronomic Sciences, University of Abomey Calavi

Scientific writing training on "Importance of quality scientific communication, scientific writing, plagiarism and self-plagiarism in scientific writing and detecting predatory journals".

Laboratoire de Biomathématiques et d'Estimations Forestières (LABEF/FSA/UAC) with financial support from Alexander von Humboldt-Stiftung.

(2) 19/11/2023 – 03/12/2023 Technical University of Kenya

Summer course on sustainable natural resource management: Data management for sustainable natural resource use, translating research into practice and policy; system dynamics and thinking about natural resource management; and modeling dynamic systems with VENSIM. *Organized by Technical University of Kenya with financial support from Leibniz Universität - Hanover (Germany).*

(3) 03/05/2022 – 13/05/2023 WASCAL Competence Center, Ouagadougou, Burkina Faso

Joint WASCAL-ICTP hands-on workshop on HPC technology for climate science. *Organized by WASCAL Competence Center and International Center for Theoretical Physics* https://e-portal.ictp.it ;

Annex 4. Data collection files

Structured interview questionnaire

Date: GPS Coordinate: X [___________] Y[____________]

I- General information

1. Country: **Benin** Region/Depart: ______________________/
2. Municipality: ___________/ Arrond/Canton: ____________________________/
3. Village: ______________/
4. Interviewees' name: ____/
5. Age [__________] Sex [_____] *M / F*
6. Ethnicity: _______________/ Religion: __________________________________/
7. Marital situation: [____] widow*(er) = 1; single = 2; Married = 3; Divorced= 4*;
8. Education: [_______] *Uneducated = 0; Primary = 1; Secondary = 2; Tertiary = 3*
9. Main activity: ____/
10. Secondary activities: ____/
11. Residency status [_________] *Native = 1 ; Immigrant = 2*
12. *What is the total annual income (FCFA):*

II- Objective 2: Assessment of the farmers' perceptions of the relevance of Ecosystems Services provided by IV according to the management approaches.

II-1. Perception on the management approaches

1. Have you heard of : Smart-valley: [____] ; Bund-valley [____] and undeveloped-valley[____]
2. If yes, briefly describe what it is:

Smart-valley:

Bund-valley:

Undeveloped-valley :

3. Do you recognize each of these approaches?

Photos by AKODEKOU A. David in 2022 at Akété (Collines); Photos by AKODEKOU A. David in 2022 at Ouinhi (Zou)

Photos by AKODEKOU A. David in 2022 at Ouinhi (Zou)

4. Which approach(es) do you mainly adopt?
   Smart-valley: [____] ; Bund-valley [____] and undeveloped-valley[____]

II-2. Perceptions of the importance of ecosystem services according to management approaches

1. How are these broad categories of services being provided by IV according to your experience ? (1- Very Low provision, 2- Low provision, 3- Moderate provision, 4- High provision, 5- Very high provision)

Ecosystem service	The global IV	Undeveloped-valley *(From 1 to 5)*	Bund-valley *(From 1 to 5)*	Smart-valley *(From 1 to 5)*
Provisioning				
Supporting				
Regulating				
Cultural and cultual				

2. How do you perceive the importance of the ES listed below provided by IVs as part of the following approach(es). (1- Very Low important, 2- Low important, 3- Moderately important; 4- Highly important; 5- Very highly important)

Sub-services	The global IV	Undeveloped valley *(From 1 to 5)*	Bund-valley *(From 1 to 5)*	Smart-valley *(From 1 to 5)*
Provision of food				
Provision of fresh water				
natural medicines and pharmaceuticals				
Provision of genetic resources				
Provision of fiber and firewood				
Provision of ornamental resources				
Clay, mineral, aggregate harvesting				
Waste disposal				
Flood hazard regulation				
Regulation of human diseases				
Pest regulation				
Local climate regulation				
Pollination				
Water regulation				
Fire regulation				
Salinity regulation				
Erosion regulation				
Global climate regulation				
Water purification				
Storm hazard regulation				
Air quality regulation				
Noise and visual buffering				
Educational and research				
Spiritual and religious value				
Social relations				
Aesthetic value				

Cultural heritage				
Recreation and tourism				
Inspirational value				
Habitat				
Water recycling				
Nutrient cycling				
Primary production				
Soil formation				
Other :				

III. Threats to IV sustainability

III.1. How do the following threats affect the sustainability of IV? (1- Very Low provision, 2- Low provision, 3- Moderate provision, 4- High provision, 5- Very high provision)

List of threats from FGDs	The global IV (From 1 to 5)	Undeveloped-valley (From 1 to 5)	Bund-valley (From 1 to 5)	Smart-valley (From 1 to 5)
High chemical fertilizer pesticide use				
Sedimentation				
Drought				
Urbanization				
Invasive species				
Flood				
Fire outbreak				
Drainage				
Waste deposition				

Hazard assessment questionnaire

Identification of drought and flooding occurrence predictors in Inland Valley Landscapes and Enabling Factors for small-scale crop Farmers' Mitigation Measures in Benin.

Hypothesis

(1) Climate change contributes significantly to the aggravation of drought/flood scenarios in vulnerable areas of the inland valleys of Southern Benin;

(2) Hydrological characteristics and management practices perform more significantly in predicting the occurrence of drought or flooding in the inland valleys of Southern Benin compared to physical characteristics;

(3) The spatial variation of drought and flood duration (the longest period of consecutive months with SPEI < -1) over the last 30 years differs significatively with the region;

(4) Determinants of small-farmers commitment to using drought/flood mitigation measures depend significatively on the biophysical and socio-economical characteristics of the inland valleys;

(5) The water holding capacity of the soil significantly affects the vulnerability of inland valleys to drought and flood scenarios.

Theme	Description	Select the best answers
Farmers' experience with drought in their inland valley the last 10 years	drought occurrence	Yes [_____] No [_____]
	Frequency of drought events (year)	Year [_____]
	Frequency of entire crop harvest loss (year)	Year [_____]
	Frequency of crop yield reduction	All year [_], 1 to 2 years [_], 3 to 6 years [_], >6 year [_], Never [_], do not know [__]
Adaptive management of crop farmers to drought or floods occurring in inland valley	use of drought-resistant varieties	Yes [_____] No [_____]
	change in cultivation areas	Yes [_____] No [_____]
	investment of irrigation facilities	Yes [_____] No [_____]
	change in cropping seasons	Yes [_____] No [_____]
Nature-based solutions ***(Yes / No + description)***	Organic farming	
	Managed rewilding	
	Agro-forestry	
	Land restoration	
	Wetlands restoration	
	Trapping sediment with vegetational measures	
	other adaptation strategies to drought or flood ***(Select from the annex list)***	
Physical characteristics of inland valley (a)	Inland valley size	[_____] ha
	Average width	[_____] m

	Cross-sectional shape	Convex [_____] concave [_____] flat [_____]
	Sand content *	[_____] %
	Clay content *	[_____] %
	Soil carbon content *	[_____] %
Hydrology of inland valley	Water source	Spring [_____] River [_____] other [_____] …………….
	Flooding regime	Seasonal [__] Permanent [__] sporadic[__] do not know [__]
	duration of flooding	[_____] week
	duration of the emerging water table	[_____] week
	drainage/irrigation infrastructure	No [_____] Yes [_____]:…………………………… ………….
	flow accumulation **	
Management practices	Crop type and varieties for each type	**Type 1**[_______] : local var [__]; improved var [__] both [__] **Type 2**[_______] : local var [__]; improved var [__] both [__] **Type 3**[_______] : local var [__]; improved var [__] both [__]
	Soil fertility management	no fertilizer [___] only mineral fertilizer [___]only organic fertilizer [___]both mineral and organic fertilizers [___]
	Bund	Yes [_____] No [_____]
Socio-economic characteristics of inland valley	Distance to road	[_____] Km
	Distance to market	[_____] Km
	Quality of road to market	No road [___] path [___] dirt road [___] paved road [___]
	Land ownership	Individual [___] family [___] village [___] state [___]
	Origin of inland valley users	Native [_____] Migrant [_____]
	Percentage of women in the inland valleys	[_____] %
	Mode of exploitation	Individual [___] Collective [___] both [___]

	Source of seeds and other agricultural inputs	In the village [___] <25Km [___] 25-50 Km [___] 51-100 Km [___] >100Km [___]
	Support from institution	Yes [_____] No [_____]
	Affiliation with farmers' organization	Yes [_____] No [_____]
	Role of crop farming in production system	1st main activity [_____] 2nd main activity [_____] marginal activity [_____]
Weather data of inland valley (b)	Daily minimum temperature ***	
	Daily maximum temperature ***	
	Daily rainfall ***	

M1 bund, M2 bund + compost + mulching, M3 : bund + early sowing; M4 bund + early sowing + organic fertilizer; M5 bund + organic manure; M6 bund + organic manure + early sowing; M7 bund + organic manure + irrigation; M8 dry sowing + organic manure; M9 early sowing; M10 irrigation; M11 irrigation + contour tillage; M12 none; M13 off-season cropping + irrigation; M14 organic manure; M15 tillage + organic manure; M18 water conservation measures
**to be collected from Africa Soil Information Service (AfSIS) for each region*
*** to be collected from Shuttle Radar Topography Mission (SRTM), URL: http://srtm.csi.org*
**** to be collected from the closed weather station*

FICHE DE COLLECTE DES DONNEES D'EXPERIMENTATION

Echantillon biomasse

SMART SITE

		SR1F0Ne	SR1F0IR	SR1F0AUr	SR1F1Ne	SR1F1IR	SR1F1AUr	SR1F2Ne	SR1F2IR	SR1F2AUr
Jour 1	*Humide*									
	Sec									
Jour21	*Humide*									
	Sec									
Jour42	*Humide*									
	Sec									
Jour63	*Humide*									
	Sec									
Jour84	*Humide*									
	Sec									
Jour105	*Humide*									
	Sec									
		SR2F0Ne	SR2F0IR	SR2F0AUr	SR2F1Ne	SR2F1IR	SR2F1AUr	SR2F2Ne	SR2F2IR	SR2F2AUr
Jour 1	*Humide*									
	Sec									
Jour21	*Humide*									
	Sec									
Jour42	*Humide*									
	Sec									
Jour63	*Humide*									
	Sec									
Jour84	*Humide*									
	Sec									
Jour105	*Humide*									
	Sec									

TRADITIONAL SITE

		TR1F0Ne	TR1F0IR	TR1F0AUr	TR1F1Ne	TR1F1IR	TR1F1AUr	TR1F2Ne	TR1F2IR	TR1F2AUr
Jour 1	*Humide*									
	Sec									
Jour21	*Humide*									
	Sec									
Jour42	*Humide*									
	Sec									
Jour63	*Humide*									
	Sec									
Jour84	*Humide*									
	Sec									
Jour105	*Humide*									
	Sec									
		TR2F0Ne	TR2F0IR	TR2F0AUr	TR2F1Ne	TR2F1IR	TR2F1AUr	TR2F2Ne	TR2F2IR	TR2F2AUr
Jour 1	*Humide*									
	Sec									
Jour21	*Humide*									
	Sec									
Jour42	*Humide*									
	Sec									
Jour63	*Humide*									
	Sec									
Jour84	*Humide*									
	Sec									
Jour105	*Humide*									
	Sec									

Site :

Date de floraison à 50%

Date de semis : 08 – 09 Aout 2022

SMART

Sub plot	SR1F0Ne	SR1F0IR	SR1F0AUr	SR1F1Ne	SR1F1IR	SR1F1AUr	SR1F2Ne	SR1F2IR	SR1F2AUr
Date									
Sub plot	SR2F0Ne	SR2F0IR	SR2F0AUr	SR2F1Ne	SR2F1IR	SR2F1AUr	SR2F2Ne	SR2F2IR	SR2F2AUr
Date									
Sub plot	SR3F0Ne	SR3F0IR	SR3F0AUr	SR3F1Ne	SR3F1IR	SR3F1AUr	SR3F2Ne	SR3F2IR	SR3F2AUr
Date									
Sub plot	SR4F0Ne	SR4F0IR	SR4F0AUr	SR4F1Ne	SR4F1IR	SR4F1AUr	SR4F2Ne	SR4F2IR	SR4F2AUr
Date									

TRADITIONAL

Sub plot	TR1F0Ne	TR1F0IR	TR1F0AUr	TR1F1Ne	TR1F1IR	TR1F1AUr	TR1F2Ne	TR1F2IR	TR1F2AUr
Date									
Sub plot	TR2F0Ne	TR2F0IR	TR2F0AUr	TR2F1Ne	TR2F1IR	TR2F1AUr	TR2F2Ne	TR2F2IR	TR2F2AUr
Date									
Sub plot	TR3F0Ne	TR3F0IR	TR3F0AUr	TR3F1Ne	TR3F1IR	TR3F1AUr	TR3F2Ne	TR3F2IR	TR3F2AUr
Date									
Sub plot	TR4F0Ne	TR4F0IR	TR4F0AUr	TR4F1Ne	TR4F1IR	TR4F1AUr	TR4F2Ne	TR4F2IR	TR4F2AUr
Date									

Conditions hydriques : 1 : eau stagnante, 2 : surface du sol humide, 3 : surface du sol sec

SMART Site

Jour	SR1F0Ne	SR1F0IR	SR1F0AUr	SR1F1Ne	SR1F1IR	SR1F1AUr	SR1F2Ne	SR1F2IR	SR1F2AUr
Jour 1									
Jour 4									
Jour 7									
Jour 10									
Jour 13									
Jour 16									
Jour 19									

Conditions hydriques : 1 : eau stagnante, 2 : surface du sol humide, 3 : surface du sol sec

Traditionnal site

Jour	TR1F0Ne	TR1F0IR	TR1F0AUr	TR1F1Ne	TR1F1IR	TR1F1AUr	TR1F2Ne	TR1F2IR	TR1F2AUr
Jour 1									
Jour 4									
Jour 7									
Jour 10									
Jour 13									
Jour 16									
Jour 19									

Conditions hydrologiques : Utiliser le TMS-4 Long et mesurer en deux points à profondeurs de 0-20 cm e(20-40 cm
Traditionnal site

Jour	TR1F0Ne		TR1F0IR		TR1F0AUr		TR1F1Ne		TR1F1IR		TR1F1AUr		TR1F2Ne		TR1F2IR		TR1F2AUr	
Point	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40
Exemple	*2/3*	*2/3*	*2/3*	*2/3*														
Jour 1 (1 /2)																		
Jour 4																		
Jour 7																		
Jour 10																		
Jour 13																		
Jour 16																		
Jour 19																		

Conditions hydrologiques : Utiliser le TMS-4 Long et mesurer en deux points à profondeurs de 0-20 cm e(20-40 cm
SMART SITE

Jour	SR1F0Ne		SR1F0IR		SR1F0AUr		SR1F1Ne		SR1F1IR		SR1F1AUr		SR1F2Ne		SR1F2IR		SR1F2AUr	
Point	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40
Exemple	*2/3*	*2/3*	*2/3*	*2/3*														
Jour 1 (1 /2)																		
Jour 4																		
Jour 7																		
Jour 10																		
Jour 13																		
Jour 16																		
Jour 19																		

Piezomètre measurement

SMART Site

Jour	Amont 1	Amont 2	Amont 3	Milieu 1	Milieu 2	Milieu 3	Avale 1	Avale 2	Avale 3
Jour 1									
Jour 2									
Jour 3									
Jour 4									

Piezomètre measurement

Traditionnal Site

Jour	Amont 1	Amont 2	Amont 3	Milieu 1	Milieu 2	Milieu 3	Avale 1	Avale 2	Avale 3
Jour 1									
Jour 2									
Jour 3									
Jour 4									

Rainfall data

Month1	Jour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
	Valeur																
	Jour	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Valeur																
Month 2	Jour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
	Valeur																
	Jour	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Valeur																
Month 3	Jour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
	Valeur																
	Jour	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Valeur																
Month 4	Jour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
	Valeur																
	Jour	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Valeur																
Month 5	Jour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
	Valeur																
	Jour	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Valeur																