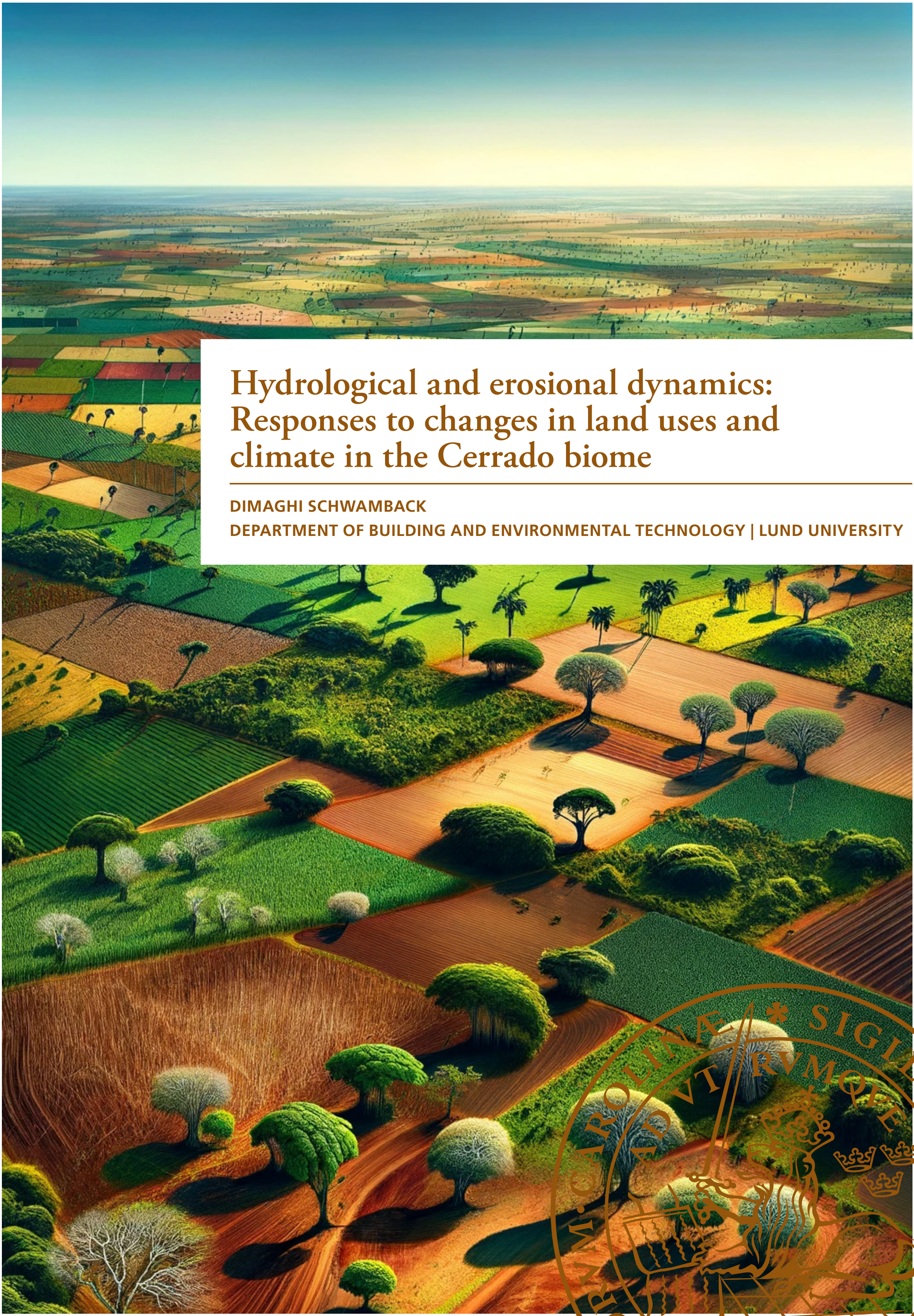
LUND UNIVERSITY

Hydrological and erosional dynamics: Responses to changes in land uses and climate in the Cerrado biome

Schwamback, Dimaghi

2024

Citation for published version (APA):
Schwamback, D. (2024). *Hydrological and erosional dynamics: Responses to changes in land uses and climate in the Cerrado biome*. Department of Building and Environmental Technology, Lund University.



Hydrological and erosional dynamics: Responses to changes in land uses and climate in the Cerrado biome

DIMAGHI SCHWAMBACK
DEPARTMENT OF BUILDING AND ENVIRONMENTAL TECHNOLOGY | LUND UNIVERSITY

DIMAGHI SCHWAMBACK has been enrolled at Lund University (Sweden) and the University of São Paulo (Brazil) during his double degree PhD studies. Mr. Schwamback grew up on a farm near Ibituba, a tiny village with 500 inhabitants located in the state of Espírito Santo-Brazil. Surrounded by incredible nature, fell in love with water and agriculture conservation.

There, lived until 17 years old, when moved to the state capital (Vitória) to attend his bachelor's in environmental engineering at the Federal University of Espírito Santo. Later, Mr. Schwamback finished his master's degree in Hydraulics and Sanitation Engineering and an MBA in Project Management until starting his PhD studies. In 2016, Schwamback started his studies with land cover, sediment, and rural hydrology.

During his career, he has collaborated with major recognized research centers: Yale University, Drexel University, University of São Paulo, Federal University of Mato Grosso do Sul, and Federal University of Espírito Santo. Besides professional aptitude, Mr. Schwamback is deeply passionate about cultivating flowers, biking rides, and admiring the sunset in friends' company.

LUND
UNIVERSITY

Faculty of Engineering
Department of Building and Environmental Technology

ISBN 978-91-8104-040-1

9 789181 040401

Printed by Media-Tryck, Lund 2024 NORDIC SWAN ECOLABEL 3041 0903

Hydrological and erosional dynamics: Responses to changes in land uses and climate in the Cerrado biome

Hydrological and erosional dynamics:

Responses to changes in land uses and climate in the Cerrado biome

by Dimaghi Schwamback

LUND
UNIVERSITY

DOCTORAL DISSERTATION

Faculty opponent
Prof. Dr. Prof. Marcos Alberto Lana
Swedish University of Agricultural Sciences

To be presented, with the permission of the Faculty of Engineering of Lund University, for public criticism at V-building, John Ericssons Väg 1, Lund, room V:C on June 14, 2024 at 9:00.

DOKUMENTDATABLAD enl SIS 61 41 21

Organization
LUND UNIVERSITY
Department of Building and Environmental Technology
Box 118
SE–221 00 Lund, Sweden

Document name
DOCTORAL THESIS

Date of disputation
2024-06-14

Sponsoring organization
São Paulo Research Foundation
Coordination of Superior Level Staff Improvement
Lars Erik Lundberg Foundation

Author(s)
Dimaghi Schwamback

Title and subtitle
Hydrological and erosional dynamics: Responses to changes in land uses and climate in the Cerrado biome

Abstract

The Brazilian Cerrado is the major national epicenter for agricultural production and a main contributor to the Brazilian economy. Thus, the biome faces increasing pressure from agricultural expansion that alters local and regional hydrological processes (infiltration, runoff, evapotranspiration, soil loss). There is a lack of understanding how these processes will respond to climate change. Consequently, this thesis investigates the intricate interplay between land cover and land use (LCLU) patterns and climate change on soil loss and on the dynamics of water balance components (surface flux, evaporation, soil-water storage, infiltration, groundwater flux, and root uptake) in a study area within the Cerrado biome. Using a multidisciplinary approach, surface runoff, soil losses and meteorological parameters were measured in experimental plots (100 m^2 and 9% slope) during 10 years. The plots contained five typical LCLU in Brazil (sugarcane, pasture, Cerrado, soybean, and bare soil). Besides using standard equipment, two novel innovations for the design and construction of low-cost equipment for real-time measurements of surface runoff and soil water content were proposed. Based on the experimental data, we calibrated consolidated models for soil loss (Universal Soil Loss Equation - USLE) and subsurface water movement (Hydrus). Subsequently, we coupled the models to SSP2-4.5 and SSP5-8.5 future scenarios of climate model projections from the last generation (CMIP6) to predict the intermediate (2040-2070) and distant future (2071-2100) climate impact on hydrodynamics processes. The effects of climate change may lead to an increase of up to 4.9% (SSP2-4.5 scenario) and 7.6% (SSP5-8.5 scenario) of soil loss for all LCLU up to the end of the century. The climate change effects on water balance components are larger, with an increase of up to 28% in root water uptake for sugarcane areas (SSP5-8.5 scenario) by the end of the century. By assessing the interactions between land use, climate variability, and hydrological and erosion processes, this thesis informs decision-makers and stakeholders about the critical need for proactive conservation and adaptation measures in the face of ongoing environmental changes in the Cerrado ecosystem.

Key words
Land cover and land use, Low-cost monitoring, Runoff, Soil loss, Infiltration, Climate change, Cerrado

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language
English

ISSN and key title

ISBN
978-91-8104-040-1 (print)
978-91-8104-041-8 (pdf)

Recipient's notes

Number of pages
208

Price

Security classification

Signature ____________________

Date 2024-04-26

Hydrological and erosional dynamics:

Responses to changes in land uses and climate in the Cerrado biome

by Dimaghi Schwamback

LUND
UNIVERSITY

A doctoral thesis at a university in Sweden takes either the form of a single, cohesive research study (monograph) or a summary of research papers (compilation thesis), which the doctoral student has written alone or together with one or several other author(s).

In the latter case the thesis consists of two parts. An introductory text puts the research work into context and summarizes the main points of the papers. Then, the research publications themselves are reproduced, together with a description of the individual contributions of the authors. The research papers may either have been already published or are manuscripts at various stages (in press, submitted, or in draft).

Cover illustration front: Command given by Dimaghi Schwamback to DALL·E (v1.5) on March 19th, 2024.

Funding information: The thesis work was financially supported by The São Paulo Research Foundation, Coordination for the Improvement of Higher Education Personnel, and The Lars Erik Lundberg Foundation.

Faculty of Engineering, Department of Building and Environmental Technology

isbn: 978-91-8104-040-1 (print)
isbn: 978-91-8104-041-8 (pdf)

Printed in Sweden by Media-Tryck, Lund University, Lund 2024

NORDIC SWAN ECOLABEL
Printed matter
3041 0903

Media-Tryck is a Nordic Swan Ecolabel
certified provider of printed material.
Read more about our environmental
work at www.mediatryck.lu.se

MADE IN SWEDEN

Just as Adam and Eve were entrusted with the duty
to watch over and care for divine creations,
we must have the same attitude today in relation
to the environment and the natural resources
that are available on our planet.

Contents

Acknowledgements

Pursuing a PhD is a long and laborious journey, compared to opening a clearing in a dense forest, as my close friend Thais Fujita used to say. There were sunny days with perfect temperature and sharp ax that you make great advance. Nonetheless, there were rainy and cold days, when no matter what you do, you can't make any progress. On those days, it is a time to, instead of wasting energy, save your soul in a warm tent near a forest. Later, on the following day, and well rested, you wake up early and try again to keep opening the forest until reach the lake on the other side during the thesis defense. I would like to use this great opportunity to give thanks to people who have cheered, accompanied, challenged, and shared the tent with me during my PhD work over the last four years when I needed a hug.

Firstly, my acknowledgment is to God in recognition that in Him are hidden all the treasures of wisdom and knowledge (Colossians 2:3), for all the times I prayed for answers, and they were never left behind.

I am profoundly grateful to my parents, Darli Schwamback and Dalva A. Schwamback, for their unwavering love, support, and understanding during the ups and downs of this journey. Their encouragement and belief in my abilities have been a constant source of motivation. Even though they didn't reach high school (and sometimes had no idea of what my thesis was about haha), my parents understood the relevance of knowledge and always supported and cheered for me. Mom, I will never forget each tear you had on my face every time I left home for school on Sunday afternoon. If now I'm a doctor, this is your victory as well. I love you two.

I would like to express my deepest gratitude to my supervisor, prof. Edson Wendland and prof. Magnus Persson, for their unwavering support, guidance, and encouragement throughout the entire process of completing this thesis. I also acknowledge the contribution of Prof. Ronny Berndtsson and Prof. Linus Zhang, while making the effort of welcoming me in Lund and working together. André Torre, your knowledge, help, and friendship turned my days brighter, and much of what I know in electronics, it is because of you, thank you very much. The expertise, patience, and insightful feedback of each of you have been invaluable in shaping my work.

My heartfelt thanks go to the University of São Paulo and Lund University, for providing the necessary resources and facilities that helped the completion of this thesis. Additionally, I acknowledge Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) through process nº 2019/24292-7 for the financial support.

My gratitude to Roberto Bérgamo, a technician at the Department of Hydraulics and Sanitation Engineering at USP, for his patience, joy, and readiness to teach and help when necessary. I always wondered what my thesis would be without your creativity in solving practical problems.

Thanks to everyone who helped during my field trips for data collection, especially to Alex Watanabe, Felipe Zepon; Lucas Scutti, and Luis Castro. I really couldn't do it without you guys.

I am grateful to all the friends who generously contributed to my papers: Abderraman Brandão, Alex Kobayashi, Edson Wendland, Jamil Anache, Linus Zhang, Lívia Rosalem, Luis Bertotto, Magnus Persson, Paulo Oliveira, and Ronny Berndtsson. Their time and insights into this study, without whom this research would not have been possible.

Thanks to all the people at TVRL (Division of Water Resources Engineering) and LHC (Computational Hydraulics Laboratory). TVRL was so kind while receiving me and promoting awesome fika and social activities. My colleagues at LHC have been my everyday friends for the last 6 years, thanks guys!

A big hug and thanks to my Lund friends (I can't mention everyone, but especially my "team name Nike"). Be aware that you were deeply special in my life and will never be forgiven. Jag älskar dig!

I appreciate my fellow friends at Fitdance class, "Testemunhas de Giba" volleyball team, and "Amigos do pedal" mountain bike club for your company, laugh, and love. Knowing I would see you after working hours always made me happier.

I would like to extend my heartfelt thanks to my close friends – Jullian Sone, Gabriela Chiquito, Alex Kobayashi, Luana Lavagnoli, and Ney Simenc, whose unwavering support and encouragement have been a constant source of strength throughout this journey. Your belief in me, your willingness to listen, and your words of encouragement have lifted my spirits during the challenging times and made the joyful moments even more special. Your friendship has enriched my life in countless ways, and I am truly grateful for each of you. Thank you for being there, for cheering me on, and for being the wonderful friends that you are. All the meet calls, conference trips, laughs, and jokes raised saved my soul on gray days.

Lastly, to my dearest Daniel Isgren, I want to express my deepest gratitude for your unwavering love, support, and presence in my life. You have been my rock, my confidant, and my greatest source of joy. Your understanding, patience, and unwavering belief in me have been a guiding light, especially during the toughest of times. Your love has filled my days with warmth and happiness, and I am endlessly thankful for the beautiful moments we've shared. I recognize all your effort in understanding my work over the uncountable times you took notes while I was explaining, for the times you called when I was on the breakdown, and for each motivation audio. Thank you for your endless love, for being my partner in every adventure, and for making my world infinitely brighter.

Abstract

The Brazilian Cerrado is the major national epicenter for agricultural production and a main contributor to the Brazilian economy. Thus, the biome faces increasing pressure from agricultural expansion that alters local and regional hydrological processes (infiltration, runoff, evapotranspiration, soil loss). There is a lack of understanding how these processes will respond to climate change. Consequently, this thesis investigates the intricate interplay between land cover and land use (LCLU) patterns and climate change on soil loss and on the dynamics of water balance components (surface flux, evaporation, soil-water storage, infiltration, groundwater flux, and root uptake) in a study area within the Cerrado biome. Using a multidisciplinary approach, surface runoff, soil losses and meteorological parameters were measured in experimental plots (100 m^2 and 9% slope) during 10 years. The plots contained five typical LCLU in Brazil (sugarcane, pasture, Cerrado, soybean, and bare soil). Besides using standard equipment, two novel innovations for the design and construction of low-cost equipment for real-time measurements of surface runoff and soil water content were proposed. Based on the experimental data, we calibrated consolidated models for soil loss (Universal Soil Loss Equation - USLE) and subsurface water movement (Hydrus). Subsequently, we coupled the models to SSP2-4.5 and SSP5-8.5 future scenarios of climate model projections from the last generation (CMIP6) to predict the intermediate (2040-2070) and distant future (2071-2100) climate impact on hydrodynamics processes. The effects of climate change may lead to an increase of up to 4.9% (SSP2-4.5 scenario) and 7.6% (SSP5-8.5 scenario) of soil loss for all LCLU up to the end of the century. The climate change effects on water balance components are larger, with an increase of up to 28% in root water uptake for sugarcane areas (SSP5-8.5 scenario) by the end of the century. By assessing the interactions between land use, climate variability, and hydrological and erosion processes, this thesis informs decision-makers and stakeholders about the critical need for proactive conservation and adaptation measures in the face of ongoing environmental changes in the Cerrado ecosystem.

Popular Science Summary

Brazil has many factors favorable for agriculture, such as climatic, fertile lands, a large domestic market, an extensive coastline favorable for export, and development of high technology applied to agriculture. Consequently, large areas have undergone land cover conversion and other anthropic interference, mainly aimed for converting natural land to land used for agriculture and livestock. Currently, more than 50% of Brazil's agricultural production takes place in the country's central region, in the biome called Cerrado. Since the mid-twentieth century, the Cerrado has been under agricultural expansion (mainly cattle pastures and high-income crops) leading to a loss of 53% of the original forest vegetation and listing the biome as one of the 25 global biodiversity threatened areas. Changes in Land Cover and Land Use (LCLU) through the conversion of natural areas into agricultural or urban areas interfere with the environment in different ways. Compared to native land uses, agricultural areas commonly have: lower evapotranspiration rates, a more superficial root system less efficient in creating preferential paths for water infiltration, reduced leaf area for intercepting raindrops, less production of organic matter for the agglutination of soil particles, and higher potential to surface runoff and soil loss (detachment and transport of soil particles). Additionally, climate changes (e.g. alteration in rainfall amount, wind speed, and maximum temperature) might intensify the impact of changes in LCLU on the environment. In this thesis, this thesis investigated the relationship between vegetation-water-soil-climate in the Cerrado biome. Plots (100 m^2 rectangular areas) with typical LCLU in Brazil (Cerrado, sugarcane, pasture, soybean, and bare soil) were monitored for 10 years. Two designs of low-cost instruments for monitoring runoff and soil moisture were described in the thesis. The findings predicted an increase in several water cycle components (infiltration, groundwater recharge, and root water uptake) and soil loss due to climate change up to the end of the century. The intensification of soil loss results in several environmental and economic losses. The removal of fine particles (clay and silt) and organic matter from the soil hamper the proper functioning of the physical, chemical, and biological processes that ensure the survival of agriculture, limiting agricultural production and interfering with food security. This thesis contributes to understanding the actual changes on environment due to changes of LCLUs in the Cerrado biome, as well as provides glimpses about the potential impact of climate change.

Resumo em linguagem não técnica

O Brasil possui diversas características favoráveis às práticas agrícolas, tais como condições climáticas, terras férteis, amplo mercado interno, extenso litoral favorável às exportações e desenvolvimento de alta tecnologia aplicada à agricultura. Consequentemente, grandes áreas sofreram, ao longo do tempo, processos de conversão da cobertura do solo e de interferência antrópica, visando principalmente o uso da terra para agricultura e pecuária. Atualmente, mais de 50% da produção agrícola do Brasil ocorre na região central, no bioma Cerrado. Desde meados do século XX, o Cerrado está sob expansão agrícola (principalmente pastagens para gado e agricultura de larga escala) que levou à perda de 53% da vegetação florestal original, listando o bioma como uma das 25 áreas globais de ameaçadas à biodiversidade. As mudanças na Cobertura e Uso da Terra (LCLU, sigla em inglês) através da conversão de áreas naturais em áreas agrícolas ou urbanas interferem no meio ambiente de diferentes maneiras. Em comparação com os usos da terra nativa, as áreas agrícolas comumente apresentam: taxas de evapotranspiração mais baixas, sistemas radiculares superficiais menos eficientes na criação de caminhos preferenciais para infiltração de água, área foliar reduzida para interceptação de gotas de chuva, menor produção de matéria orgânica para aglutinação de partículas do solo e maior potencial ao escoamento superficial (fluxo superficial) e perda de solo (desprendimento e transporte de partículas de solo). Além disso, as mudanças climáticas (por exemplo, alteração na quantidade de precipitação, velocidade do vento e temperatura máxima) podem intensificar o impacto da LCLU no ambiente. Esta tese investiga a relação vegetação-água-solo-clima no bioma Cerrado através do monitoramento de áreas retangulares de 100m^2 durante 10 anos cobertas com usos do solo típicos do Brasil (Cerrado, cana-de-açúcar, pastagem, soja e solo descoberto). Além disso, propusemos dois protótipos de instrumentos alternativos de baixo custo, que podem ser replicados em outras condições, para monitorar o escoamento superficial e a umidade do solo. Com base em simulações matemáticas, os resultados indicam mudanças crescentes nos componentes do ciclo da água (infiltração, recarga de águas subterrâneas e absorção de água pelas raízes) e perda de solo devido às alterações climáticas até ao final do século. Estas mudanças no ciclo da água e aintensificação da perda de solo resulta em diversas perdas ambientais e econômicas. A remoção de partículas finas (argila e silte), nutrientes e matéria orgânica do solo dificulta o bom funcionamento dos processos físicos, químicos e biológicos que garantem a sobrevivência da agricultura podem limitar a produção agrícola e interferir na segurança alimentar. Esta tese contribui para a compreensão das atuais mudanças no meio ambiente devido às alterações das LCLUs no bioma Cerrado, bem como fornece informações sobre o potencial impacto das mudanças climáticas.

Populärvetenskaplig sammanfattning på svenska

Brasilien har många förutsättningar som är gynnsamma för jordbruk, såsom klimatförhållanden, bördiga marker, stor hemmamarknad, en vidsträckt kustlinje som är gynnsam för export och högteknologisk utveckling som tillämpas av jordbruket. Följaktligen har stora områden med tiden drabbats av processer för omvandling av markanvändning och antropisk inblandning, främst inriktade på användning av mark för jordbruk och boskap. För närvarande bedrivs mer än 50% av Brasiliens jordbruksproduktion i den centrala regionen, i biomen som kallas Cerrado. Sedan mitten av 1900-talet har Cerrado varit under jordbruksexpansion (främst boskapsbetesmarker och kontantgrödor) vilket har lett till en förlust av 53% av den ursprungliga skogsvegetationen och som gjort att biomet listas som ett av de 25 områden som hotas av biologisk mångfald globalt. Förändringar i marktäckning och markanvändning (LCLU) genom omvandling av naturområden till jordbruks- eller stadsområden påverkar miljön på olika sätt. Jämfört med ursprunglig markanvändning har jordbruksområden vanligtvis: lägre evapotranspirationshastigheter, ytliga rotsystem som är mindre effektiva för att skapa preferentiella vägar för vatteninfiltration, minskad bladyta för att fånga upp regndroppar, mindre produktion av organiskt material för agglutinering av jordpartiklar och högre potential till ytavrinning och jordförlust (lossning och transport av jordpartiklar). Dessutom kan klimatförändringar (t.ex. förändringar i nederbördsmängd, vindhastighet och maximal temperatur) förstärka effekterna av förändringar i LCLU på miljön. I denna avhandling undersöktes sambandet mellan vegetation-vatten-jord-klimat i Cerrado-biomet. Mätningar utfördes i 100 m^2 plottar i 10 år täckta med typisk LCLU i Brasilien (Cerrado, sockerrör, betesmark, sojabönor och bar jord). I avhandlingen föreslås också två utformningar av billiga alternativa instrument för att övervaka avrinning och markfuktighet som kan replikeras under andra förhållanden. Baserat på matematiska simuleringar förutspådde vi ökade förändringar i vattenkretsloppskomponenter (infiltration, grundvattenpåfyllning och rotvattenupptag) och markförlust på grund av klimatförändringar fram till slutet av seklet. Den intensifierade jordförlusten resulterar i flera miljömässiga och ekonomiska förluster. Avlägsnandet av fina partiklar (lera och silt) och organiskt material från marken hindrar att de fysiska, kemiska och biologiska processerna fungerar korrekt som säkerställer jordbrukets överlevnad, vilket begränsar jordbruksproduktionen och påverkar livsmedelssäkerheten. Denna avhandling bidrar till att förstå de faktiska förändringarna på miljön på grund av förändringar av LCLU i Cerrado-biomen, samt ger glimtar om de potentiella effekterna av klimatförändringar.

List of Publications

This thesis is based on the following publications, referred to by their Roman numerals:

i **Automated low-cost soil moisture sensors: Trade-off between cost and accuracy**
Schwamback, D., Persson, M., Berndtsson, R., Bertotto, L.E., Kobayashi, A.N.A. & Wendland, E.
Sensors, 2023, 23, 2451

ii **Adaptive design of tipping bucket flow meters for continuous runoff measurement**
Schwamback, D., Persson, M., Berndtsson, R., Anache, J.A.A., & Wendland, E.
Frontiers in Environmental Science, 2023, 11:1286929

iii **Land use transformations in the Brazilian Savanna: A decade of soil erosion and runoff measurements**
Schwamback, D., Brandão, A.R.A., Rosalem, L.M.P., Oliveira, P.T.S., Anache, J.A.A., Wendland, E., Berndtsson, R., & Persson, M.
Under review at *Catena* (2024)

iv **Quantifying soil loss in the Brazilian Savanna Ecosystem: Current rates and anticipated impact of climate changes**
Schwamback, D., Brandão, A.R.A., Bertotto, L.E., Zhang, L., Berndtsson, R., Wendland, E., & Persson, M.
Under review at *Land Degradation and Development* (2024)

iv **Assessment of water fluxes under the dual threat of changes in land cover and climate variability in the Brazilian Cerrado biome**
Schwamback, D., Brandão, A.R.A., Berndtsson, R., Wendland, E., & Persson, M.
Under preparation (2024)

All papers are reproduced with permission of their respective publishers.

Author´s contribution to appended papers

Paper i: Automated low-cost soil moisture sensors: Trade-off between cost and accuracy

The author planned the study together with the co-authors, designed the instrument and performed the lab and field studies. The author was the main contributor to the writing of all sections and the final review of the paper, while the coauthors provided useful commentary and discussion on the paper.

Paper ii: Adaptive design of tipping bucket flow meters for continuous runoff measurement

The author planned the study together with the co-authors, designed the instrument and performed the lab and field studies. The author was the main contributor to the writing of all sections and the final review of the paper, while the coauthors provided useful commentary and discussion on the paper.

Paper iii: Land use transformations in the Brazilian Savanna: A decade of soil erosion and runoff measurements

The author lead field data collection over the last five years that field monitoring dataset comprehend, while the remaining data were collected by colleagues that coauthored the paper. The statistical analysis and data curation were performanced by the author, with the help of coauthors. The author was the main contributor to the writing of all sections and the final review of the paper, while the coauthors provided useful commentary and discussion on the paper.

Paper iv: Quantifying soil loss in the Brazilian Savanna Ecosystem: Current rates and anticipated impact of climate changes

The author was responsible for the theoretical conception of the study, data compilation, and model application. The author was the main contributor to the formal analysis and writing of all sections and the final review of the paper, while the coauthors provided useful commentary and discussion on the paper.

Paper v: Assessment of water fluxes under the dual threat of changes in land cover and climate variability in the Brazilian Cerrado biome

The author was responsible for the theoretical conception of the study, data compilation, model application, and data visualization. The author was the main contributor to the formal analysis and writing of all sections and the final review of the paper, while the coauthors provided useful commentary and discussion on the paper.

Hydrological and erosional dynamics: Responses to changes in land uses and climate in the Cerrado biome

Chapter 1

Introduction

This introductory chapter outlines the problems investigated in this thesis research, as well as, the approach and goals. The chapter closes by presenting the thesis structure and briefly describing the appended papers and their interconnection.

1.1 Background

Given the current trajectory of population growth, it is projected that the global population will reach 9.7 billion by 2050 (Zhou et al., 2019). Consequently, agricultural production will need to increase by between 1.4 and 2.2 times the current levels to accommodate food for this population surge (Pardey et al., 2014; van Dijk et al., 2021). Within this context, Brazil emerges as a potential global food contributor, with an expected 40% increase in its current production up to 2050 (OCDE, 2015). Climate change poses a threat to agricultural production and environmental services, by imposing shifts in precipitation, temperature, and evapotranspiration. The effects of these shifts will have effects on future hydrological processes and water availability (Clifton et al., 2018; Gong et al., 2023). Understanding the link between land-climate-water is of paramount relevance for local and global food and water security, considering Brazil's international importance as an exporter of agricultural goods. The significance of examining the interrelations among water, land cover, and climate was emphasized by Blöschl et al., 2019 as one of the 23 key objectives to steer hydrological research in the forthcoming decades. Additionally, a comprehensive assessment of the connections between land degradation and climate change assumes fundamental importance in shaping policies for soil and water conservation and establishing climate-resilient agroecological systems, in alignment with the objectives laid out in the United Nations' 17 Sustainable Development Goals.

Brazil boasts a set of advantageous characteristics for agricultural pursuits, encompassing favorable climatic conditions, fertile terrain, sizable domestic market, long coastline conducive to export, and a burgeoning biofuel production sector (Arias et al., 2017). Such potential has been strengthened by national scientific development of agricultural species resistant to acid soil, dry periods, and insects. Over the decades, however, substantial portions of native vegetation regions have experienced a gradual transformation due to human intervention, predominantly aimed at reshaping the land for agricultural and livestock production (Trigueiro et al., 2020).

The primary epicenter of Brazilian agricultural activities resides within the Cerrado biome, situated at the country's heart. This biome sustains a significant portion of the nation's agricultural output, contributing 55% to the total meat production (Vendrame et al., 2010) and more than 50% to the productive agricultural land (Spera, 2017), particularly for key crops such as sugarcane, soy, corn, and wheat. The Cerrado is Brazil's second-largest biome, with an area equivalent to the combined landmasses of Germany, France, England, Italy, and Spain. The biome is complex, from grass to a mosaic of more than four thousand small, tortuous, six to seven m high tree species (Alberton et al., 2014), with most of these having a thick cork on their trunks, stiff leathery leaves, and xeromorphic characteristic (Ribeiro and Walter, 2008). Since the mid-twentieth century, the Cerrado has experienced substantial agricultural expansion, resulting in the loss of nearly 50% of its native forest vegetation (Strassburg et al., 2017), with less than 3% of its original extent conserved within protected areas (Costa Junior et al., 2012). This extensive land transformation poses a significant threat not only to the region's flora and fauna, but to nearby ecosystems that depend on large-scale atmospheric phenomena due to Cerrado' spatial magnitude and relevance for the regional hydrological cycle. Consequently, the Cerrado has garnered recognition as one of the top 25 global biodiversity hotspots (Myers et al., 2000).

The alteration of land cover and land use (LCLU) is intricately connected to local hydrological processes, as it influences infiltration and surface runoff (Susha Lekshmi et al., 2014). During precipitation events, vegetation cover functions as a protective barrier, mitigating the impact of raindrops on the soil (splash effect). This protection helps prevent alterations in the physical structure of the soil, such as particle disaggregation, compaction, surface sealing, and the conversion of moisture into water vapor (Schwamback et al., 2020). With the escalating global population and the consequent heightened demands for food and energy, human interference in the environment has increased, leading to more intense adverse effects, such as higher soil and nutrient losses, lower infiltration and aquifer recharge rates, soil acidification, and greater demand for irrigation, among others.

To achieve efficient water utilization and preservation of natural resources, it is imperative to gain a comprehensive understanding of the physical mechanisms governing the hydrological cycle in various land-use contexts (J. Anache et al., 2018). In this scenario, the soil moisture content is a pivotal component influencing agricultural development, vegetation growth, microbial activities, and physicochemical processes (Adla et al., 2020). When infiltration capacity of the soil is reached, surface runoff is the main driver of soil particles that reshape landscape, as well as a driver of nutrient transport from the agricultural areas. Factors such as vegetation characteristics (root depth and type, water requirements, and leaf properties), soil properties (porosity, structure, hydraulic conductivity, and granulometry), and climatic conditions (precipitation volume, duration, maximum intensity, air temperature range, solar radiation, wind speed and direction, and sunlight duration) all impact infiltration capacity, water storage quantity, and water movement. Consequently, monitoring of these becomes indispensable for a more profound comprehension of phenomena rooted in the intricate interplay among soil, vegetation, and the atmosphere, including surface runoff, erosion, and infiltration (Placidi et al., 2020a).

Predictions suggest that alterations in regional water fluxes have the potential to exacerbate and feed climate change (Gosling et al., 2017; Resende et al., 2019; Zhu et al., 2023). The changes in climate are expected to manifest through modifications in precipitation patterns (intensity, duration, and seasonal shifts), variations in wind (speed, duration, and direction), fluctuations in solar radiation intensity, and shifts in minimum and maximum temperature, among other related variables. Higher precipitation may compromise soil aeration, disrupt the absorption of nutrients by plant roots, and lead to increased runoff and nutrient leaching (Teng et al., 2012). Despite significant advancements in technological solutions aimed at enhancing agricultural resilience to extreme weather events (e.g., development of drought-resistant plant species), climate change continues to pose a substantial threat to agricultural productivity and sustainable development (Birindelli et al., 2022; Ma et al., 2024; Resende et al., 2019). It is important to note that these potential impacts extend beyond local and regional scales and have global relevance, posing threats to global food security and the availability of water resources (Alcamo et al., 2007; C.-C. Lee et al., 2024). While the effects of climate change are inherently global, the local and regional consequences may be more pronounced and devastating in terms of environmental impacts and the magnitude of experienced changes, encompassing shifts in temperature, precipitation, wind patterns, solar radiation, and more. Therefore, the significance of conducting local and regional studies that specifically address the effects of climate change on localized processes can not be understated (Zhang et al., 2023).

Recent studies have highlighted a global escalation in environmental degradation, resulting in the deterioration of water resources, soils, vegetation, and biodiversity (du Plessis, 2022; Kumar et al., 2024; Prăvălie et al., 2021; Sartori et al., 2024). Paradoxically, the expansion of monitoring networks and the development of innovative monitoring and diagnostic methodologies have not kept pace with this alarming trend (Lopes et al., 2010; J. A. Anache et al., 2017). In situ data collection and monitoring of hydrological variables over long periods are scarce, especially in developing countries. One of the major factors contributing to this deficiency is the exorbitant cost associated with acquisition and maintaining monitoring equipment, rendering it inaccessible to the majority of research institutions. Hence, development and implementation of monitoring techniques and methodologies capable of assessing soil and water degradation are imperative, with a focus on ensuring food, energy, and water security.

In light of escalating demands for food, fiber, and energy production, coupled with the substantial environmental transformations arising from the conversions of LCLU and climate change, it becomes imperative to undertake research endeavors aimed at comprehending the influence of anthropogenic alterations on hydrological processes under actual and future climate conditions. Furthermore, a comprehensive grasp of infiltration and surface runoff mechanisms assumes pivotal significance as a foundational step in devising strategies for the restoration and conservation of natural vegetation, ultimately ensuring the sustainability of ecosystems. Lastly, more assertive assumptions about soil-vegetation-climate connections are feasible under economically accessible sensor employment (1) long-term hydro-climatic monitoring and (2) hydrological and climate change modelling (3).

1.2 Objectives

The overall objective of this thesis is to provide a better understanding of how changes in land use and land cover and climate influence water fluxes (surface, subsurface movement, and runoff) and soil loss in the Cerrado biome. To achieve this goal, the following specific goals are stated:

1. Develop low-cost solutions for runoff and soil water content monitoring, addressed through **Paper I** and **Paper II**;
2. Evaluate the current trend (last 10 years) and differences in surface runoff and soil loss in experimental plots under common agricultural land uses in the Southeast region of Brazil (Cerrado, soybean, pasture, sugarcane, and bare soil), addressed through **Paper III** ;

3. Evaluate the interactions between soil-vegetation-atmosphere and their influence on soil loss (**Paper IV**) and water balance components (**Paper V**) under scenarios of climate change at intermediate (year 2070) and distant (year 2100) future periods.

1.3 Thesis structure

This thesis follows the format of a compilation of papers introduced in the thesis summary. These papers are appended just after this summary while a brief description of the appended papers and their interconnection is presented below:

Automated soil moisture systems are commonly used in precision agriculture. By employing affordable sensors, it is possible to maximize spatial coverage, albeit at the potential expense of accuracy. In **Paper I**, an assemblage of low-cost hardware and open-source micro-controllers to create an affordable soil moisture monitoring station is proposed. The proposed setup is an accessible alternative for the monitoring of soil water content at research centers and farms with budgetary constraints.

The monitoring of surface runoff at experimental plots and small catchments is a laborious, time-consuming, and costly task. **Paper II** brings a novel standardized framework for the design of flow meter tipping buckets (here called TB) that can be used for low-cost and real-time runoff monitoring under many different conditions. The proposed framework is adaptable to most environmental conditions to provide continuous runoff data records. Both technologies proposed in **Paper I** and **Paper II** were tested in laboratory and later employed in field monitoring study areas, providing complementary soil moisture and runoff data.

Based on 10 years field monitoring, **Paper III** presents a detailed investigation of the long-term trade-off between common agricultural land covers (sugarcane, pasture, and soybean), runoff, and soil loss rates. In **Paper III**, a comparison between different agricultural land uses in relation to native forest (wooded Cerrado) and bare soil conditions enabled conclusions about the actual rates in runoff and soil transport under changes in land treatment.

Paper III highlights that extensive agricultural-driven land-use changes have significantly altered the landscape, causing increased soil erosion. However, what are the expected variation in soil loss due to alterations in rainfall patterns (rainfall intensity and amount) due to climate change? **Paper IV** describes the employment of calibrated Universal Soil Loss Equation (USLE) to predict changes in soil loss for the different LCLUs.

Finally, **Paper V** advances in the investigation of climate change effects on common LCLU, now looking at changes in water balance components (surface flux, evaporation, soil-water storage, infiltration, bottom flux, and root uptake) under different LCLUs. Analyses in **Paper IV** and **Paper V** are relative to intermediate (2040-2070) and distant future (2071-2100) periods.

This thesis summary comprises five chapters. Chapter 2 (Theoretical Background) offers a concise overview of the theoretical foundation, introducing key concepts and references that underpin the attached studies. In Chapter 3 (Materials and Methods), the materials and procedural steps taken in the development of the attached manuscripts are presented. Moving in Chapter 4 (Results and Discussion), the primary findings of the studies are highlighted, related to each other, and connected to the main goal of the thesis. Finally, Chapter 5, entitled ”General Conclusions” presents the primary conclusions drawn from the thesis and outlines potential societal contributions.

Chapter 2

Theoretical background

This chapter describes the theoretical background to the thesis development and presents the main references on which the thesis is based. The chapter is composed of three sections: water cycle and related components (i), low-cost monitoring and technologies (ii), and climate change projections (iii).

2.1 Water cycle

2.1.1 Superficial flux

The soil has a maximum infiltration rate ($mm.h^{-1}$), once the precipitation intensity exceeds this capacity, surface runoff begins. This phenomenon is characterized by the accumulation of water in a laminar manner on the surface which, due to the action of gravity, follows the slope of the land, running superficially. The impact of water drops on the soil, a phenomenon called splash, disintegrates soil particles that are transported by water to other regions. During this transport, the shear stress of the water under the soil plus the collision of previously removed particles collide and disaggregate other particles, as in a cascade effect.

Surface runoff (from now on just called runoff) is associated with different environmental conditions, which can be grouped into two distinct groups. The first of these refers to climatological variables, such as intensity, duration, distribution of precipitation, and antecedent humidity conditions. Finally, the second group refers to geomorphological variables, covering land use and cover, soil type, contributing area, slope, relief, elevation, and drainage network (Hillel, 2003; Nearing et al., 2017).

It is important to highlight that surface runoff is a natural phenomenon, however, it is also strongly affected by human interference by changing its maximum intensity, response speed, and duration. Changing LCLU through the conversion of natural areas into agricultural or urban areas affects surface runoff in different ways. Compared to native land uses, agricultural areas commonly have lower evapotranspiration rates, higher density of superficial root that are less efficient in creating preferential paths for water infiltration, reduced leaf area for interception of raindrops, smaller production of potential organic matter for the agglutination of soil particles, and are subject to constant agricultural management that destabilizes and disrupts the surface layers of the soil (Roderick and Farquhar, 2011).

The intensification of surface runoff associated with erosion results in several environmental and economic losses. The removal of fine particles (clay and silt) and organic matter from the soil reduces its stability and water storage capacity, increasing vulnerability to crusting and water stress (Stroosnijder, 2009). The removal of these particles prevents the proper functioning of the physical, chemical, and biological processes that guarantee the survival of agriculture, limiting agricultural production and interfering with food security (Wolka et al., 2018). In this context, it is estimated that erosion is responsible for the decline in agricultural production of between 0.5-1% in Burkina Faso (Niemeijer and Mazzucato, 2002) and 1-2% in Ethiopia (Adgo et al., 2013).

2.1.2 Sub-superficial fluxes

Soil can be classified as an unsaturated compound (vadose zone) - a three-phase medium composed of solid material (soil particles and minerals), liquid (water), and gaseous material (oxygen and carbon dioxide, mainly) - or saturated, when composed only of solids and liquids (Libardi, 2005). The soil water content is a constituent part of the soil, indicating ratio (mass or volume) of water per solid constituent. Briggs, 1897 was one of the pioneers in subsurface studies and he highlighted that soil moisture manifests itself in three ways: gravitational, capillary, and hygroscopic. Gravitational soil water represents the water content present between the macropores. Being governed by gravitational forces, it drains quickly in around two to three days. The water content present in the soil's micropores is called capillary soil water. In this case, water is linked to the soil through adhesion and cohesion forces that prevent rapid movement in the soil under the action of gravity. This is the portion of water used in all physical, chemical, biological, and mineralogical reactions. Lastly, hygroscopic humidity is that layer of water that covers the surface of fine particles and as they are not stored within pores, they are difficult to remove due to the presence of intense adhesion forces. Subsurface flow is defined as the vertical movement of water through soil layers, resulting from the action of gravity and soil capillarity. Soils with larger pores facilitate the action of gravity, while smaller pores make the passage of water difficult and favor capillarity (Libardi, 2005).

Soil water content and movement are functions of the infiltration rate, defined as the amount of water that passes through a given surface area of soil per unit of time. Notably, the soil infiltration speed tends to decrease throughout the precipitation process due to the saturation of the soil pores. A graph whose ordinate axis is the infiltration rate and the abscissa axis is time is known as the infiltration law. When the infiltration rate reaches a constant value, the maximum infiltration capacity of this soil is identified and with an increase in precipitation beyond this capacity, surface runoff occurs (Kirkham, 2014). The infiltration soil capacity is a function of several variables, including: porosity, permeability, structure, texture, soil cover, hydraulic conductivity, precipitation intensity and duration, and antecedent humidity (Morbidelli et al., 2018).

One of the most known studies involving water flow in vadose zone were carried out by Darcy, 1856. In his work he showed that the water flow through a porous material can be expressed as a function of the material's hydraulic conductivity and the hydraulic gradient, this is known as the Darcy's law (Equation 2.1). The negative sign of the equation is due to the flow direction being opposite to the gradient.

$$q = -K\left(\frac{\partial\psi}{\partial z}\right) \tag{2.1}$$

Where: q is the water flow in the porous medium per unit of time ($m.h^{-1}$); K is the saturated hydraulic conductivity ($m.h^{-1}$), ψ is the soil potential (m), and ∂z is the infinitesimal depth difference (m).

Darcy's Law is valid only for incompressible and isothermal liquids flowing in saturated porous media under one-dimensional and laminar flow at low velocities (Bouwer, 1978). In unsaturated environments, soil pores are filled by the air-water mixture, reducing the effective area for water flow (Hillel, 2003). In these systems, hydraulic conductivity is lower when compared to saturated soil, and simulation difficulties and uncertainties increase.

Later, in 1907, Darcy's equation was generalized for flows in unsaturated media, called the Darcy-Buckingham Law. Richards (1931) was the one who organized the mathematical functions that determine the flow in an unsaturated medium (Equation 3.2), in which hydraulic conductivity is no longer a constant, but a function of soil water content (Morais, 2012).

$$q = -K(\theta)\left(\frac{\partial \psi}{\partial z} + 1\right) \tag{2.2}$$

Where: q is the water flow in the porous medium per unit of time ($m.h^{-1}$), $K(\theta)$ is the unsaturated hydraulic conductivity, ψ is the soil matric potential (m), and ∂z is the infinitesimal depth difference (m).

Libardi, 2005 cites the soil water content as the most relevant among the various factors that influence the hydraulic conductivity of unsaturated soil. Falleiros et al., 1998 found that the relationship between soil water content and soil conductivity is so significant that a variation between 1 and 2% on soil water content resulted in changes greater than 170% in hydraulic conductivity.

The total soil matric potential, mentioned in the Richards Equation (Equation 3.2), is the sum of the gravitational, pressure, matrix, and osmotic potentials. The gravitational and pressure potentials depend on the position and gravity reference, and can be determined by the available liquid column. The matrix potential is estimated by the suction pressure or adhesion force of water to soil particles, a function of the water column, and the water retention curve in the soil. Finally, the osmotic potential is a function of the salt variation in the medium and, due to its difficult quantification, is commonly ignored (Reichardt, 1996).

2.2 Low-cost monitoring

The agriculture is under pressure to increase productivity in response to global population growth under a latent scenario of climate change (Benke and Tomkins, 2017) and post-pandemic (Montoya et al., 2020). In this context, the use of sensors and hardware are potential aids in increasing productivity, monitoring pests, and reducing the consumption of inputs (fertilizers and agrochemicals) and water. However, the use of automation systems and monitoring centers requires a high acquisition investment which is, in most cases, unfeasible even for large agricultural producers (O'Sullivan et al., 2019).

Advances and investments in the information technology, automation, long-lasting hardware, and communication sector allow the development of low-cost instruments to be used in agriculture and environment monitoring. The vast majority of current sensors are used to monitor climatological variables and irrigation automation (Hong and Hsieh, 2016), since water is the limiting input in the agriculture sector. Other applications include data transmission centers (Spinelli and Gottesman, 2019), continuous monitoring systems to determine the best harvest time (Jiang et al., 2018), and monitoring of pests and diseases (Trilles et al., 2020). The importance of using low-cost sensors goes far beyond their potential and latent application in agriculture, covering topics such as validating monitoring carried out by remote sensing (Cosh et al., 2016), investigating the influence of vegetation on hydrological processes (Baatz et al., 2015) or the characterization of variability in soil properties (Qu et al., 2014).

Currently, the hydrological monitoring network used in Brazil is almost entirely made up of imported sensors and hardware that have high acquisition and maintenance costs. When any of this equipment has an operational problem, monitoring is stopped permanently or temporarily over months while the equipment is sent abroad for maintenance. These are some of the factors that make the historical series of the Brazilian monitoring network temporally limited and spatially heterogeneous. Similar, such situation is also the case in other countries. In this context, there is an urgent demand for greater investments in the technological sector for the development of technologies using low-production-cost hardware (Schwamback et al., 2023).

2.3 Climate change

Climate change refers to modifications in local, regional, and global climate patterns, resulting mainly from anthropogenic activities occurring in the last 100 years (Bindoff et al., 2013). Global warming is one of the effects of climate change and refers to the increase in the long-term global average temperature of the Earth's surface due to emissions of greenhouse gases since the pre-industrial period. This warming is currently estimated to be between 0.55° and 0.80°C (Hawkins et al., 2017). Climate change impacts are distributed globally with an unpredictable pattern across the globe (Løvsletten and Rypdal, 2016), where some regions actually are experiencing longer winters (Cohen et al., 2018). However, what has generally been observed is an increase in the global average temperature resulting in mild winters and intense heat waves during summers (Y. H. Kim et al., 2016).

Climate change projections are carried out through General Circulation Models (GCMs), representing the physical processes occurring in the atmosphere, ocean, cryosphere, and Earth's surface. As they cover global phenomena, they have difficulties in representing climate events occurring in the lower atmosphere, on a spatial scale smaller than 200 km (Maraun et al., 2010). Aiming to identify the global response to anthropogenic changes, the Coupled Model Intercomparison Projects (CMIP) were created by the World Climate Research Program. Models integrating this project, in addition to the aforementioned physical processes, include the historical forcing of greenhouse gas emissions to project the long-term climate (e.g. up to the year 2100) under different emission scenarios (Gulcebi et al., 2021).

In CMIP5, the center of climate projections is based on the consideration of CO_2 emission or atmosphere concentration scenarios at the end of the 21st century, called Representative Concentration Pathways (RCPs). Four RCPs were formulated that are based on a series of projections of future population growth, technological development and societal responses to climate change. The labels for the RCPs provide a rough estimate of solar radiation forcing in the year 2100 (relative to pre-industrial conditions). For example, the forcing in RCP8.5 projected a increase of solar throughout the 21st century reaching a level of about 8.5 $W.m^2$at the end of the century. In addition to this "high" scenario, there are two intermediate scenarios (RCP4.5 and RCP6) and one low (RCP2.6) emission projection, where solar radiation reaches a maximum near the middle of the 21st century before decreasing to an eventual nominal level of 2.6 $W.m^2$ by the end of the century (Taylor et al., 2012).

Currently, the models that make up the CMIP group are part of its sixth edition (CMIP6) and are used during the preparation of Assessment Reports by the Intergovernmental Panel on Climate Change (IPCC), linked to the United Nations Environment Program and the World Meteorological Organization. Current models that integrate the state of the art in climate projections appear based on addressing the main limitation of their predecessor CMIP5: representation of physical processes on a better spatial scale (Stouffer et al., 2017), improvements in capturing observed global and regional patterns of temperature extremes (Y.-H. Kim et al., 2020). Additionally, CMIP6 has a larger historical time window. Its predecessor included data between 1950 and 2005, compared to current models that integrate historical series between 1850 and 2014 (Eyring et al., 2016).

The foundation of CMIP6 is made up of a wider spectrum of forcings (Shared Socio-Economic Pathway - SSP) than the RCPs at CMIP5 models, including more comprehensive socioeconomic conditions. In a simplified way, RCPs and SSPs are similar, but the latter allows for a more detailed assessment of how socioeconomic and political decision-making interferes with processes at different spatial scales (Eyring et al., 2016). Since CMIP6 has many simulations for the same forcing, there is a reduction in the internal variability of the model (Bourdeau-Goulet and Hassanzadeh, 2021; Eyring et al., 2016; Stouffer et al., 2017), which ends up differing from the RCPs curves (Figure 2.1).

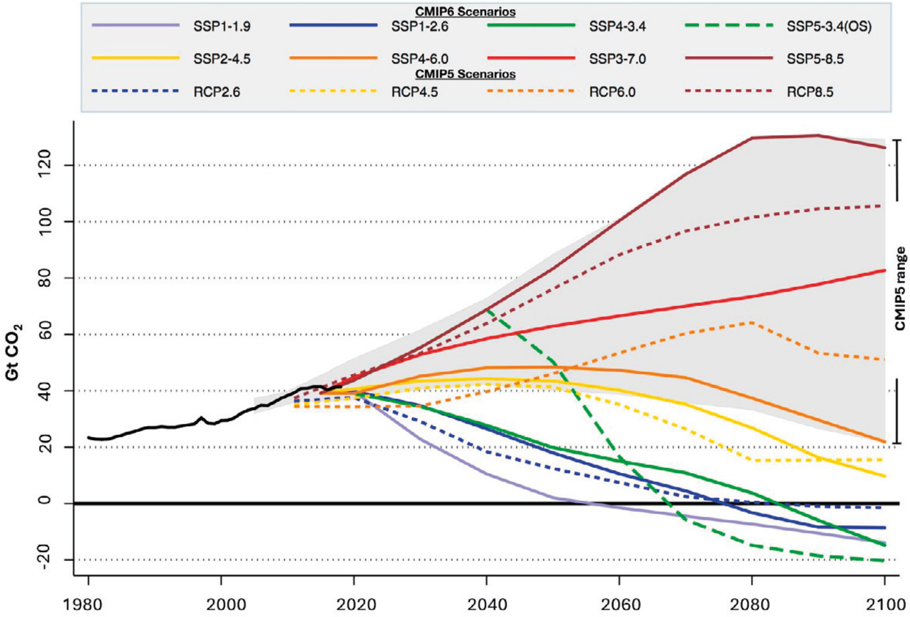


Figure 2.1: Comparison between different RCRs of fifth generation (CMIP5) and SSPs of sixth generation (CMIP6, O'Neill et al., 2016).

Chapter 3

Materials and Methods

This chapter summarizes the study area (section i), as well as methodological processes and material employed during field monitoring (section ii) and simulations of soil loss, water balance components and climate change (section iii). For a more extensive methodology description, please check the appended papers referred at each section.

3.1 Study area

The study area is located at the Arruda Botelho Institute (IAB) in Itirapina, located in the central region of the State of São Paulo, Brazil (latitude 22°10'S, longitude 47°52'W, elevation 790m, Figure 3.1). The area experiences an average annual rainfall of approximately 1,500 mm, mean temperature of 21.6 °C, and relative humidity of 71%. According to Köppen's classification (Alvares et al., 2013), the climate is categorized as humid subtropical (Cwa), featuring hot and humid summers (November to March), while winters are cold and dry. The characteristic soil in the study area is the Ortic Quartzarene Neossolo (RQo), characterized by a sandy texture, good drainage, acidity, and poor nutrient content (EMBRAPA, 1997). See on Table 3.1 the pedological characteristics of the study area.

The field monitoring took place on experimental plots, limited standardized areas of 100 m^2 (20 m long and 5 m wide) with 9% slope gradient. The plots are spread on two sites based on the land treatments that are commonly found on the Southeast region of Brazil: sugarcane (here used the acronym SC), pasture (PS), soybean (SB), and bare soil (BS) at Site 1, and wooded Cerrado (WC) remnant area at Site 2. More details about agricultural procedures on land treatment is given on **Paper III**. The pasture plots were replaced with soybean in November 2019 to follow the same agricultural

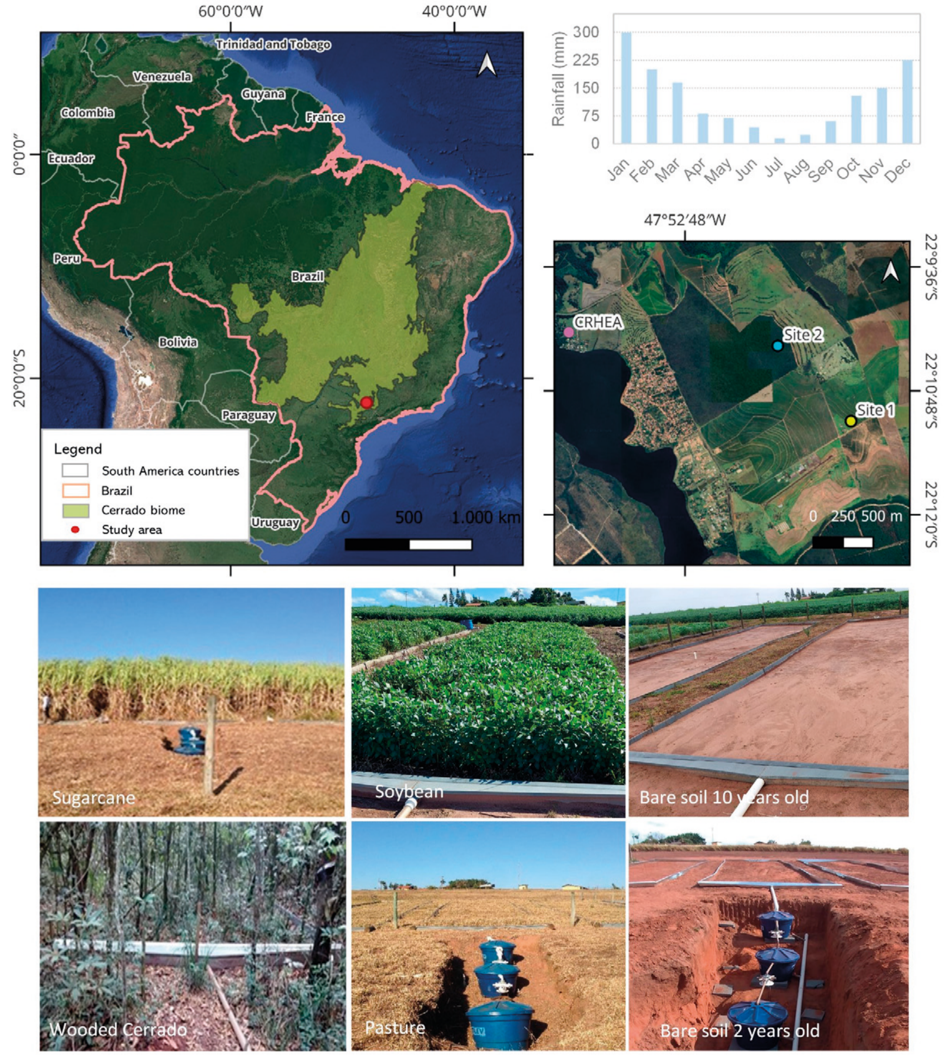


Figure 3.1: Study sites location, monthly rainfall distribution, and photos of experimental plots.

land treatment from the surrounding farm. After nine years of exposure to atmospheric conditions, plot without vegetation (bare soil) had suffered from weathering, which was identified on pedological analysis (**Paper III**) and even visually in Figure 3.1 . Therefore, we idealized that long-term weather exposure is a natural phenomena and understand such behavior on erosion and surface runoff is important. For such investigations, new plots under bare soil were constructed in 2020 (here called BS2) to be comparable with monitoring from those installed on 2011 (BS10). In Figure 3.2 there are some photographs of the construction process, while in Figure 3.3 we provide a timeline of monitoring according to each land treatment.

Table 3.1: Pedological characteristics of the study area.

Depth (cm)	Bulk density ($g.cm^{-3}$)	Sand (%)	Silt (%)	Clay (%)	pH	Particle Density ($g.cm^{-3}$)	Hydraulic Conductivity ($mm.h^{-1}$)
15	1.399	85	4	11	4.73	-	-
30	1.499	83	4	13	4.55	2.64	147.31
60	1.495	81	5	14	4.52	2.65	117.01
90	1.501	81	8	12	4.33	2.65	129.34

3.2 Field monitoring

3.2.1 Conventional monitoring

The total runoff measurement in each land treatment after a rainfall event was indicated by the volume stored in 310L boxes. The sediment concentration in the runoff following each event was assessed gravimetrically in the laboratory. The identical gravimetric procedure was applied to determine the solid mass of soil collected from outlet border that did not reach the storage tanks. Consequently, the total soil loss after a rainfall event was calculated as the sum of the product of sediment concentration and runoff volume with the dry mass of soil retained in the collectors.

Besides runoff and soil loss, atmospheric data (rainfall, air humidity and velocity, maximum and minimum temperature, and solar radiation) was collected at daily resolution by an automatic weather station located near site 1 (Centro de Recursos Hídricos e Estudos Ambientais - CRHEA station). Figure 3.4 provide the climate variable oscillation from the entire timeline of field monitoring (from Nov/2012 to April/2022).

When the experimental plots were constructed (2011), soil moisture at plots under WC, PS and SC were monitored using Frequency Domain Reflectometry (FDR) sensors. The FDR is composed of conductive plates in parallel separated by insulating material, forming a capacitor, which leads to this probe be also known as a capacitance probe. The probes are called EnviroSCAN, purchased from Campbell Scientific. In SC and PS plots, the probe was installed at 30, 60 and 90 cm deep, while at 10, 50, and 70 cm deep in WC. In both areas, the probes collect data at 10-minute intervals. Figure 3.5 shows a schematic drawing of the EnviroSCAN probe and photos of the probes installed in the field.

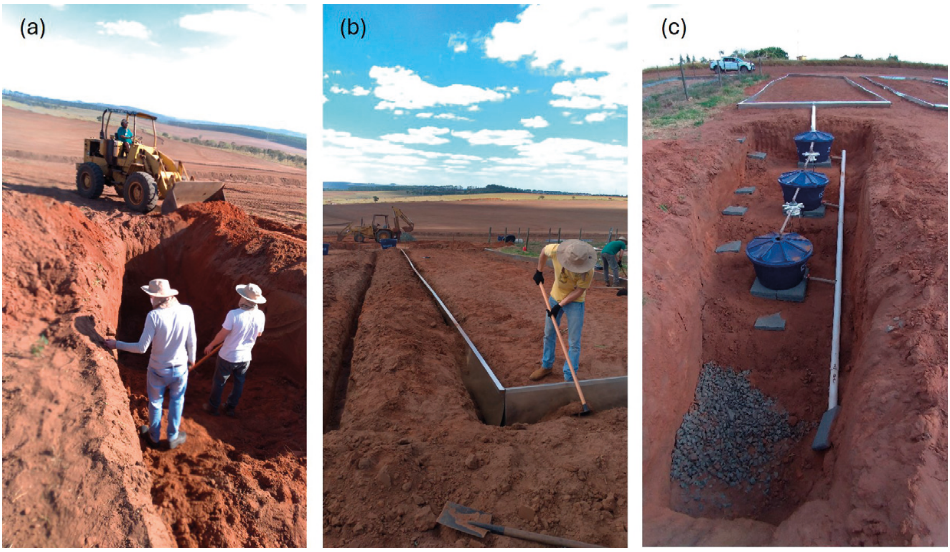


Figure 3.2: Photographs of the construction process of new experimental monitoring plots under bare soil. In the details of excavation for drainage system (a), barriers installation (b), and when completed (c).

3.2.2 Soil moisture monitoring employing low-cost sensors

When the experimental plots were installed (2011), the soil moisture monitoring was based on commercial sensors. However, by reaching lifespan after eight years, some of those commercial sensor stopped readings or had inaccurate results. Understanding the societal purpose of research to test alternative solutions to common challenges, the first technology proposed was a low-cost alternative for soil water content (SWC) monitoring. We had tested different resistive and capacitive commercial sensors and the most reliable one was the SKU:SEN0193 capacitive sensor, hereafter just called SKU sensor.

Among the advantages, the SKU sensor has a low-acquisition cost (around $5), easily found in electronics stores, adapted to open-source micro-controllers (arduino or raspeberry), and operates under low-voltage (3.3 to 5.5 V). The device outcome data is expressed through frequency oscillation, commonly between 260 Hz (high soil water content) and 520 Hz (low soil water content). Once you buy the SKU sensor, it comes as shown in Figure 3.6a, with exposed electronic components that need to be protected for longer lifespan. Considering the sensor optional soil contact area and durability, electronic components were impermeability with enamel, wrapped with heat shrink, protected with a plastic case, and later filled with silicone (Figure 3.6b). A better description of the sensor is given on **Paper I** and by Placidi et al., 2020b.

The sensors were tested in laboratory and field conditions to investigate the sensor´s re-

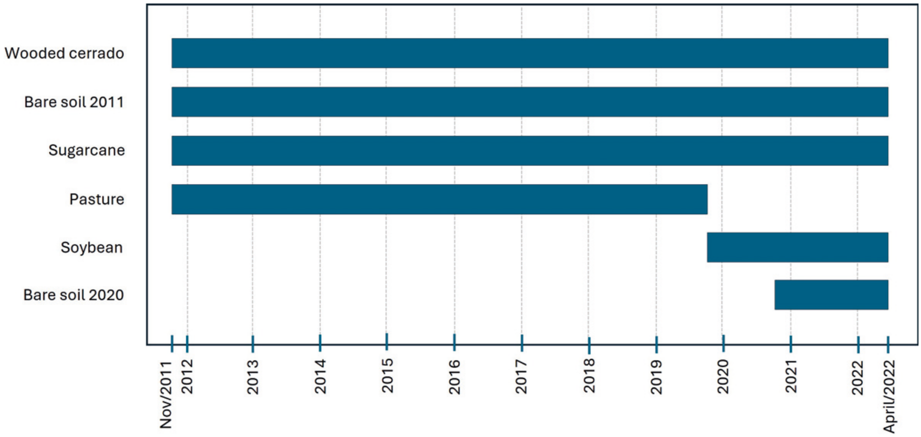


Figure 3.3: Period of field monitoring according to the each land treatment.

sponse under different input voltage, temperature, and soil moisture conditions. The first setup in laboratory aimed to evaluate the reliability of sensors during calibration. We employed 11 pots of 600 cm^3 of disturbed soil samples with known volumetric soil water content collected at 30 cm deep in the area where the field tests were later carried out (see soil composition on Table 3.1). The same calibration procedure was followed using input voltage of 3.3 and 5.5 volts. Lastly, to explore the temperature interference, sensor's response on soil samples with a SWC of 0.18 $m^3.m^{-3}$ were analysed during the switch from room temperature (20 ºC), to refrigerator (2 ºC), and later to inside an oven with a controlled temperature (32 ºC).

The last stage was installing the sensors under atmospheric conditions at the study area. The sensors were installed in April/2021 at depths of 10, 30, 60, and 90 cm. We built an monitoring station, where data storage were enabled throughout the datalogger shield, while a relay shield allowed current to pass to the sensors only at the time of data collection, saving power and expanding the sensors' lifetime. The station was powered by solar panels during daylight, while by batteries during night. In **Paper I** a setup of the monitoring stationis provided including cost of materials and electronic scheme for replication. In Figure 3.7 there some photographs of sensors and monitoring station in the field.

3.2.3 Runoff monitoring employing TBs

Once the infiltration capacity of the soil is reached during a precipitation event, surface runoff begins and, due to gravity, moves superficially following the terrain slope. The experimental plots were installed in November, 2011 and since then, runoff monitoring had been limited to the total volume stored on box after a rainfall event, as described on related research developed on the same study area (J. A. Anache et al., 2018; Oliveira, Wendland, et al., 2015; Oliveira, Nearing, and Wendland, 2015). Acknowledging that having more detailed information regarding start, peak and end flow would benefit future modeling and better understanding of hydrological processes under different land treatments. Therefore, the second technology proposed during this thesis was the use of large tipping buckets (TBs) for the monitoring of surface runoff. Among the options for real time monitoring, we chose TBs as it is a simple, durable, low-cost alternative and adapted to remote areas that lack electricity. Its operational principles is the same behind rain gauge equipment, but at large scale: when a cavity attains a critical volume (its nominal volume), the structure's center of mass is influenced by gravity, causing a shift toward the side with the filled cavity (see Figure 3.8). This movement directs the water volume downward, expelling it, while the other cavity begins to fill.

The first tipping bucket flow meter record used for measuring runoff in experimental plots (hillslope for runoff measurement) dates back to 1928 (Nebol'sin, 1928). Since then, there are many descriptions of constructing designs of TBs that differ based on the cavity shape (rectangular, circular, or triangular), rotating angle (180° or 360°), and number of cavities (two or multiple ones). However, there was not found a follow-up design or description that allow the reproducibility based on local flow conditions.

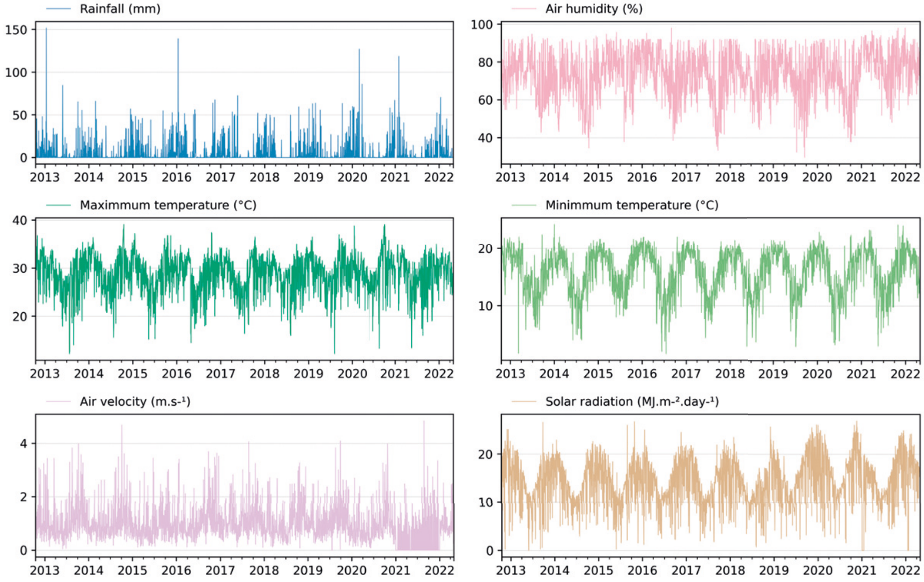


Figure 3.4: Climate variables (rainfall, air humidity and velocity, maximum and minimum temperature, and solar radiation) from study case.

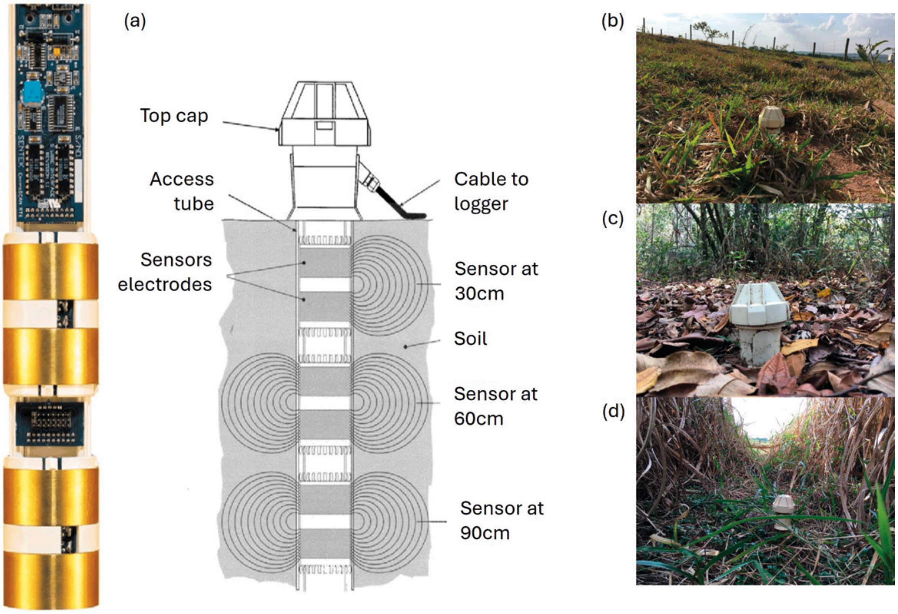


Figure 3.5: Schematic drawing of the EnviroSCAN probe (a) and photos of the probes installed in experimental plots covered with pasture (b), Cerrado (c), and sugarcane (d).

Therefore, on **Paper II** we introduced an innovative standardized framework for designing flow meter TBs. This framework facilitates the replication and deployment of TBs, enabling low-cost and real-time runoff monitoring in diverse environmental conditions.

The framework starts on identifying the inlet mean flow to be measured, here based on rational method but can be estimated by other methods. The second step was to identify the cavity volumetric and size, based on proposed empirical equations. Considering the volumetric capacity, later it is selected the cavity construction material (steel or PVC) and shape (cylindrical or rectangular). On **Paper II** is given all the assumptions, equations and step-to-step for TB sizing.

The proposed framework was applied for the sizing of four TBs aiming the runoff monitoring derived from experimental plots covered with sugarcane (here called TB1), soybean (TB2), and bare soil built in 2011 (TB3) and 2020 (TB4), see Figure 3.9. The equipment were tested in laboratory under known inflows ranging up to estimated rates corresponding to 100 year return period. Once constructed the calibration curves that correlated number of tipping to inflow, the TBs were installed in field on November, 2021 (see Figure 3.10).

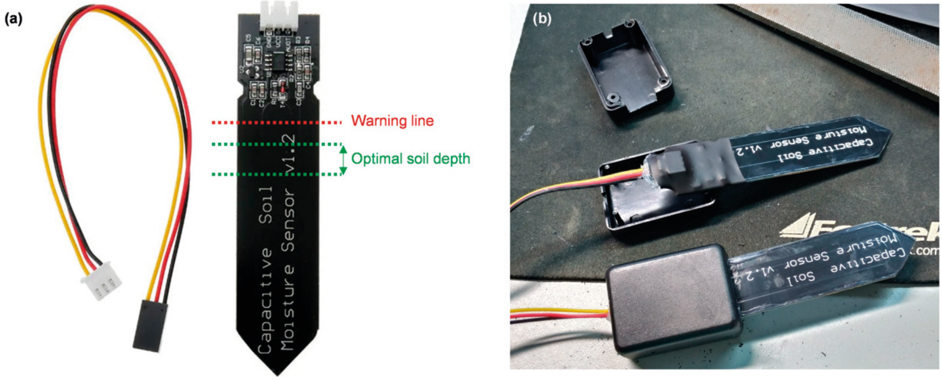


Figure 3.6: The optimal soil contact zone for the SKU:SEN0193 capacitive sensor for best response (a) and protection of its electronic components (b).

3.3 Simulations

3.3.1 Soil Loss: Universal Soil Loss Equation

To estimate the soil loss under current and future conditions, we employed the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith, 1978. The USLE is a well-established, worldwide used equation to estimate the average annual soil loss related with sheet and rill erosion occurrence, being composed by five factors describing the influence of climate (R), soil (K), topography (LS), vegetation (C), and management aspects (P):

$$A = R \times K \times LS \times C \times P \tag{3.1}$$

where A is the mean annual soil loss per unit area ($ton.ha^{-1}.yr^{-1}$), R is the rainfall erosivity factor ($MJ.mm.ha^{-1}.h^{-1}yr^{-1}$), C is the cover and management factor (dimensionless), K is the soil erodibility factor ($ton.ha.h.ha^{-1}MJ^{-1}.mm^{-1}$), L is the slope-length factor (dimensionless), S is the slope-steepness factor (dimensionless), and P is the support practice factor (dimensionless).

USLE related parameters were estimated based on field monitoring (precipitation and soil loss) occurring between Nov/2012 to Jun/2019 at bare soil, cerrado, pasture, and sugarcane covered plots. The remaining land treatments (newest bare soil and soybean) were not studied yet since they do not have sufficient data records that minimize occurrence of year-to-year outliers, as required by USLE designers. Rainfall erosivity of each erosive event was computed by the Rainfall Intensity Summarization

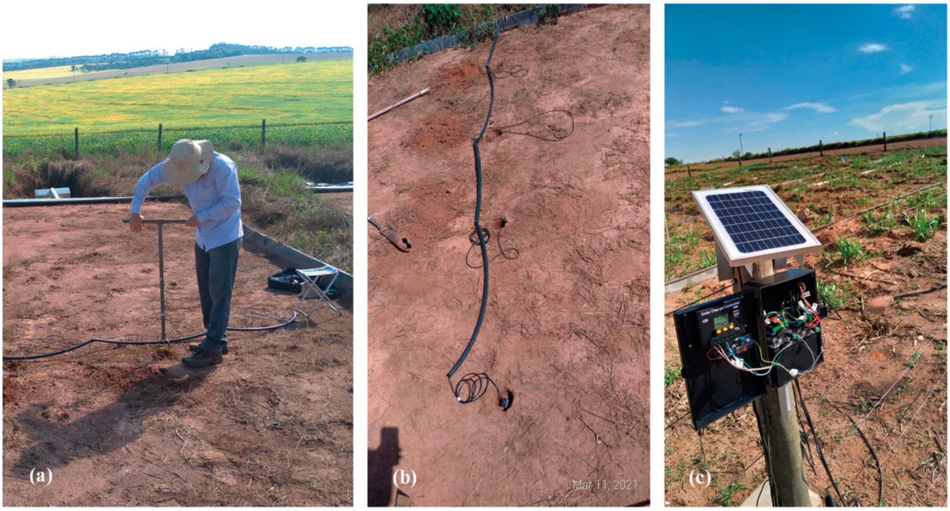


Figure 3.7: Photographs during drilling the soil (a) to install sensors at different depths (b), and a monitoring center station for soil water content (c).

Tool (RIST, USDA, 2013) employing the kinetic energy equation of each raindrop defined by L. C. Brown and G. R. Foster, 1987. The topography factor was calculated using D. K. McCool et al., 1987 equation, based on the field experimental plots setup of 9% slope and 20 m of plot length. The cover and management factor was derived by comparing the soil loss from each treatment to observation from bare soil. Soil erodibility were estimated based on a simplification of Equation 3.1 applied to long term soil loss conditions under bare soil treatment, where C factor is equals to 1. Lastly, no conservation practices were assumed (P factor equals to 1). More details about assumptions made for parameters related to USLE and soil loss estimations can be found on **Paper IV**.

3.3.2 Water fluxes: Hydrus

In **Paper V** we employed the Hydrus computational package (Šimůnek et al., 2008) to simulate the water balance components under current and future climate conditions. The software uses the finite element method to perform numerical solution of the Richards equation (Equation 3.2) to describe saturated/unsaturated flow:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + cos(\beta)\right)\right] - S(h) \tag{3.2}$$

The solution of Equation 3.2 requires knowledge of unsaturated soil hydraulic prop-

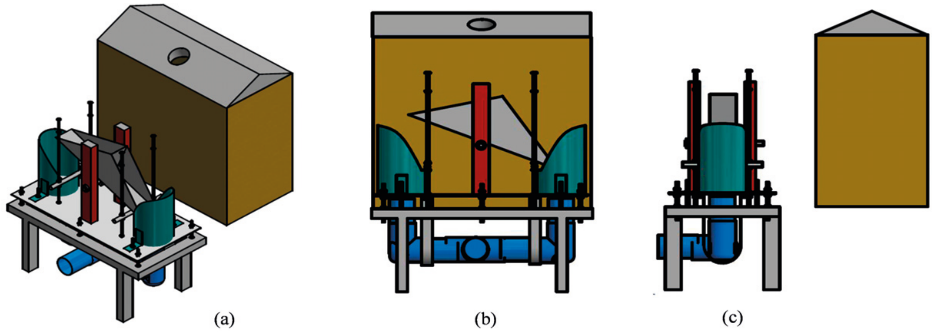


Figure 3.8: Illustration of the tipping buckets for monitoring surface runoff in perspective (a), front (b) and side (c) views.

erties ($K - \theta - h$), which may be described using the analytical functions defined by the van Genuchten-Mualem model (Mualem, 1976; van Genuchten, 1980):

$$K(h) = k_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{3.3}$$

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \tag{3.4}$$

where h is the air entry value, $m = 1 - 1/n$; θ_s is the saturated water content ($cm^3.cm^3$); θ_r is the residual water content ($cm^3.cm^3$) and equals the air-dried water content; θ_s is the saturated water content ($cm^3.cm^3$); k_s is the saturated hydraulic conductivity ($cm.min^{-1}$); $K(h)$ is the unsaturated hydraulic conductivity at pressure head h; α, m, and n are empirical constants that are related to inverse air-entry pressure value ($1.cm^1$), S_e is the effective water content (dimensionless); β is the angle between the flow direction and the vertical axis; and pore-size distribution, respectively; l is a shape parameter that equals to 0.5.

Out of the six experimental plots only three of them (cerrado, pasture and sugarcane covered) had long soil moisture records to enable Hydrus calibration. So, we employed daily soil water content data from those mentioned plots to calibrated soil parameters (residual and saturated soil water content, saturated hydraulic conductivity, tortuosity, and parameters α and n in the soil water retention function) that are related to water balance components (soil-water storage, bottom water flux, infiltration, surface water flux, evaporation, and root uptake). Monitoring from October 17th, 2012 to December 31st, 2016 were used during calibration while, from January 1st, 2017 to April 11th, 2019 were used for validation. After 2019, soil water content

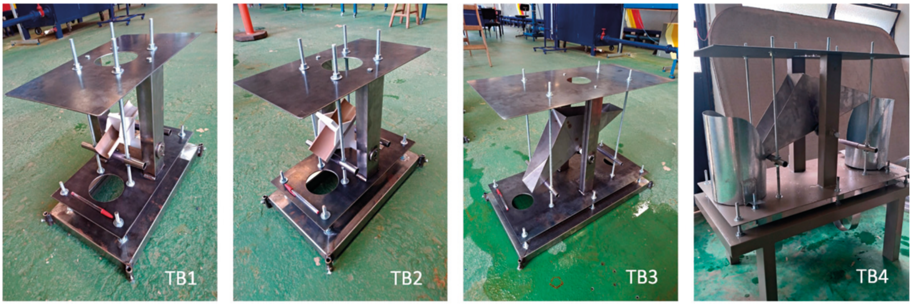


Figure 3.9: Photographs of the designed tipping buckets (TB) employed for monitoring at sugarcane (TB1), soybean (TB2), and bare soil built in 2011 (TB3) and 2020 (TB4).

monitoring sensor passed through instabilities and ending date was set to maximize the common period and provided the most reliable comparison among land treatments.

Based on observed soil texture and bulk density at each soil layer and plot coupled to the Rosetta Lite application (see Rosetta input data on Table 3.1), we estimated the soil parameters. All simulations were made in a 1-m deep soil profile with atmospheric conditions at the upper boundary and free drainage as the bottom boundary conditions. On **Paper V** we provide more information about crop parameter employed and other information not mentioned here.

3.3.3 Climate change

To evaluate the changes in water balance components (**Paper V**) and soil loss (**Paper IV**), we employed 17 climate models from Climate Change Dataset for Brazil (ClimBRA, Ballarin et al., 2023) that provided precipitation, maximum and minimum temperature, solar net radiation, near-surface wind speed, and relative air humidity data. The models are from the sixth generation of climate models (CMIP6, O'Neill et al., 2016), bias-corrected and at a 0.25° spatial resolution. The simulations encompassed a baseline period (1980–2013) and a future period (2015–2100), each propelled by two Shared Socioeconomic Pathways (SSPs): the middle of the road scenario (SSP2-4.5, updated CMIP5 RCP4.5 pathway) and the path characterized by fossil-fueled expansion (SSP5-8.5, updated CMIP5 RCP8.5 pathway). In Table 3.2 we provide a list of the climate models employed on the climate change analysis. Some models did not share statistical similarities between baseline period and local observations, and so they were not used on the erosion prediction (more details about this can be found on **Paper IV**). However, we did not take such consideration on the simulation of water balance components (**Paper V**) since we would end up with a very limited number of models.

Figure 3.10: Photographs of tipping buckets installed on study area for real time runoff monitoring.

Table 3.2: CMIP6 Climate Models employed on the climate change analysis.

Model	Country/Region	Reference
ACCESS-CM2[1]	Australia	Bi et al., 2020
ACCESS-ESM1-5[1,2]	Australia	Law et al., 2017; Ziehn et al., 2020
CMCC-ESM2[2]	Europe	Cherchi et al., 2019
EC-EARTH3[1,2]	Europe	Döscher et al., 2022
GFDL-CM4[1]	USA	Held et al., 2019
GFDL-ESM4[1]	USA	Dunne et al., 2020
HadGEM3-GC31-LL[1]	UK	Williams et al., 2018
INM-CM4-8[2]	Russia	Volodin et al., 2018
INM-CM5[2]	Russia	Volodin et al., 2017
IPSL-CM6A-LR[2]	France	Boucher et al., 2020
K-ACE[1]	South Korea	J. Lee et al., 2020
MIROC6[1,2]	Japan	Tatebe et al., 2019
MPI-ESM1.2-HR[1,2]	Germany	Gutjahr et al., 2019; Müller et al., 2018
MRI-ESM2[1,2]	Japan	Yukimoto et al., 2019
NESM3[1]	China	Cao et al., 2018
NorESM2-MM[2]	Norway	Seland et al., 2020
UKESM1-0-LL[1]	UK	Sellar et al., 2019

Notes: [1] indicate climate models employed for water balance components (**Paper V**); while [2] indicate models employed for erosion (**Paper IV**) predictions under climate change scenarios.

Chapter 4

Results and Discussion

In this chapter, the main results obtained from the appended papers are described and discussed, as well as how the results of these individual studies are connected to achieve the main goal of this thesis. In Section 4.1 details the setup of the monitoring station. In Section 4.2 presents the monitoring results, which are utilized in Section 4.3 to simulate soil loss under both current and future scenarios. Lastly, Section 4.4 applies these simulations to the assessment of the water balance in different LULCs under current and projected future conditions.

4.1 Development of low-cost alternatives for environment monitoring

Paper I summarized the setup, calibration, lab and field tests of the proposed low-cost soil water content (SWC) monitoring station. The tests of 63 sensors evaluated their sensitivity to temperature and voltage. Utilizing a supply voltage of 5.5 V made the correlation between the output and soil water content weaker. Therefore, we recommend employing a 3.3 V supply voltage. Soil temperature had a negligible effect on the sensor output, with a change of 0.001 $m^3.m^{-3}$ in SWC per degree Celsius.

Readings from different sensors could be different for the same soil water content, probably due to unregulated standardized electronic components among companies that manufactures the sensors. Therefore, each sensor needs to be individually calibrated using local soil sample from where they will installed. During individual calibrations, a good linear correlations between sensor output and soil moisture content was found (R^2 higher than 0.94). The scalability of the sensors are limited be the need for individual calibration. Therefore, in **Paper I** a single point (sensors response at dry soil) calibration is suggested as well as universal calibration curves.

After calibration, the sensors were tested in the laboratory under controlled conditions (constant temperature and inlet water flow) and were able to identify the wetting front arrival. Later, sensors were tested under field conditions (Figure 4.1). Similarly, the sensor were able to identify changes in the SWC near surface (10 cm depth) due to rainfall events. In addition to the hydrological oscillations, we observed daily fluctuations occurring more prominently for the near surface sensor and to a lesser extent at deeper depths. Owing to its proximity to the surface, soil water content experiences a decrease due to evaporation from solar radiation during the day. Conversely, during the night, lower soil layers replenish moisture to the upper layers, restoring the previously measured soil water content and generating cyclical variations. While these oscillations can be associated with the air temperature variations, their significance is limited due to the fact that the depths of the sensors are inversely proportional to the observed daily fluctuations.

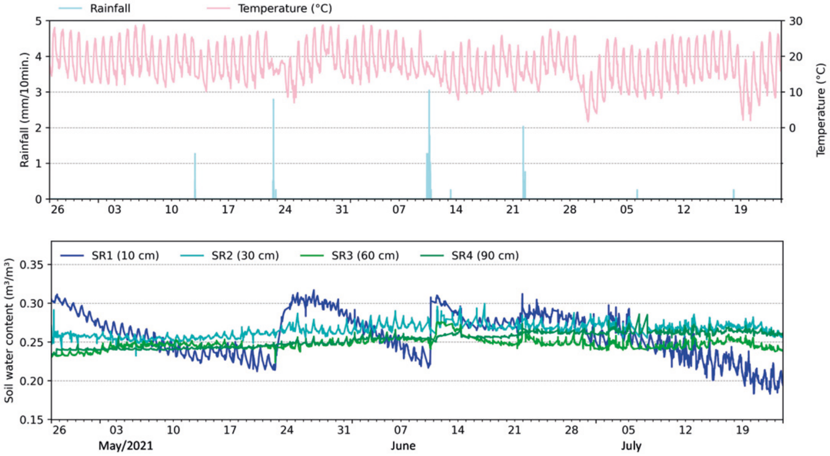


Figure 4.1: Observed soil moisture oscillations under field conditions employing low-cost sensors.

Similarly, the tipping buckets were firstly tested in laboratory under controlled conditions (continuous known in-flow rates) and later in field. During laboratory phrase, by implementing simple linear calibration curves we reached a good correlation (R^2 higher than 0.99) and a low mean error (smaller than 5%) between reference and measured flows. The field test showed that considering the designed operating velocity, most TBs were within the criteria of covering 85% of the accumulated runoff: TB1 (97%), TB2 (93%), TB3 (86%), and TB4 (67%), demonstrating that TBs are operating within a good velocity range and were well sized. In TB4, there is that unexpected lower performance, due to underestimation of runoff coefficient at bare soil plot (actual 0.098 instead of 0.063). To reach most suitable operation capacity, TB4 volumetric capacity needs to be adapted and it can be easily reached by lowering the height control bar, which will raise the inclination angle of the cavity at rested position (θ) from the actual 23° (0.4 radians) to 29° (0.5 radians). The entire description of calibration processes can be seem in **Paper II**.

The operating principle of TBs for measuring surface runoff and rainfall is the same, therefore, the errors to which they are susceptible are similar. As intensely described by Schwamback et al., 2022, errors can be grouped into two categories: systematic/mechanical and random. Systematic errors arise from the operation, construction material, and design of the equipment and are, therefore, more predictable and easier to correct. Random errors, on the other hand, are not predicted and result from unusual field operation situations, justifying constant verification during field trips. Despite the uncertainties arising from errors associated with monitoring, it was possible to correct the data collected through the volumes stored in the boxes and thus obtain flow curves that accurately represent the hydrological processes. To date, the most common obstacles identified in the field have been:

1. Clogging and sediment deposition bare soil plots due to high erosive capacity;
2. No data recording due to loss of lubrication due to rain events and high temperatures;
3. Failure in the electronic component related to recording system (reed switch and data logger);
4. Animals destroying the data transmission cable;
5. Entry of rodents and reptiles into the tipping buckets access pipe.

The use of automated TBs will not only allow for the quantification of surface runoff, but also the creation of runoff curves over time for different soil covers. Based on field monitoring phrase (**Paper II**), as expected, surface runoff was be greater in bare soil, followed by soybean, and sugarcane. Looking in detailed to runoff curves

Employing TBs for surface runoff monitoring is directly related to hydrographs that furnish details on the peak, volume, and duration of runoff events (See Figure 4.2). Acknowledging that individual runoff events are functions of many hydrological (rainfall duration, intensity, amount etc.) and pedological phenomena (soil disturbance, soil waster content, porosity, compaction, root density, leave area index etc.), we have assembled data to draw better conclusion (Figure 4.3). Comparing agricultural land cover, it was observed that the experimental plot covered with soybeans exhibited a mean runoff volume three times higher, along with shorter runoff duration and peak time, in comparison to plots covered with sugarcane. This discrepancy can be attributed to the fact that the soybean plot possesses a superficial root system, has a shorter life span, and undergoes annual harvesting and replanting, causing soil disturbance. In contrast, sugarcane boasts a deeper root system, slow vegetative development, and, in addition to yearly harvesting, is replanted along contour lines every four years. Comparing bare soil areas, the extended exposure period in BS10 induced changes in the pedological features, leading to differences on pore clogging, displacement of the surface soil layers, and particle breakdown. These modifications directly influence the soil's infiltration capacity, subsequently affecting the total drained volume and the duration of runoff. We highlight that up to the moment, **Paper II** is the only one that provide insights about agricultural runoff features occurring at event temporal scale at Neossolo Quartzarenic soil type.

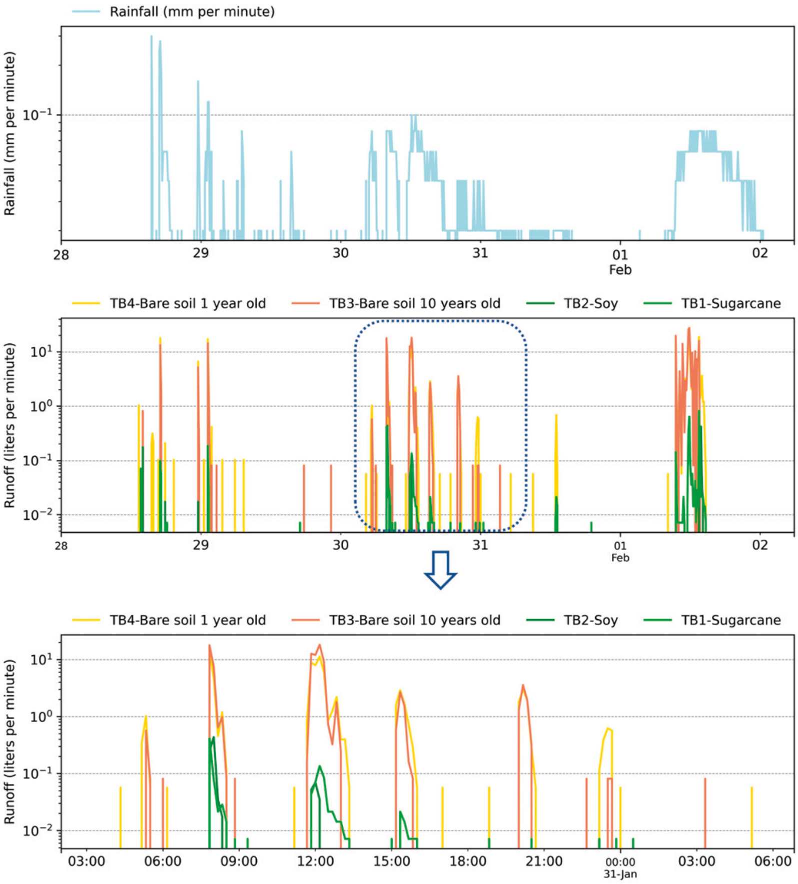


Figure 4.2: Real-time runoff by large tipping buckets flow meters monitored at experimental plots under bare soils 10 (BS10) and 2 (BS2) years old, soybean (SB), and sugarcane (SC) land covers.

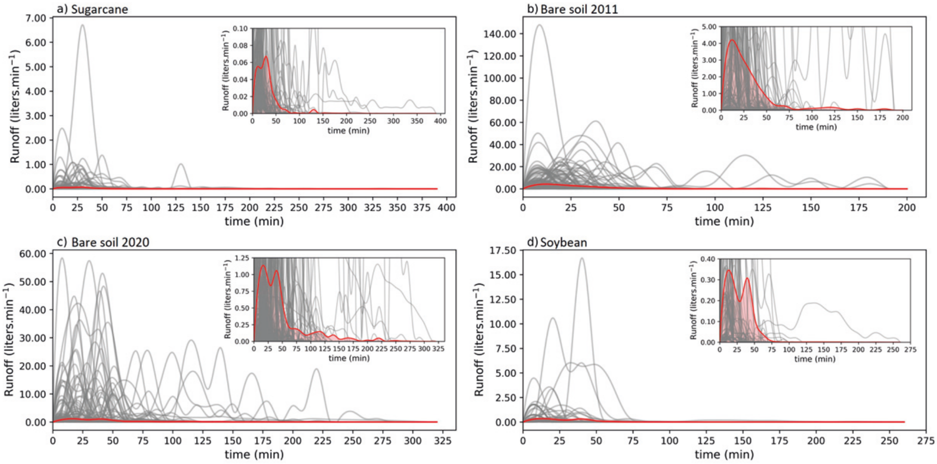


Figure 4.3: Runoff ensemble curves (grey color) monitored at experimental plots covered with sugarcane (A), bare soil since 2011 (B) and 2020 (C), and soybean (D). Inside each plot, we zoomed in for a better visualization of the mean runoff distribution (red color).

The proposed framework for TB design is easily adapted in diverse scenarios, encompassing various land uses, slopes, soil types, and hill slope sizes. In **Paper II**, some examples of TB volumetric capacity based on hypothetical contributing area and runoff factors were given. Understanding that the C-factor is most of the time complex to determine in ungauged areas, we also provided C-factor based on relief, infiltration capacity, vegetation cover types and surface storage. Using the standardized framework that we had presented, hydrologists have the ability to size and construct an inexpensive TB tailored to the specific environmental conditions they encounter (experimental plots, stem, green roof, or paved surfaces), enabling them to gather real-time runoff data.

The collection of in-situ data and the continuous monitoring of hydrological variables over extended periods are limited, particularly in developing countries. Monitoring water movement faces challenges, with factors such as high-acquisition costs of monitoring equipment straining the limited research budgets. The adoption of low-cost technologies could address this constraint, turning monitoring accessible to research centers with budgetary limitations. It is important to note that the sensors described for soil moisture (**Paper I**) and runoff (**Paper II**) are not designed to match the accuracy of commercial sensors. Instead, their purpose is to encourage monitoring from new perspectives (e.g. higher spatial coverage) without sacrificing an appropriate level of accuracy.

Lastly, in **Paper I** the trade-off components between accuracy and cost at commercial and low-cost sensors were highlighted. Commercial sensors offer high-reliability single-point information but come with a significant acquisition cost. In contrast, low-cost sensors, though less accurate and potentially requiring more labor, can be obtained in larger quantities with a lower initial investment. This enables a broader access to spatial and temporal variability of soil moisture. We concluded then that, the use of low-cost sensors are ideal for short-term and limited-budget projects in which high accuracy of the data collected is not required.

4.2 Long-term monitoring of runoff, soil loss, and soil water content

Table 4.1 provides a summary of the long-term average soil loss and runoff observed in the experimental plots, while bellow we point some of the correlating factors (linear relationship between soil loss and runoff, weather exposure time, rainfall intensity, rainfall duration, among others) and more details are given in **Paper III**. As anticipated, forest land cover (Wooded Cerrado) exhibited the lowest soil loss rate at 0.10 $ton.ha^{-1}.year^{-1}$, followed by agricultural land covers ranging from 0.16 to 0.57 $ton.ha^{-1}.year^{-1}$, and bare soil showing the highest rates at 22.4 to 27.8 $ton.ha^{-1}.year^{-1}$. A similar pattern was observed for runoff, with Wooded Cerrado having the lowest rate at 2.0 $mm.year^{-1}$, followed by agricultural land (11.3 to 38.5 $mm.year^{-1}$) and bare soil (115.1 to 121.0 $mm.year^{-1}$). Among the agricultural land covers, sugarcane had the highest soil loss, while pasture exhibited the highest runoff, making it unclear which agricultural land cover had the greatest environmental impact considering these two variables.

Table 4.1: Long-term annual mean soil loss ($ton \cdot ha^{-1} \cdot year^{-1}$), runoff ($mm \cdot year^{-1}$), and runoff ratios regarding rainfall monitored in the study site. Data based on sample size of 2796 monitored events and considering a mean rainfall of 1347 ± 195 mm.

Land Cover	Mean Soil Loss ± SD	Mean Runoff ± SD	Ratio between Mean Runoff and Rainfall
Wooded Cerrado	$0.10a \pm 0.08$	$2.02a \pm 1.14$	0.15%
Sugarcane	$0.57a \pm 0.70$	$11.33a \pm 14.26$	0.84%
Soybean	$0.19a \pm 0.16$	$16.33a \pm 9.54$	1.21%
Pasture	$0.16a \pm 0.17$	$38.47a \pm 25.58$	2.86%
Bare Soil 2 years old	$27.83b \pm 13.60$	$115.14b \pm 46.60$	8.55%
Bare Soil 10 years old	$22.39b \pm 10.66$	$120.99b \pm 49.54$	8.98%

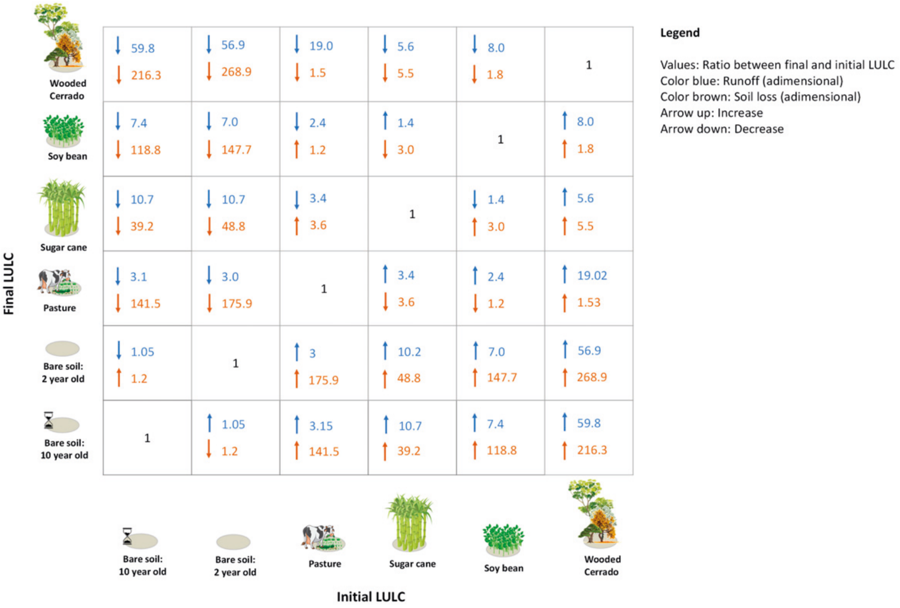
Note: a and b denote the statistical levels of the Tukey test means; that is, means followed by different letters are significantly different at 95% probability; conversely, means followed by the same letter are not statistically different. Lastly, SD indicate the standard deviation

In Figure 4.4 we present a summary of trade-offs concerning runoff and soil loss across various land covers. The conversion of wooded Cerrado to agricultural areas (soybean, pasture, and sugarcane) results in a substantial increase in runoff (1.5 to 5.5 times) and soil loss (5.6 to 19 times). Notably, transitions between common agricultural covers in Brazilian farms also yield significant alterations. For instance, converting pasture to sugarcane leads to a 3.6 times increase in soil loss but a 3.4 times reduction in runoff. Conversely, transforming soybean to sugarcane results in a 1.4 times reduction in runoff but a threefold increase in soil loss. This disparity between soil loss and runoff contributes to a shift in the ranking of endangered land covers (see Table 4.1). Areas exposed to environmental conditions without any cover in the short term (up to two years) exhibit heightened runoff (up to 10 times) and soil loss (up to 176 times) compared to agricultural areas.

In the case of heavily disturbed lands (refer to Table 4.1), specifically BS2 and BS10, the long-term mean annual soil loss rates exceeded the maximum acceptable threshold for deep, permeable, and well-drained soils like Neosolo (12 $ton.ha^{-1}.year^{-1}$, as per Bertoni and Lombardi Neto, 2017). Conversely, the mean annual soil loss rates for moderately disturbed lands resulting from agricultural activities (PS, SB, and SC) and natural lands (WC) were considerably below the minimum acceptable soil loss rate recommended by Bertoni and Lombardi Neto, 2017, as well as the previously estimated mean soil loss for the state of São Paulo (30 $ton.ha^{-1}.year^{-1}$, as per Medeiros et al., 2016). Among various factors, the reduced soil loss rates observed can primarily be attributed to compaction at PS and the implementation of conservation practices in the studied agricultural plots. Notably, practices like no-tillage, although increasingly adopted, have not yet been universally embraced as a conventional practice in Brazilian agriculture. Drawing upon other Brazilian studies conducted under similar Land Use and Land Cover (LULC) conditions as the present research (Brito et al., 2005; Castro et al., 2022; Engel et al., 2009; Marchioro and Augustin, 2007; Moreira et al., 2015; Youlton et al., 2016), the observed mean soil loss and runoff align within the range of previous measurements. Conflicting research findings regarding variations in runoff and soil loss rates among croplands underscore that the influence of land cover and cropping practices on runoff generation and soil loss production is highly contingent on the specific context of the study area (Ebabu et al., 2023), including factors such as rainfall patterns, compaction, and slope.

Based on the 2796 events over the 10 years of monitoring data described in **Paper III**, we could create an likelihood of occurrence of soil loss and runoff events. It is noteworthy that the curves representing the likelihood of soil loss events for bare soil plots are sharp, while curves for plots with vegetation are clustered and positioned away from those referring to bare plots. In contrast, runoff curves from all plots exhibit a gentle slope and are dispersed across the plotting area, indicating that runoff is more responsive to land cover changes than soil loss.

Runoff serves as the mechanism propelling soil particles out of the experimental plot and basin, but the nature of this relationship begs exploration. In **Paper III**, we con-



Final LULC \ Initial LULC	Bare soil: 10 year old	Bare soil: 2 year old	Pasture	Sugar cane	Soy bean	Wooded Cerrado
Wooded Cerrado	↓ 59.8 ↓ 216.3	↓ 56.9 ↓ 268.9	↓ 19.0 ↓ 1.5	↓ 5.6 ↓ 5.5	↓ 8.0 ↓ 1.8	1
Soy bean	↓ 7.4 ↓ 118.8	↓ 7.0 ↓ 147.7	↓ 2.4 ↑ 1.2	↑ 1.4 ↓ 3.0	1	↑ 8.0 ↑ 1.8
Sugar cane	↓ 10.7 ↓ 39.2	↓ 10.7 ↓ 48.8	↓ 3.4 ↑ 3.6	1	↓ 1.4 ↑ 3.0	↑ 5.6 ↑ 5.5
Pasture	↓ 3.1 ↓ 141.5	↓ 3.0 ↓ 175.9	1	↑ 3.4 ↓ 3.6	↑ 2.4 ↓ 1.2	↑ 19.02 ↑ 1.53
Bare soil: 2 year old	↓ 1.05 ↑ 1.2	1	↑ 3 ↑ 175.9	↑ 10.2 ↑ 48.8	↑ 7.0 ↑ 147.7	↑ 56.9 ↑ 268.9
Bare soil: 10 year old	1	↑ 1.05 ↓ 1.2	↑ 3.15 ↑ 141.5	↑ 10.7 ↑ 39.2	↑ 7.4 ↑ 118.8	↑ 59.8 ↑ 216.3

Legend

Values: Ratio between final and initial LULC
Color blue: Runoff (adimensional)
Color brown: Soil loss (adimensional)
Arrow up: Increase
Arrow down: Decrease

Figure 4.4: Trade-off in terms of runoff and soil loss due to land cover change (wooded Cerrado, sugarcane, soybean, pasture and bare soil).

ducted a correlation analysis between runoff (on the abscissa) and soil loss (on the ordinate) data obtained from all experimental plots. Our findings revealed a distinct linear correlation among these variables. However, upon examining individual land covers, we observed that each land cover exhibited a unique relationship with soil loss and runoff, characterized by the correlation and slope of the regression curve. For instance, BS10 demonstrated a steep (Soil loss = 0.159 runoff) and significant relationship (R^2=0.6, p-value <0.05) between soil loss and runoff, while SC and PS displayed weak relations but significant (R^2=0.38 and 0.02 respectively), and other land covers showed non-significant relations (p-value > 0.05). Despite the limitation of short-term observations, many field experiments typically focus on monitoring only runoff, as collecting soil loss data involves numerous soil samples and laboratory analyses. Utilizing the regression equations described in **Paper III**, soil loss can be estimated at the event scale based on runoff data from the tipping bucket (**Paper II**) or extrapolated to monthly or yearly time scales in other study areas. It's crucial to note that this application is contingent to specific conditions studied, such as soil type, climate, and the developmental stage of vegetation.

Runoff and soil loss are functions of not only land cover change, but also of rainfall intensity and duration (**Paper III**), affecting also the infiltration and evapotranspiration rates, nutrient availability, and biochemical processes. Additionally, some variables (porosity, organic matter, and electric conductivity) that are indicators of soil physical and chemical health were investigated in **Paper III**. Soil samples obtained from deeper zones (beyond 30 cm) exhibited less susceptibility to the influence of land cover changes. Variables analyzed across different land treatments displayed greater similarity at greater depths, likely due to higher root density and increased biological activity near the surface. This particularly sensitive zone corresponds to the topsoil area, which serves as a natural source for most nutrients utilized in agriculture. Additionally, it plays a crucial role in connecting the atmosphere with subsurface processes such as percolation and aquifer recharge. Consequently, we emphasize that forthcoming studies addressing the qualitative aspects and conservation of soil, particularly in the context of land cover interactions, should concentrate on depths up to 30 cm.

Lastly, **Paper III** also describe that soil loss is influenced not only by land cover, but also by the duration of exposure. Areas with similar environmental characteristics (soil and weather conditions) but subjected to long-term environmental exposure (10 years) without land cover protection demonstrated higher susceptibility to soil loss compared to areas with shorter exposure. These findings hold significant relevance for the hydrological and agricultural communities, challenging the assumption that soil loss is a linear process over time. This insight is of greater relevance of future environmental modeling research.

4.3 Simulation of soil loss under current and future scenarios

The extensive changes in land use resulting from agricultural expansion have transformed the landscape, causing shifts in runoff patterns and increasing soil loss (**Paper III**), posing a threat to water and food security. There is an immediate imperative to account for forthcoming climate changes in the estimation of soil loss (Aslan et al., 2019; Hateffard et al., 2021). Rainfall erosivity, denoting the potential of rainfall to induce soil loss, is expected to be influenced by climate change (See Figure 4.5), exhibiting varying intensities on local scale at the study area. Therefore, accurately quantifying soil erosion under both current and future scenarios is crucial for establishing a foundation for the implementation of mitigation strategies, particularly in agricultural-natural hotspots like the Cerrado biome.

While numerous previous studies have addressed erosivity and soil loss under climate change scenarios, many relied on simulations without field monitoring for calibration during the historical period, thus limiting the accuracy of future predictions. Additionally, a thorough assessment of the connections between land degradation and climate change is essential for devising policies to mitigate soil erosion and constructing

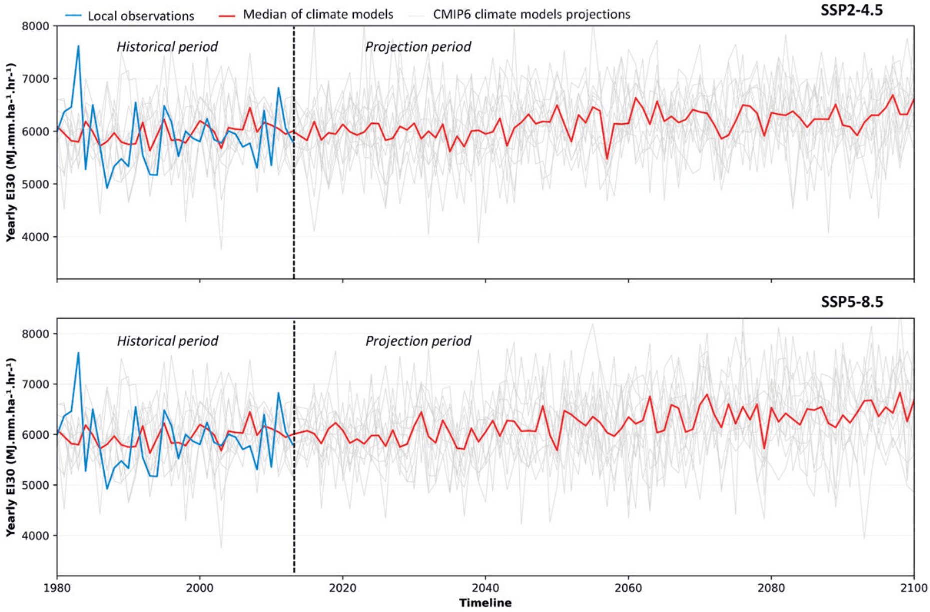


Figure 4.5: Annual rainfall erosivity ($MJ \cdot mm \cdot ha^{-1} \cdot hr^{-1}$) from individual CMIP6 climate projection models and field observations.

climate-resilient agroecological systems (Webb et al., 2017).

In this investigation, I utilized a part of the database described in **Paper III** encompassing seven years of soil loss observations monitored at experimental plots covered with sugarcane, pasture, bare soil, and wooded Cerrado. The USLE model related variables: Land cover factor (C-factor), soil erodibility (K-factor) and rainfall erositivity (R-factor) were estimated. Those factors described in **Paper IV** are of great relevance and can be employed for soil loss estimation in ungauged areas under similar climatic, land cover, and pedological conditions.

The long-term mean predicted soil loss by USLE model was slightly underestimated for bare soil (3.5%), while it was overestimated for sugarcane (26.7%), wooded Cerrado (102.0%), and pasture (121.3%) covered plots (Figure 4.6). However, the bias between observed and predicted soil loss was predominantly systematic, resulting in a strong linear correlation between these two variables (see Figure 4.6). This correlation can be utilized to rectify the Universal Soil Loss Equation estimations at other sites under the same LULC. The USLE predictions performed most effectively for the bare soil plot (R^2 = 0.85), followed by pasture (R^2 = 0.80), wooded Cerrado (R^2 = 0.74), and sugarcane (R^2 = 0.73). It is noteworthy that agricultural plots exhibited a slight decline in model performance compared to the others, primarily attributable to soil management practices.

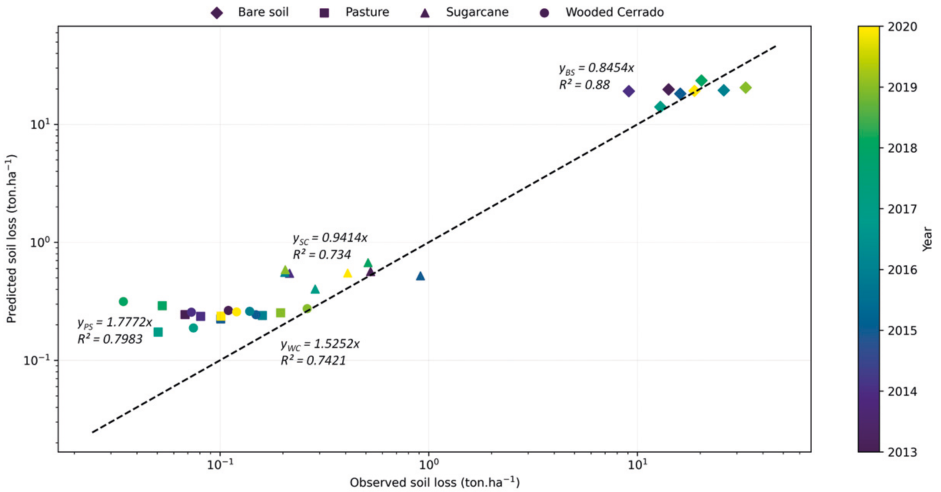


Figure 4.6: Scatter of monitored and predicted soil loss ($ton.ha^{-1}.yr^{-1}$) for the land cover analyzed.

Looking again at the projected erosivity described on Figure 4.5, we note that climate models incorporate annual oscillations. Consequently, analyzing individual annual erosivity would lack consistency. So, we calculated soil loss over two distinct periods, utilizing a 30-year mean erosivity: the intermediate future (2041-2070) and distant future (2071-2100), based on CMIP6 SSP2-4.5 and SSP5-8.5 climate projections. These predictions were compared against mean values from the baseline period for climate models, as summarized in Table 4.2. In both scenarios, there is a noteworthy increase in soil loss attributed to escalating rainfall erosivity. This effect is particularly pronounced in SSP5-8.5, which accounts for higher anthropogenic interference on the environment, especially in the distant future. During the intermediate future period (2040-2070), both SSP2-4.5 and SSP5-8.5 scenarios projected an increase of 3.8% and 3.9%, respectively. Looking ahead to the distant future (2070-2100), the SSP2-4.5 trajectory is expected to elevate soil loss by 4.9%, while the SSP5-8.5 scenario predicts a significant surge in soil loss, approximately 7.6%. In **Paper IV**, the estimations are lower compared to other soil loss estimations that employed single or short number of climate models of previous generations. However, we have a wide range of expected change (minimum of -34.1% and maximum of 43.7% expected change in soil loss at SSP5-8.5 for period 2071-2100, see Table 4.2). Lastly, the findings of **Paper IV** are based on the assemble of 12 climatic models, lowering the possibility of being influenced by individual model assumptions, based then on the consensus of multiple mathematical and physical approaches of these 12 models.

Lastly, connecting long-term field monitoring of **Paper III** to the predicted alterations in soil loss under different LCLU of **Paper IV**, we noted that by that end of the century

Table 4.2: Estimated annual rainfall (mm), erosivity ($MJ.mm.ha^{-}1.hr^{-}1$), and soil loss ($ton.ha^{-}1.yr^{-}1$) based on CMIP6 SSP2-4.5 and SSP5-8.5 climate projections and USLE model. Each cell contains the variable value indicated on the top column accompanied to the standard deviation (after the sign +).

	Monitored	Baseline	SSP2-4.5 Scenario		SSP5-8.5 Scenario	
Period	2012-2019	1980-2013	2041-2070	2071-2100	2041-2070	2071-2100
Rainfall	1330+176	1503+85	1559 + 81	1595 + 75	1558+82	1676+102
Erosivity	6804+1002	5966+571	6193+625	6261+635	6196+718	6417+758
Cerrado	0.120+0.071	0.23+0.02	0.23+0.02	0.23+0.02	0.23+0.03	0.24+0.03
Pasture	0.10+0.06	0.21+0.02	0.22+0.02	0.21+0.02	0.21+0.02	0.22+0.02
Sugarcane	0.41+0.26	0.48+0.05	0.50+0.05	0.51+0.05	0.50+0.06	0.52+0.06
Bare soil	18.79+8.31	16.86+1.61	17.50+1.77	17.70+1.79	17.51+2.03	18.14+2.14
Change*	-	-	3.8%	5.0%	3.9%	7.6%

Note: *Value based on the ratio between mean soil loss between projected and baseline periods of climate models.

at most radical climate change scenario (SSP 5-8.5), current land cover changes pose a bigger threat to soil conservation than climate change. The mean historical soil loss from agricultural areas (sugarcane and pasture) was 4.2 times higher than at natural forest, while climate change will rise 7.5% actual soil loss (Table 4.2). Cerrado biome has already lost 53% of its natural cover (Beuchle et al., 2015) due to deforestation. Such large scale LCLU alteration might impact at water circulation at continental up to 40%, as estimated by Wongchuig et al., 2023 due to Amazon deforestation. Alterations of rainfall patterns due to climate change may lead to changes in rainfall erosivity, that will impact the soil loss potential. Therefore, land conversion poses threats to soil loss at local and continental scales.

4.4 Simulation of water balance components under current and future scenarios

Expected patterns alteration in rainfall (intensity, duration, and seasonal shifts), wind (speed, duration, and direction), solar radiation (intensity), temperature (both minimum and maximum), air humidity (value), and other related variables is expected due to climate change. Despite technological advancements aimed at enhancing agricultural resilience to extreme events, such as the development of drought-resistant species, climate change continues to pose a substantial threat to productivity and sustainable development (Birindelli et al., 2022; Ma et al., 2024; Resende et al., 2019). More intense precipitation has the potential to compromise soil aeration, impede root nutrient absorption, and increase runoff (Teng et al., 2012), leading to nutrient leaching. Temperature fluctuations may either retard or accelerate plant development (Li et al., 2016), while higher solar radiation could result in fruit damage and increased leaf transpiration. These potential impacts extend globally, posing a threat to global food security and water availability (Alcamo et al., 2007; C.-C. Lee et al., 2024). Although the effects of climate change are inherently global, the significance of local and regional impacts cannot be understated, particularly in terms of their environmental components and experienced intensities (such as temperature changes, precipitation variations, wind alterations, solar radiation fluctuations, etc.). Consequently, local and regional studies addressing the specific processes affected by climate change become imperative (Zhang et al., 2023). Therefore, **Paper V** extended the investigation of climate change alteration in water fluxes (surface water flux, evaporation, soil-water storage, infiltration, groundwater flux, and root uptake) at current and future conditions due to climate change occurring over the Brazilian Cerrado Biome.

Hydrus was calibrated and validated employing more than six years of soil moisture observations for experimental plots at four soil depths with low Root Mean Square Error (RMSE), ranging from 0.01 to 0.015 $m^3.m^{-3}$ during both the calibration and validation, respectively. While demonstrating commendable overall performance, it is important to highlight a notable observation: simulations showed diminished accuracy particularly during prolonged dry seasons. This discrepancy could be attributed to the model's challenge in accurately representing water fluxes in sandy soil characterized by its low water retention capacity, coupled with elevated evaporation rates, as observed in our specific case study area (de Alcântara et al., 2021). Despite these acknowledged limitations, the robust statistical correlation between predicted and monitored soil moisture underscores the effectiveness of Hydrus as a potent and easily implementable tool for simulating water fluxes under varying atmospheric conditions. The validated models are valuable resource for making assumptions in the context of future scenarios, including climate change and hypothetical land cover changes. **Paper V** provide a better description about calibration performance and calibrated variables, as well as correlate the findings to other similar studies.

Figure 4.7 shows the relative changes in water balance components for the sub-surface (including soil-water storage, bottom water flux, infiltration, and root uptake) and surface (encompassing surface water flux and evaporation) attributed to climate change. The initial observation underscores the inability to assert that climate change selectively impacts surface water fluxes over sub-surface water fluxes. This is due to the distinct behavior exhibited by each variable under the influence of climate change. Nevertheless, it is evident that the most substantial alterations are predicted in root water uptake, succeeded by evaporation, surface water flux, infiltration, bottom water flux, and finally, soil-water storage. When assigning equal weight to the analyzed variable components, we observe that the impact of climate change is most pronounced on sugarcane, followed by wooded cerrado, and lastly on pasture when utilizing the SSP2-4.5 models during the distant period (2071-2100). However, a shift in this order occurred (sugarcane, pasture, and lastly, cerrado) when employing the SSP5-8.5 models. The results indicate that intensively managed land cover types will experience a more significant impact from climate change, as also reported by Horel et al., 2022. This is attributed to the fact that forests, with their deep roots capable of reaching water sources, are likely to be less affected by changes occurring in the vadose and surface zones. In **Paper V** the authors speculate the profound meaning and impact of those changes in crops development, productivity, harvest season and even to global food security.

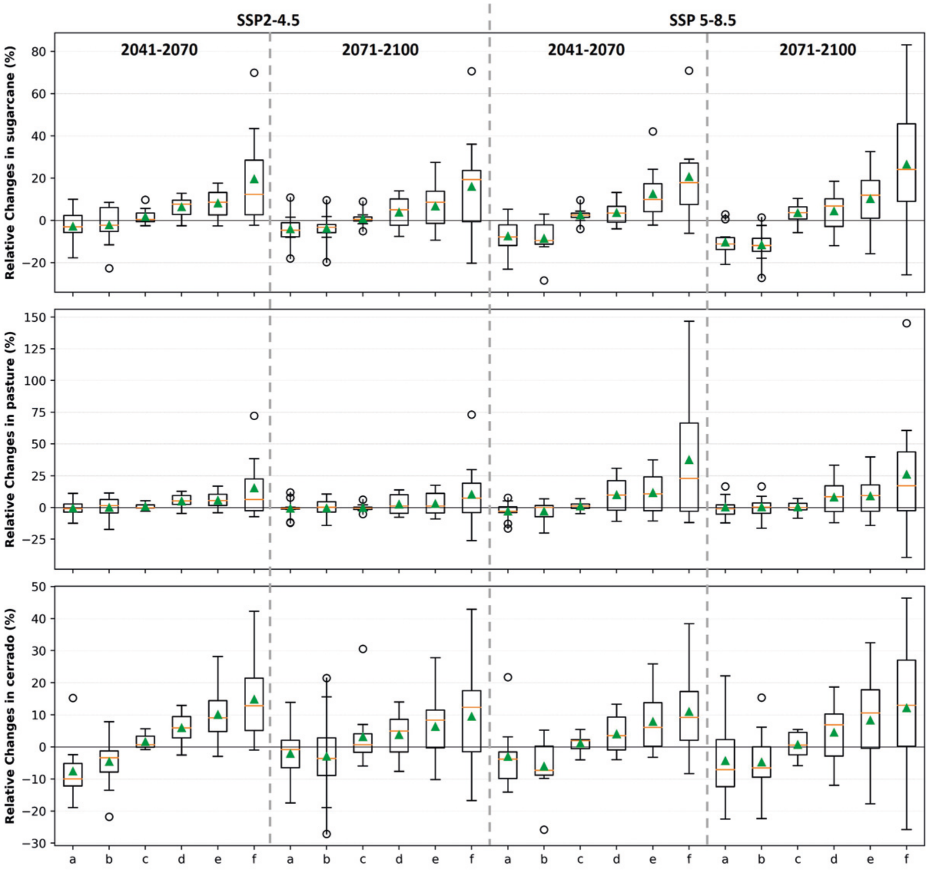


Figure 4.7: Relative changes in the yearly distribution of soil-water storage (column a), bottom flux (column b), infiltration (column c), surface flux (column d), evaporation (column e), and root uptake (column f) considering climate change models SSP2-4.5 at periods of 2041-2070 and 2071-2100, and SSP5-8.5 at periods of 2041-2070 and 2071-2100 compared baseline period (1980-2013).

Chapter 5

General conclusions

This chapter summarizes some conclusions of the manuscripts derived from the thesis, as well as how they contribute to the hydrology scientific community, Brazilian agriculture, and stakeholders related to soil and water conservation within Cerrado biome.

Brazil is a large continental country with a great diversity of natural resources, as well as a climatic and technological vocation for agriculture. Land use shifts have added to losses of natural areas that poses a threat to soil and water conservation. Achieving effective soil and water resource conservation and unlocking agricultural potential depend on obtaining relevant information about soil, water, and vegetation properties. Additionally, we can only rely on food and water security by understanding the interconnections between soil-water-atmosphere-vegetation under actual and future conditions due to climate change.

Despite constituting a minor proportion of the world's freshwater resources, soil-water content plays a crucial role in water storage within the hydrological cycle and holds fundamental significance for hydrological, biological, and biogeochemical processes. Monitoring soil moisture across various vegetation covers facilitates a deeper comprehension of water movement through different soil layers. Most soil moisture sensors have high acquisition/maintenance cost. Low-cost hardware coupled to open source controllers (as presented in **Paper I**) constitutes alternatives to more expensive equipment. The use of these setups for water content monitoring is ideal for short-term and limited-budget projects. During laboratory tests, different calibration alternatives (individual, single point, and universal) were evaluated and checked for temperature and voltage sensitivity.

Flow monitoring (as given in **Paper II**) over short-time scale providing time to flow onset, peak time, maximum flow, and flow duration is a valuable tool for hydrological investigations. In urban areas, such information is essential for the construction of flood alarms, indicating whether a given precipitation event has the potential to cause material and non-material damage. On the other hand, in rural areas, they are tools that allow for identifying how changes in land use interfere with hydrological processes, such as infiltration capacity, surface runoff, and consequent transport of sediments and nutrients. **Paper II** provided an unique framework for the design of flow meter tipping buckets that allow for up-scaling of such observations under various land cover, rainfall, and contributing area.

Long-term field studies in hydrology, particularly those addressing erosion and runoff, remain scarce due to their high costs for maintenance. Nevertheless, acquiring site-specific data is imperative for accurate soil erosion estimation, particularly in regions like Brazil, where land use and management practices exhibit significant variations, exerting a considerable impact on agriculture. Investigations into the long-term trade-offs in runoff and soil loss resulting from changes in land cover (**Paper III**) possess significant potential to enhance our comprehension of the current and potential repercussions of human activities. Furthermore, the findings described in **Paper III** play a crucial role in the formulation of policies geared towards promoting sustainability, e.g., calibration of hydrological models that predict hydrological response under climate change scenarios.

In **Paper IV**, USLE related factors (land cover, soil erodibility, and rainfall erosivity) were estimated based on long-term monitoring. The USLE can be applied for soil loss estimation over large areas with similar soil composition and LCLUs. Soil erosion maps can be constructed that are valuable tools for the development of public policies, indication of where investments should be allocated, and recommendation of implementation of conservation practices in erosion-prone areas. In **Paper IV**, the climate change projections indicated a rise in soil loss between 4.9% (scenario SSP2-4.5) and 7.6% (scenario SSP5-8.5) between 2070-2100. Such increase on soil loss might be attenuated by the employment of soil conservation practices, such as crop rotation, terrace farming, contour farming, and tillage.

The investigation of climate change interference of common LCLUs found in Brazil was expanded in **Paper V**, now looking at water balance components (surface water flux, evaporation, soil-water storage, infiltration, groundwater flux, and root uptake). Findings in **Paper V** indicated that among the fluxes, root water uptake was the most sensitive variable, with expected mean change of 26.5% for sugarcane, 26.1% for pasture, and 12.2% for Cerrado. Root systems are essential for regulating the exchange of water, nutrients, and involvement in stress signaling pathways within the soil-water-atmosphere continuum. Higher root water uptake means higher water demands from the agriculture sector, which is already the largest worldwide water consumer. Such water extraction might occur from surface or ground, compromising urban water supply and resulting in groundwater over-exploitation. Other fluxes also showed significant changes, such as evaporation, surface water flux, and infiltration. A comprehensive knowledge of these interactions is imperative for foreseeing and effectively controlling the consequences of climate change on distinct ecosystems.

Climate change will increase soil erosion and change water balance components. The thesis highlights that soil and water conservation faces a paramount peril of greater severity than climate change – namely, current alterations in LCLU. Grounded on local measurements, soil erosion within agricultural domains surpasses that within natural forests by a factor of 4.2, underscoring the pivotal role of land cover in soil conservation endeavors. This is especially pertinent considering that over 53% of the Cerrado biome have already undergone conversion into agricultural zones.

Lastly, the findings n **Paper IV** and **Paper V** were derived from the analysis of a unique dataset comprising 2796 monitored runoff and soil loss events spanning from November 2011 to April 2022 (**Paper III**). This dataset is openly available for further analysis, recognizing that long-term monitoring contributes to advancements in hydro-erosive studies and supports policies aimed at the sustainable development of agriculture within the Cerrado biome. By providing a comprehensive database and critical analysis, **Paper III** situates the Cerrado, one of the largest and most threatened biomes globally, within the broader context of well-described erosive regions worldwide.

References

Adgo, E., Teshome, A., & Mati, B. (2013). Impacts of long-term soil and water conservation on agricultural productivity: The case of Anjenie watershed, Ethiopia. *Agricultural Water Management*, *117*, 55–61. https://doi.org/10.1016/j.agwat.2012.10.026

Adla, S., Rai, N. K., Karumanchi, S. H., Tripathi, S., Disse, M., & Pande, S. (2020). Laboratory calibration and performance evaluation of low-cost capacitive and very low-cost resistive soil moisture sensors. *Sensors (Switzerland)*, *20*(2). https://doi.org/10.3390/s20020363

Alberton, B., Almeida, J., Helm, R., Torres, R. d. S., Menzel, A., & Morellato, L. P. C. (2014). Using phenological cameras to track the green up in a cerrado savanna and its on-the-ground validation. *Ecological Informatics*, *19*, 62–70. https://doi.org/10.1016/J.ECOINF.2013.12.011

Alcamo, J., Dronin, N., Endejan, M., Golubev, G., & Kirilenko, A. (2007). A new assessment of climate change impacts on food production shortfalls and water availability in Russia. *Global Environmental Change*, *17*(3-4), 429–444. https://doi.org/10.1016/j.gloenvcha.2006.12.006

Alvares, C. A., Stape, J. L., Sentelhas, P. C., De Moraes Gonçalves, J. L., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Anache, J., Flanagan, D., Srivastava, A., & Wendland, E. (2018). Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado. *Science of the Total Environment*, *622-623*, 140–151. https://doi.org/10.1016/j.scitotenv.2017.11.257

Anache, J. A., Flanagan, D. C., Srivastava, A., & Wendland, E. C. (2018). Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado. *Science of The Total Environment*, *622-623*, 140–151. https://doi.org/10.1016/j.scitotenv.2017.11.257

Anache, J. A., Wendland, E. C., Oliveira, P. T., Flanagan, D. C., & Nearing, M. A. (2017, May). Runoff and soil erosion plot-scale studies under natural rainfall:

A meta-analysis of the Brazilian experience. https://doi.org/10.1016/j.catena.2017.01.003

Arias, D., Vieira, P. A., Contini, E., Noronha Farinelli, B. C., & Morris, M. (2017). *Agriculture productivity growth in Brazil : recent trends and future prospects* (tech. rep.). The World Bank. http://documents.worldbank.org/curated/en/268351520343354377/Agriculture-productivity-growth-in-Brazil-recent-trends-and-future-prospects

Aslan, Z., Erdemir, G., Feoli, E., Giorgi, F., & Okcu, D. (2019). Effects of Climate Change on Soil Erosion Risk Assessed by Clustering and Artificial Neural Network. *Pure and Applied Geophysics*, *176*(2), 937–949. https://doi.org/10.1007/s00024-018-2010-y

Baatz, R., Bogena, H. R., Hendricks Franssen, H. J., Huisman, J. A., Montzka, C., & Vereecken, H. (2015). An empirical vegetation correction for soil water content quantification using cosmic ray probes. *Water Resources Research*, *51*(4), 2030–2046. https://doi.org/10.1002/2014WR016443

Ballarin, A. S., Sone, J. S., Gesualdo, G. C., Schwamback, D., Reis, A., Almagro, A., & Wendland, E. C. (2023). CLIMBra - Climate Change Dataset for Brazil. *Scientific Data*, *10*(1), 47. https://doi.org/10.1038/s41597-023-01956-z

Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice, and Policy*, *13*(1), 13–26. https://doi.org/10.1080/15487733.2017.1394054

Bertoni, J., & Lombardi Neto, F. (2017). *Conservação do solo* (10th ed.). Ícone.

Beuchle, R., Grecchi, R. C., Shimabukuro, Y. E., Seliger, R., Eva, H. D., Sano, E., & Achard, F. (2015). Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach. *Applied Geography*, *58*, 116–127. https://doi.org/10.1016/j.apgeog.2015.01.017

Bi, D., Dix, M., Marsland, S., O'Farrell, S., Sullivan, A., Bodman, R., Law, R., Harman, I., Srbinovsky, J., Rashid, H. A., Dobrohotoff, P., Mackallah, C., Yan, H., Hirst, A., Savita, A., Dias, F. B., Woodhouse, M., Fiedler, R., & Heerdegen, A. (2020). Configuration and spin-up of ACCESS-CM2, the new generation Australian Community Climate and Earth System Simulator Coupled Model. *Journal of Southern Hemisphere Earth Systems Science*, *70*(1), 225–251. https://doi.org/10.1071/ES19040

Bindoff, N., Stott, P., AchutaRao, K., Allen, M., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., Mokhov, I., Overland, J., Perlwitz, J., Sebbari, R., & Zhang, X. (2013). Detection and Attribution of Climate Change: from Global to Regional. In T. Stocker, D. Qin, G. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. Midgley (Eds.), *Climate change 2013: The physical science basis. contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

Birindelli, G., Bonanno, G., Dell'Atti, S., & Iannuzzi, A. P. (2022). Climate change commitment, credit risk and the country's environmental performance: Empirical evidence from a sample of international banks. *Business Strategy and the Environment*, *31*(4), 1641–1655. https://doi.org/10.1002/bse.2974

Blöschl, G., Bierkens, M. F., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., Kirchner, J. W., McDonnell, J. J., Savenije, H. H., Sivapalan, M., Stumpp, C., Toth, E., Volpi, E., Carr, G., Lupton, C., Salinas, J., Széles, B., Viglione, A., Aksoy, H., … Zhang, Y. (2019). Twenty-three unsolved problems in hydrology (UPH) – a community perspective. *Hydrological Sciences Journal*, *64*(10), 1141–1158. https://doi.org/10.1080/02626667.2019.1620507

Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D'Andrea, F., … Vuichard, N. (2020). Presentation and Evaluation of the IPSLCM6ALR Climate Model. *Journal of Advances in Modeling Earth Systems*, *12*(7). https://doi.org/10.1029/2019MS002010

Bourdeau-Goulet, S. C., & Hassanzadeh, E. (2021). Comparisons Between CMIP5 and CMIP6 Models: Simulations of Climate Indices Influencing Food Security, Infrastructure Resilience, and Human Health in Canada. *Earth's Future*, *9*(5), e2021EF001995. https://doi.org/10.1029/2021EF001995

Bouwer, H. (1978). *Ground Hydrology*. McGraw-Hil.

Briggs, L. J. (1897, November). *The mechanics of soil moisture*. Wentworth Press. https://doi.org/10.5962/bhl.title.43273

Brito, M. L. N., Liziane de Figueiredo Silva, Palha, N. C., Leite, F. P., Ferreira, M. M., & Souza, L. (2005). Water erosion of very clayey Red Latosol (Oxisol) in an undulated area of eucalypt post-planting at Rio Doce Valley, Center East region of Minas Gerais State, Brazil. *Scientia Forestalis*, *67*(4), 27–36.

Cao, J., Wang, B., Yang, Y.-M., Ma, L., Li, J., Sun, B., Bao, Y., He, J., Zhou, X., & Wu, L. (2018). The NUIST Earth System Model (NESM) version 3: description and preliminary evaluation. *Geoscientific Model Development*, *11*(7), 2975–2993. https://doi.org/10.5194/gmd-11-2975-2018

Castro, R. M., dos Santos Alves, W., Loures de Oliveira Marcionilio, S. M., Borges de Moura, D. M., & Márcio da Silva Oliveira, D. (2022). Soil losses related to land use and rainfall seasonality in a watershed in the Brazilian Cerrado. *Journal of South American Earth Sciences*, *119*. https://doi.org/10.1016/j.jsames.2022.104020

Cherchi, A., Fogli, P. G., Lovato, T., Peano, D., Iovino, D., Gualdi, S., Masina, S., Scoccimarro, E., Materia, S., Bellucci, A., & Navarra, A. (2019). Global Mean Climate and Main Patterns of Variability in the CMCCCM2 Coupled Model. *Journal of Advances in Modeling Earth Systems*, *11*(1), 185–209. https://doi.org/10.1029/2018MS001369

Clifton, C. F., Day, K. T., Luce, C. H., Grant, G. E., Safeeq, M., Halofsky, J. E., & Staab, B. P. (2018). Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA. *Climate Services*, *10*, 9–19. https://doi.org/10.1016/j.cliser.2018.03.001

Cohen, J., Pfeiffer, K., & Francis, J. A. (2018). Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. *Nature Communications*, *9*(1), 1–12. https://doi.org/10.1038/s41467-018-02992-9

Cosh, M. H., Ochsner, T. E., McKee, L., Dong, J., Basara, J. B., Evett, S. R., Hatch, C. E., Small, E. E., Steele-Dunne, S. C., Zreda, M., & Sayde, C. (2016). The Soil Moisture Active Passive Marena, Oklahoma, In Situ Sensor Testbed (SMAP-MOISST): Testbed Design and Evaluation of In Situ Sensors. *Vadose Zone Journal*, *15*(4), 1–11. https://doi.org/10.2136/vzj2015.09.0122

Costa Junior, C., Píccolo, M. d. C., Neto, M. S., de Camargo, P. B., Cerri, C. C., & Bernoux, M. (2012). Carbono em agregados do solo sob vegetação nativa, pastagem e sistemas agrícolas no bioma Cerrado. *Revista Brasileira de Ciencia do Solo*, *36*(4), 1311–1321. https://doi.org/10.1590/S0100-06832012000400025

D. K. McCool, L. C. Brown, G. R. Foster, C. K. Mutchler, & L. D. Meyer. (1987). Revised Slope Steepness Factor for the Universal Soil Loss Equation. *Transactions of the ASAE*, *30*(5), 1387–1396. https://doi.org/10.13031/2013.30576

Darcy, H. (1856). *Les Fountaines Publiques de la Ville de Dijon: appendice D* (tech. rep.). Dalmont. Paris, France.

de Alcântara, L. R. P., Coutinho, A. P., dos Santos Neto, S. M., Carvalho de Gusmão da Cunha Rabelo, A. E., & Antonino, A. C. D. (2021). Modeling of the Hydrological Processes in Caatinga and Pasture Areas in the Brazilian Semi-Arid. *Water*, *13*(13), 1877. https://doi.org/10.3390/w13131877

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., … Zhang, Q. (2022). The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6. *Geoscientific Model Development*, *15*(7), 2973–3020. https://doi.org/10.5194/gmd-15-2973-2022

Dunne, J. P., Horowitz, L. W., Adcroft, A. J., Ginoux, P., Held, I. M., John, J. G., Krasting, J. P., Malyshev, S., Naik, V., Paulot, F., Shevliakova, E., Stock, C. A., Zadeh, N., Balaji, V., Blanton, C., Dunne, K. A., Dupuis, C., Durachta, J., Dussin, R., … Zhao, M. (2020). The GFDL Earth System Model Version 4.1 (GFDL￾ESM 4.1): Overall Coupled Model Description and Simulation Characteristics. *Journal of Advances in Modeling Earth Systems*, *12*(11). https://doi.org/10.1029/2019MS002015 du Plessis, A. (2022). Persistent degradation: Global water quality challenges and required actions. *One Earth*, *5*(2), 129–131. https://doi.org/10.1016/j.oneear.2022.01.005

Ebabu, K., Taye, G., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Fenta, A. A., Meshesha, D. T., Sultan, D., Aklog, D., Admasu, T., van Wesemael, B., & Poesen, J. (2023). Land use, management and climate effects on runoff and soil loss responses in the highlands of Ethiopia. *Journal of Environmental Management*, *326*(PA), 116707. https://doi.org/10.1016/j.jenvman.2022.116707

Engel, F., Bertol, I., Ritter, S., Paz González, A., Paz-Ferreiro, J., & Vidal Vázquez, E. (2009). Soil erosion under simulated rainfall in relation to phenological stages of soybeans and tillage methods in Lages, SC, Brazil. *Soil and Tillage Research*, *103*(2), 216–221. https://doi.org/10.1016/j.still.2008.05.017

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Falleiros, M. C., Portezan, O., Oliveira, J. C., Bacchi, O. O., & Reichardt, K. (1998). Spatial and temporal variability of soil hydraulic conductivity in relation to soil water distribution, using an exponential model. *Soil and Tillage Research*, *45*(3-4), 279–285. https://doi.org/10.1016/S0933-3630(97)00021-4

Gong, L., Zhang, X., Pan, G., Zhao, J., & Zhao, Y. (2023). Hydrological responses to co-impacts of climate change and land use/cover change based on CMIP6 in the Ganjiang River, Poyang Lake basin. *Anthropocene*, *41*, 100368. https://doi.org/10.1016/j.ancene.2023.100368

Gosling, S. N., Zaherpour, J., Mount, N. J., Hattermann, F. F., Dankers, R., Arheimer, B., Breuer, L., Ding, J., Haddeland, I., Kumar, R., Kundu, D., Liu, J., van Griensven, A., Veldkamp, T. I. E., Vetter, T., Wang, X., & Zhang, X. (2017). A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1 °C, 2 °C and 3 °C. *Climatic Change*, *141*(3), 577–595. https://doi.org/10.1007/s10584-016-1773-3

Gulcebi, M. I., Bartolini, E., Lee, O., Lisgaras, C. P., Onat, F., Mifsud, J., Striano, P., Vezzani, A., Hildebrand, M. S., Jimenez-Jimenez, D., Junck, L., Lewis-Smith, D., Scheffer, I. E., Thijs, R. D., Zuberi, S. M., Blenkinsop, S., Fowler, H. J., Foley, A., Sisodiya, S. M., … Zara, F. (2021, March). Climate change and epilepsy: Insights from clinical and basic science studies. https://doi.org/10.1016/j.yebeh.2021.107791

Gutjahr, O., Putrasahan, D., Lohmann, K., Jungclaus, J. H., von Storch, J.-S., Brüggemann, N., Haak, H., & Stössel, A. (2019). Max Planck Institute Earth System Model (MPI-ESM1.2) for the High-Resolution Model Intercomparison

Project (HighResMIP). *Geoscientific Model Development*, *12*(7), 3241–3281. https://doi.org/10.5194/gmd-12-3241-2019

Hateffard, F., Mohammed, S., Alsafadi, K., Enaruvbe, G. O., Heidari, A., Abdo, H. G., & Rodrigo-Comino, J. (2021). CMIP5 climate projections and RUSLE-based soil erosion assessment in the central part of Iran. *Scientific Reports*, *11*(1), 1–17. https://doi.org/10.1038/s41598-021-86618-z

Hawkins, E., Ortega, P., Suckling, E., Schurer, A., Hegerl, G., Jones, P., Joshi, M., Osborn, T. J., Masson-Delmotte, V., Mignot, J., Thorne, P., & Van Oldenborgh, G. J. (2017). Estimating changes in global temperature since the preindustrial period. *Bulletin of the American Meteorological Society*, *98*(9), 1841–1856. https://doi.org/10.1175/BAMS-D-16-0007.1

Held, I. M., Guo, H., Adcroft, A., Dunne, J. P., Horowitz, L. W., Krasting, J., Shevliakova, E., Winton, M., Zhao, M., Bushuk, M., Wittenberg, A. T., Wyman, B., Xiang, B., Zhang, R., Anderson, W., Balaji, V., Donner, L., Dunne, K., Durachta, J., … Zadeh, N. (2019). Structure and Performance of GFDL's CM4.0 Climate Model. *Journal of Advances in Modeling Earth Systems*, *11*(11), 3691–3727. https://doi.org/10.1029/2019MS001829

Hillel, D. (2003). Surface Runoff and Water Erosion. In *Introduction to environmental soil physics* (pp. 283–295). Universidade de Massachusetts.

Hong, G. Z., & Hsieh, C. L. (2016). Application of Integrated Control Strategy and Bluetooth for Irrigating Romaine Lettuce in Greenhouse. *IFAC-PapersOnLine*, *49*(16), 381–386. https://doi.org/10.1016/j.ifacol.2016.10.070

Horel, Á., Zsigmond, T., Farkas, C., Gelybó, G., Tóth, E., Kern, A., & Bakacsi, Z. (2022). Climate Change Alters Soil Water Dynamics under Different Land Use Types. *Sustainability*, *14*(7), 3908. https://doi.org/10.3390/su14073908

Jiang, J. s., Kim, H. J., & Cho, W. J. (2018). On-the-go Image Processing System for Spatial Mapping of Lettuce Fresh Weight in Plant Factory. *IFAC-PapersOnLine*, *51*(17), 130–134. https://doi.org/10.1016/j.ifacol.2018.08.075

Kim, Y. H., Min, S. K., Zhang, X., Zwiers, F., Alexander, L. V., Donat, M. G., & Tung, Y. S. (2016). Attribution of extreme temperature changes during 1951–2010. *Climate Dynamics*, *46*(5-6), 1769–1782. https://doi.org/10.1007/s00382-015-2674-2

Kim, Y.-H., Min, S.-K., Zhang, X., Sillmann, J., & Sandstad, M. (2020). Evaluation of the CMIP6 multi-model ensemble for climate extreme indices. *Weather and Climate Extremes*, *29*, 100269. https://doi.org/10.1016/j.wace.2020.100269

Kirkham, M. (2014). *Principles of Soil and Plant Water Relations* (2nd Editio). Kansas State University.

Kumar, D., Kumar, R., Sharma, M., Awasthi, A., & Kumar, M. (2024). Global water quality indices: Development, implications, and limitations. *Total Environment Advances*, *9*, 200095. https://doi.org/10.1016/j.teadva.2023.200095

L. C. Brown & G. R. Foster. (1987). storm Erosivity Using Idealized Intensity Distributions. *Transactions of the ASAE*, *30*(2), 0379–0386. https://doi.org/10.13031/2013.31957

Law, R. M., Ziehn, T., Matear, R. J., Lenton, A., Chamberlain, M. A., Stevens, L. E., Wang, Y.-P., Srbinovsky, J., Bi, D., Yan, H., & Vohralik, P. F. (2017). The carbon cycle in the Australian Community Climate and Earth System Simulator (ACCESS-ESM1) – Part 1: Model description and pre-industrial simulation. *Geoscientific Model Development*, *10*(7), 2567–2590. https://doi.org/10.5194/gmd-10-2567-2017

Lee, C.-C., Zeng, M., & Luo, K. (2024). How does climate change affect food security? Evidence from China. *Environmental Impact Assessment Review*, *104*, 107324. https://doi.org/10.1016/j.eiar.2023.107324

Lee, J., Kim, J., Sun, M.-A., Kim, B.-H., Moon, H., Sung, H. M., Kim, J., & Byun, Y.-H. (2020). Evaluation of the Korea Meteorological Administration Advanced Community Earth-System model (K-ACE). *Asia-Pacific Journal of Atmospheric Sciences*, *56*(3), 381–395. https://doi.org/10.1007/s13143-019-00144-7

Li, K., Yang, X., Tian, H., Pan, S., Liu, Z., & Lu, S. (2016). Effects of changing climate and cultivar on the phenology and yield of winter wheat in the North China Plain. *International Journal of Biometeorology*, *60*(1), 21–32. https://doi.org/10.1007/s00484-015-1002-1

Libardi, P. L. (2005). *Dinâmica da água no solo*. Editora da Universidade de São Paulo (edUSP).

Lopes, H. L., Candeias, A. L., Accioly, L. J., do Sobral, M. C., & Pacheco, A. P. (2010). Biophysical parameters in the detection of changes in soil cover and use in watersheds. *Revista Brasileira de Engenharia Agricola e Ambiental*, *14*(11), 1210–1219. https://doi.org/10.1590/s1415-43662010001100011

Løvsletten, O., & Rypdal, M. (2016). Statistics of regional surface temperatures after 1900: Long-range versus short-range dependence and significance of warming trends. *Journal of Climate*, *29*(11), 4057–4068. https://doi.org/10.1175/JCLI-D-15-0437.1

Ma, Q., Zhou, Y., & Wang, J. (2024). The impact of climate change on credit risk of rural financial institutions: A threshold effect based on agricultural insurance. *The North American Journal of Economics and Finance*, *1*(1), 12. https://doi.org/10.1016/j.najef.2024.102086

Maraun, D., Wetterhall, F., Ireson, A. M., Chandler, R. E., Kendon, E. J., Widmann, M., Brienen, S., Rust, H. W., Sauter, T., Themel, M., Venema, V. K., Chun, K. P., Goodess, C. M., Jones, R. G., Onof, C., Vrac, M., & Thiele-Eich, I. (2010). Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. *Reviews of Geophysics*, *48*(3). https://doi.org/10.1029/2009RG000314

Marchioro, E., & Augustin, C. (2007). Dimensão de parcelas experimentais. *Revista Geografias*, *3*(2), 7–16. https://doi.org/10.35699/2237-549X..13224

Medeiros, G. d. O. R., Giarolla, A., Sampaio, G., & Marinho, M. d. A. (2016). Estimates of Annual Soil Loss Rates in the State of São Paulo, Brazil. *Revista Brasileira de Ciência do Solo*, *40*. https://doi.org/10.1590/18069657rbcs20150497

Montoya, A. P., Obando, F. A., Osorio, J. A., Morales, J. G., & Kacira, M. (2020). Design and implementation of a low-cost sensor network to monitor environmental and agronomic variables in a plant factory. *Computers and Electronics in Agriculture*, *178*, 105758. https://doi.org/10.1016/j.compag.2020.105758

Morais, F. D. (2012). Infiltração – uma variável geomorfológica. *Caderno de Geografia*, *22*(38), 73–87.

Morbidelli, R., Saltalippi, C., Flammini, A., & Govindaraju, R. S. (2018). Role of slope on infiltration: A review. *Journal of Hydrology*, *557*, 878–886. https://doi.org/10.1016/j.jhydrol.2018.01.019

Moreira, V. S., Roberti, D. R., Minella, J. P., Gonçalves, L. G. G. d., Candido, L. A., Fiorin, J. E., Moraes, O. L. L., Timm, A. U., Carlesso, R., & Degrazia, G. A. (2015). Seasonality of soil water exchange in the soybean growing season in southern Brazil. *Scientia Agricola*, *72*(2), 103–113. https://doi.org/10.1590/0103-9016-2014-0056

Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, *12*(3), 513–522. https://doi.org/10.1029/WR012i003p00513

Müller, W. A., Jungclaus, J. H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., Bunzel, F., Esch, M., Ghosh, R., Haak, H., Ilyina, T., Kleine, T., Kornblueh, L., Li, H., Modali, K., Notz, D., Pohlmann, H., Roeckner, E., Stemmler, I., … Marotzke, J. (2018). A Higher⍰resolution Version of the Max Planck Institute Earth System Model (MPI⍰ESM1.2⍰HR). *Journal of Advances in Modeling Earth Systems*, *10*(7), 1383–1413. https://doi.org/10.1029/2017MS001217

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–858. https://doi.org/10.1038/35002501

Nearing, M. A., Xie, Y., Liu, B., & Ye, Y. (2017). Natural and anthropogenic rates of soil erosion. *International Soil and Water Conservation Research*, *5*(2), 77–84. https://doi.org/10.1016/j.iswcr.2017.04.001

Nebol'sin, S. I. (1928). *Elementary Surface Runoff* (tech. rep.). Moscow.

Niemeijer, D., & Mazzucato, V. (2002). Soil degradation in the West African Sahel: How serious is it? https://doi.org/10.1080/00139150209605596

OCDE. (2015). *OECD-FAO Agricultural Outlook 2015-2024* (tech. rep.). OECD. Paris. https://doi.org/10.1787/agr_outlook-2015-en

Oliveira, P. T. S., Wendland, E., Nearing, M. A., Scott, R. L., Rosolem, R., & da Rocha, H. R. (2015). The water balance components of undisturbed tropical woodlands in the Brazilian cerrado. *Hydrology and Earth System Sciences*, *19*(6), 2899–2910. https://doi.org/10.5194/hess-19-2899-2015

Oliveira, P. T. S., Nearing, M. A., & Wendland, E. (2015). Orders of magnitude increase in soil erosion associated with land use change from native to cultivated vegetation in a Brazilian savannah environment. *Earth Surface Processes and Landforms*, *40*(11), 1524–1532. https://doi.org/10.1002/esp.3738

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

O'Sullivan, C. A., Bonnett, G. D., McIntyre, C. L., Hochman, Z., & Wasson, A. P. (2019). Strategies to improve the productivity, product diversity and profitability of urban agriculture. *Agricultural Systems*, *174*, 133–144. https://doi.org/10.1016/j.agsy.2019.05.007

Pardey, P. G., Beddow, J. M., Hurley, T. M., Beatty, T. K., & Eidman, V. R. (2014). A Bounds Analysis of World Food Futures: Global Agriculture Through to 2050. *Australian Journal of Agricultural and Resource Economics*, *58*(4), 571–589. https://doi.org/10.1111/1467-8489.12072

Placidi, P., Gasperini, L., Grassi, A., Cecconi, M., & Scorzoni, A. (2020a). Characterization of Low-Cost Capacitive Soil Moisture Sensors for IoT Networks. *Sensors*, *20*(12), 3585. https://doi.org/10.3390/s20123585

Placidi, P., Gasperini, L., Grassi, A., Cecconi, M., & Scorzoni, A. (2020b). Characterization of Low-Cost Capacitive Soil Moisture Sensors for IoT Networks. *Sensors*, *20*(12), 3585. https://doi.org/10.3390/s20123585

Prăvălie, R., Nita, I.-A., Patriche, C., Niculiță, M., Birsan, M.-V., Roșca, B., & Bandoc, G. (2021). Global changes in soil organic carbon and implications for land degradation neutrality and climate stability. *Environmental Research*, *201*, 111580. https://doi.org/10.1016/j.envres.2021.111580

Qu, W., Bogena, H. R., Huisman, J. A., Martinez, G., Pachepsky, Y. A., & Vereecken, H. (2014). Effects of Soil Hydraulic Properties on the Spatial Variability of Soil Water Content: Evidence from Sensor Network Data and Inverse Modeling. *Vadose Zone Journal*, *13*(12), vzj2014.07.0099. https://doi.org/10.2136/vzj2014.07.0099

Reichardt, K. (1996). Infiltração da água no solo. In *Dinâmica da matéria e da energia em ecossistemas* (2.ed, pp. 317–352). Escola Superior de Agricultura Luiz de Queiroz/USP.

Resende, N. C., Miranda, J. H., Cooke, R., Chu, M. L., & Chou, S. C. (2019). Impacts of regional climate change on the runoff and root water uptake in corn crops in Parana, Brazil. *Agricultural Water Management*, *221*, 556–565. https://doi.org/10.1016/j.agwat.2019.05.018

Ribeiro, J. F., & Walter, B. M. T. (2008). As Principais Fitofisionomias do Bioma Cerrado. In S. M. Sano, S. P. d. Almeida, & J. F. Ribeiro (Eds.), *Cerrado: Ecologia e flora v. 2.* (p. 876). EMBRAPA-CERRADOS.

Roderick, M. L., & Farquhar, G. D. (2011). A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties. *Water Resources Research*, *47*(12), 0–07. https://doi.org/10.1029/2010WR009826

Sartori, M., Ferrari, E., M'Barek, R., Philippidis, G., Boysen-Urban, K., Borrelli, P., Montanarella, L., & Panagos, P. (2024). Remaining Loyal to Our Soil: A Prospective Integrated Assessment of Soil Erosion on Global Food Security. *Ecological Economics*, 108103. https://doi.org/10.1016/j.ecolecon.2023.108103

Schwamback, D., Anache, J. A., & Wendland, E. C. (2022). Calibration and error investigation of large tipping bucket flow meters. *CATENA*, *209*, 105834. https://doi.org/10.1016/j.catena.2021.105834

Schwamback, D., Moreira, L. L., & Rigo, D. (2020). Effects of native vegetation recovery on soil loss. *Journal of Applied Water Engineering and Research*, 1–11. https://doi.org/10.1080/23249676.2020.1787244

Schwamback, D., Persson, M., Berndtsson, R., Bertotto, L. E., Kobayashi, A. N. A., & Wendland, E. C. (2023). Automated Low-Cost Soil Moisture Sensors: Trade-Off between Cost and Accuracy. *Sensors*, *23*(5), 2451. https://doi.org/10.3390/s23052451

Seland, Ø., Bentsen, M., Olivié, D., Toniazzo, T., Gjermundsen, A., Graff, L. S., Debernard, J. B., Gupta, A. K., He, Y.-C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Aas, K. S., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., … Schulz, M. (2020). Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. *Geoscientific Model Development*, *13*(12), 6165–6200. https://doi.org/10.5194/gmd-13-6165-2020

Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., O'Connor, F. M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., de Mora, L., Kuhlbrodt, T., Rumbold, S. T., Kelley, D. I., Ellis, R., Johnson, C. E., Walton, J., Abraham, N. L., … Zerroukat, M. (2019). UKESM1: Description and Evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4513–4558. https://doi.org/10.1029/2019MS001739

Šimůnek, J., van Genuchten, M. T., & Šejna, M. (2008). Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes. *Vadose Zone Journal*, *7*(2), 587–600. https://doi.org/10.2136/vzj2007.0077

Spera, S. (2017). Agricultural Intensification Can Preserve the Brazilian Cerrado: Applying Lessons From Mato Grosso and Goiás to Brazil's Last Agricultural

Frontier. *Tropical Conservation Science*, *10*, 194008291772066. https://doi.org/10.1177/1940082917720662

Spinelli, G. M., & Gottesman, Z. L. (2019). A low-cost Arduino-based datalogger with cellular modem and FTP communication for irrigation water use monitoring to enable access to CropManage. *HardwareX*, *6*, e00066. https://doi.org/10.1016/j.ohx.2019.e00066

Stouffer, R. J., Eyring, V., Meehl, G. A., Bony, S., Senior, C., Stevens, B., & Taylor, K. E. (2017). CMIP5 scientific gaps and recommendations for CMIP6. *Bulletin of the American Meteorological Society*, *98*(1), 95–105. https://doi.org/10.1175/BAMS-D-15-00013.1

Strassburg, B. B., Brooks, T., Feltran-Barbieri, R., Iribarrem, A., Crouzeilles, R., Loyola, R., Latawiec, A. E., Oliveira Filho, F. J., De Scaramuzza, C. A., Scarano, F. R., Soares-Filho, B., & Balmford, A. (2017). Moment of truth for the Cerrado hotspot. *Nature Ecology & Evolution 2017 1:4*, *1*(4), 1–3. https://doi.org/10.1038/s41559-017-0099

Stroosnijder, L. (2009). Modifying land management in order to improve efficiency of rainwater use in the African highlands. *Soil and Tillage Research*, *103*(2), 247–256. https://doi.org/10.1016/j.still.2008.05.019

Susha Lekshmi, S. U., Singh, D. N., & Shojaei Baghini, M. (2014). A critical review of soil moisture measurement. *Measurement: Journal of the International Measurement Confederation*, *54*, 92–105. https://doi.org/10.1016/j.measurement.2014.04.007

Tatebe, H., Ogura, T., Nitta, T., Komuro, Y., Ogochi, K., Takemura, T., Sudo, K., Sekiguchi, M., Abe, M., Saito, F., Chikira, M., Watanabe, S., Mori, M., Hirota, N., Kawatani, Y., Mochizuki, T., Yoshimura, K., Takata, K., O'ishi, R., … Kimoto, M. (2019). Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. *Geoscientific Model Development*, *12*(7), 2727–2765. https://doi.org/10.5194/gmd-12-2727-2019

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012, April). An overview of CMIP5 and the experiment design. https://doi.org/10.1175/BAMS-D-11-00094.1

Teng, J., Vaze, J., Chiew, F. H. S., Wang, B., & Perraud, J.-M. (2012). Estimating the Relative Uncertainties Sourced from GCMs and Hydrological Models in Modeling Climate Change Impact on Runoff. *Journal of Hydrometeorology*, *13*(1), 122–139. https://doi.org/10.1175/JHM-D-11-058.1

Trigueiro, W. R., Nabout, J. C., & Tessarolo, G. (2020). Uncovering the spatial variability of recent deforestation drivers in the Brazilian Cerrado. *Journal of Environmental Management*, *275*, 111243. https://doi.org/10.1016/j.jenvman.2020.111243

Trilles, S., Torres-Sospedra, J., Belmonte, Ó., Zarazaga-Soria, F. J., González-Pérez, A., & Huerta, J. (2020). Development of an open sensorized platform in a smart agriculture context: A vineyard support system for monitoring mildew disease. *Sustainable Computing: Informatics and Systems*, *28*, 100309. https://doi.org/10.1016/j.suscom.2019.01.011

USDA. (2013). Rainfall Intensity Summarization Tool (RIST). https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/research/rist/rist-rainfall-intensity-summarization-tool/

van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, *2*(7), 494–501. https://doi.org/10.1038/s43016-021-00322-9

van Genuchten, M. T. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*, *44*(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Vendrame, P. R., Brito, O. R., Guimarães, M. F., Martins, É. S., & Becquer, T. (2010). Fertility and acidity status of latossolos (oxisols) under pasture in the Brazilian Cerrado. *Anais da Academia Brasileira de Ciências*, *82*(4), 1085–1094. https://doi.org/10.1590/S0001-37652010000400026

Volodin, E. M., Mortikov, E. V., Kostrykin, S. V., Galin, V. Y., Lykossov, V. N., Gritsun, A. S., Diansky, N. A., Gusev, A. V., & Iakovlev, N. G. (2017). Simulation of the present-day climate with the climate model INMCM5. *Climate Dynamics*, *49*(11-12), 3715–3734. https://doi.org/10.1007/s00382-017-3539-7

Volodin, E. M., Mortikov, E. V., Kostrykin, S. V., Galin, V. Y., Lykossov, V. N., Gritsun, A. S., Diansky, N. A., Gusev, A. V., Iakovlev, N. G., Shestakova, A. A., & Emelina, S. V. (2018). Simulation of the modern climate using the INM-CM48 climate model. *Russian Journal of Numerical Analysis and Mathematical Modelling*, *33*(6), 367–374. https://doi.org/10.1515/rnam-2018-0032

Webb, N. P., Marshall, N. A., Stringer, L. C., Reed, M. S., Chappell, A., & Herrick, J. E. (2017). Land degradation and climate change: building climate resilience in agriculture. *Frontiers in Ecology and the Environment*, *15*(8), 450–459. https://doi.org/10.1002/fee.1530

Williams, K. D., Copsey, D., Blockley, E. W., Bodas-Salcedo, A., Calvert, D., Comer, R., Davis, P., Graham, T., Hewitt, H. T., Hill, R., Hyder, P., Ineson, S., Johns, T. C., Keen, A. B., Lee, R. W., Megann, A., Milton, S. F., Rae, J. G. L., Roberts, M. J., … Xavier, P. K. (2018). The Met Office Global Coupled Model 3.0 and 3.1 (GC3.0 and GC3.1) Configurations. *Journal of Advances in Modeling Earth Systems*, *10*(2), 357–380. https://doi.org/10.1002/2017MS001115

Wischmeier, W. H., & Smith, D. D. (1978). *Predicting rainfall erosion losses – A guide to conservation planning*. Department of Agriculture, Science; Education Administration.

Wolka, K., Mulder, J., & Biazin, B. (2018, August). Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review. https://doi.org/10.1016/j.agwat.2018.05.016

Wongchuig, S., Carlo Espinoza, J., Condom, T., Junquas, C., Sierra, J. P., Fita, L., Sörensson, A., & Polcher, J. (2023). Changes in the surface and atmospheric water budget due to projected Amazon deforestation: Lessons from a fully coupled model simulation. *Journal of Hydrology*, *625*, 130082. https://doi.org/10.1016/j.jhydrol.2023.130082

Youlton, C., Wendland, E., Anache, J., Poblete-Echeverría, C., & Dabney, S. (2016). Changes in Erosion and Runoff due to Replacement of Pasture Land with Sugarcane Crops. *Sustainability*, *8*(7), 685. https://doi.org/10.3390/su8070685

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., Tsujino, H., Deushi, M., Tanaka, T., Hosaka, M., Yabu, S., Yoshimura, H., Shindo, E., Mizuta, R., Obata, A., Adachi, Y., & Ishii, M. (2019). The Meteorological Research Institute Earth System Model Version 2.0, MRI-ESM2.0: Description and Basic Evaluation of the Physical Component. *Journal of the Meteorological Society of Japan. Ser. II*, *97*(5), 931–965. https://doi.org/10.2151/jmsj.2019-051

Zhang, K., Morovati, K., Tian, F., Yu, L., Liu, B., & Olivares, M. A. (2023). Regional contributions of climate change and human activities to altered flow of the Lancang-mekong river. *Journal of Hydrology: Regional Studies*, *50*, 101535. https://doi.org/10.1016/j.ejrh.2023.101535

Zhou, Y., Varquez, A. C. G., & Kanda, M. (2019). High-resolution global urban growth projection based on multiple applications of the SLEUTH urban growth model. *Scientific Data*, *6*(1), 34. https://doi.org/10.1038/s41597-019-0048-z

Zhu, K., Cheng, Y., Zhou, Q., Kápolnai, Z., & Dávid, L. D. (2023). The contributions of climate and land use/cover changes to water yield services considering geographic scale. *Heliyon*, *9*(10), e20115. https://doi.org/10.1016/j.heliyon.2023.e20115

Ziehn, T., Chamberlain, M. A., Law, R. M., Lenton, A., Bodman, R. W., Dix, M., Stevens, L., Wang, Y.-P., & Srbinovsky, J. (2020). The Australian Earth System Model: ACCESS-ESM1.5. *Journal of Southern Hemisphere Earth Systems Science*, *70*(1), 193–214. https://doi.org/10.1071/ES19035