UNIVERSIDADE DE PASSO FUNDO
Graduate Program in Applied Computing

Master's Thesis

ADVANCING SPATIAL SIMULATIONS IN AGRICULTURE: INTRODUCING GSSAT2, AN ENHANCED DSSAT-BASED TOOL

NATHAN POSTAL BOMBANA

UPF

UNIVERSITY OF PASSO FUNDO

INSTITUTE OF TECHNOLOGY

GRADUATE PROGRAM IN APPLIED COMPUTING

ADVANCING SPATIAL SIMULATIONS IN AGRICULTURE: INTRODUCING GSSAT2, AN ENHANCED DSSAT-BASED TOOL

Nathan Postal Bombana

Thesis submitted to the University of Passo Fundo in partial fulfillment of the requirements for the degree of Master in Applied Computing.

Advisor: Prof. Dr. Willingthon Pavan

Passo Fundo

2024

CIP – Cataloging in Publication

B695a Bombana, Nathan Postal
Advancing spatial simulations in agriculture [electronic resource] : introducing GSSAT2, an enhanced DSSAT-Based tool / Nathan Postal Bombana. – 2023.
7 MB ; PDF.

Advisor: Prof. Dr. Willingthon Pavan.
Thesis (Master in Applied Computing) – University of Passo Fundo, 2023.

1. Agricultural informatics. 2. Crops - Simulation models. 3. Decision making. I. Pavan, Willingthon, advisor. II. Title.

CDU: 004:631
631:004

Cataloging: Librarian Jucelei Rodrigues Domingues - CRB 10/1569

UPF | PPGCA
Programa de Pós-Graduação
em Computação Aplicada

ATA DE DEFESA DO TRABALHO DE CONCLUSÃO DE CURSO DO ACADÊMICO

NATHAN POSTAL BOMBANA

Aos dezenove dias do mês de dezembro do ano de dois mil e vinte e três, às quatorze horas, realizou-se, na sala 101 do Prédio B5 do Campus 1 da UPF, a sessão pública de defesa do Trabalho de Conclusão de Curso "ADVANCING SPATIAL SIMULATIONS IN AGRICULTURE: INTRODUCING GSSAT2, AN ENHANCED DSSAT-BASED TOOL", de autoria de Nathan Postal Bombana, acadêmico do Curso de Mestrado em Computação Aplicada do Programa de Pós-Graduação em Computação Aplicada – PPGCA. Segundo as informações prestadas pelo Conselho de Pós-Graduação e constantes nos arquivos da Secretaria do PPGCA, o aluno preencheu os requisitos necessários para submeter seu trabalho à avaliação. A banca examinadora foi composta pelos doutores Willingthon Pavan, Carlos Amaral Hölbig, Alexandre Lazaretti Zanatta e José Maurício Cunha Fernandes. Concluídos os trabalhos de apresentação e arguição, a banca examinadora considerou o candidato **APROVADO**. Foi concedido o prazo de até quarenta e cinco (45) dias, conforme Regimento do PPGCA, para o acadêmico apresentar ao Conselho de Pós-Graduação o trabalho em sua redação definitiva, a fim de que sejam feitos os encaminhamentos necessários à emissão do Diploma de Mestre em Computação Aplicada. Para constar, foi lavrada a presente ata, que vai assinada pelos membros da banca examinadora e pela Coordenação do PPGCA.

Willingthon Pavan

Prof. Dr. Willingthon Pavan - UPF
Presidente da Banca Examinadora (Orientador)

Prof. Dr. Carlos Amaral Hölbig - UPF
(Avaliador Interno)

Prof. Dr. Alexandre Lazaretti Zanatta - UPF
(Avaliador Interno)

Dr. José Maurício Cunha Fernandes - Embrapa Trigo
(Avaliador Externo)

Prof. Dr. Carlos Amaral Hölbig - UPF
(Coordenador do PPGCA)

ACKNOWLEDGMENTS

I extend my profound gratitude to Professor Dr. Willingthon Pavan, who has not only guided me through the development of GSSAT2, but also believed in my potential from our very first meeting. His support was fundamental to all the steps of this work.

My sincere thanks go to the International Fertilizer Development Center (IFDC) for their keen interest in this project and for making Dr. Pavan's invaluable assistance possible. I am equally grateful to the staff of the University of Passo Fundo's Graduate Program in Applied Computing and all my previous educators who have shaped my academic journey.

I owe a debt of gratitude to my family: my mother Mariståela Postal Bombana, my father Valdair Bombana, and my grandparents Maximino and Josefina Postal, for their unwavering support and encouragement. Special thanks to my wife, Maíra Fraga Miranda, for her understanding and patience through the long nights and the disruptions brought about by this project. Additionally, a whimsical acknowledgment to Minerva, my kitten, for her moral support and occasional contributions to my typing by stepping on the keyboard.

I would also like to express my appreciation to my superiors at ScatterSpoke and Revend. John Samuelson, Peter Wellens, and Alex Reis have been incredibly accommodating, allowing me the time necessary to focus on this degree.

Lastly, I thank myself. This journey towards my degree was fraught with challenges, and there were moments when I contemplated giving up. Yet here I am, penning the final words of this extraordinary chapter of my life.

AVANÇANDO SIMULAÇÕES ESPACIAIS NA AGRICULTURA: APRESENTANDO GSSAT2, UMA FERRAMENTA APRIMORADA BASEADA NO DSSAT

RESUMO

O Decision Support System for Agrotechnology Transfer (DSSAT) é um conjunto de ferramentas para simulação de crescimento e desenvolvimento de plantas amplamente conhecido; ele acumula pesquisa, contribuições e validações por décadas de uso e desenvolvimento. Em todo o mundo, o DSSAT desempenha um papel importante para a pesquisa em áreas como mudanças climáticas e segurança alimentar. Uma grande limitação do DSSAT é sua dificuldade em trabalhar em contextos geoespaciais; ele é desenhado para executar simulações baseado em dados de entrada isolados, sem a habilidade de contextualizá-los em um espaço geográfico. Previamente, o International Fertilizer Development Center (IFDC) introduziu o Geographic Information Support System for Agrotechnology Transfer (GSSAT), uma ferramenta baseada em DSSAT para conduzir simulações geoespaciais em formato de grade. Entretanto, o GSSAT eventualmente tornou-se tecnologicamente obsoleto, o que implica na impossibilidade de utilizá-lo em sistemas modernos. Este trabalho introduz GSSAT2: uma ferramenta web, desenhada para suceder o GSSAT, também adicionando funcionalidades importantes como a coleta autônoma de dados e paralelismo entre simulações. As técnicas e tecnologias utilizadas no desenvolvimento permitiram que desenvolvêssemos uma plataforma robusta e de fácil manutenção, capaz de rodar simulações baseadas em DSSAT em contextos geoespaciais, também deixando espaço para a implementação de melhorias e o rápido desenvolvimento de novas funcionalidades devido ao ferramental utilizado.

Palavras-Chave: Aplicações Web, Computação Distribuída, Decision Support System for Agrotechnology Transfer, Modelos de Simulação de Culturas, Sistemas de Informação Geográfica.

ADVANCING SPATIAL SIMULATIONS IN AGRICULTURE: INTRODUCING GSSAT2, AN ENHANCED DSSAT-BASED TOOL

ABSTRACT

The Decision Support System for Agrotechnology Transfer (DSSAT) is a widely known toolkit for plant growth and development simulation; it accumulated research, contributions and validations over decades of use and development. Worldwide, DSSAT plays an important role for research in fields like climate change and food security. One major limitation of the DSSAT toolkit is to handle spatial contexts; it is primarily designed to run simulations based on isolated input data, without the ability to contextualize these data points in a geographical space. In the past, the International Fertilizer Development Center (IFDC) introduced Geographic Information Support System for Agrotechnology Transfer (GSSAT), a DSSAT-Based tool to allow geospatial-based simulations on a grid model. However, GSSAT eventually became technologically obsolete, implying inability to use it on modern systems. This work introduces GSSAT2: a web-based tool designed to succeed GSSAT, adding important features like autonomous data collection and simulation parallelism. The technologies and techniques used in the development allowed us to develop a robust and maintainable platform, able to run DSSAT-Based simulations on spatial contexts, as well as leaving room for improvement and fast development of extra features due to the employment tooling.

Keywords: Crop Simulation Models, Distributed Computing, Decision Support System for Agrotechnology Transfer, Geographic Information System, Web Applications.

LIST OF FIGURES

CONTENTS

1. INTRODUCTION

Geographic Information Systems (GIS) platforms have proven their utility across a myriad of fields since their conception in the 1960s, with applications including land-usage planning, natural hazards assessment, wildlife habitat analysis and more [1]. Over the decades, these platforms have evolved from basic tools to comprehensive systems capable of intricate spatial analysis, propelled by continuous technological advancements, increased computational power, and the introduction of machine learning and artificial intelligence. In the agricultural sector, GIS platforms have served for tasks such as spatial yield forecast, risk analysis and climate change impact studies [2].

The development and refinement of GIS platforms, especially those designed for agricultural applications, have become increasingly important in the face of escalating global food demand and the escalating challenges posed by climate change. These platforms can integrate disparate spatial and non-spatial data sets, allowing researchers, farmers, and policymakers to visualize and analyze complex geospatial relationships, thus enabling informed decision-making [3, 2, 4]. This integration of data contributes to sustainable agriculture and food security on a global scale.

Despite the significant strides made in developing GIS platforms and their applications in agriculture, certain limitations persist. Notably, the Geographic Information Support System for Agro-Technology Transfer (GSSAT), developed by the International Fertilizer Development Center, which integrated the crop system model (CSM) from the DSSAT toolkit with a GIS platform [4] has become technologically outdated [5]. Challenges such as compatibility issues with modern operating systems, an unintuitive user interface, and other execution difficulties limit the system's usefulness. The legacy technologies underlying GSSAT poses significant challenges to the platform's further development and evolution.

To address these issues and further contribute to the domain of GIS platforms for agricultural applications, this paper presents GSSAT2. As an evolution of its predecessor, GSSAT2 embodies advancements in technology, harnessing the power of cloud computing and web applications to offer improved compatibility with modern operating systems and a more intuitive user interface design. GSSAT2 is engineered for efficient, spatially explicit crop growth simulations, providing researchers, farmers, and policymakers a dynamic tool to make informed decisions on complex agricultural issues. This paper elaborates on the technical implementation details of GSSAT2, its potential caveats, and challenges encountered during its development. Furthermore, it includes usage reports, highlighting its performance and capabilities in real-world scenarios.

2. RELATED MATERIALS

The convergence of Geographic Information Systems (GIS) and crop simulation models has been a significant focus in the literature, elucidating its potential to augment efficiency in agriculture, fortify food security, and render a more profound comprehension of the impact of changing environmental conditions [6, 7, 8].

For instance, Pasquel *et al* [6], Coucheney *et al* [7] and Strand *et al* [8] studied problems of spatially scaling models for GIS usage: Pasquel *et al* [6] raised questions about the evaluation of the performance of spatialized crop models, especially when down scaled to finer scales. Similarly, Coucheney *et al* [7] delved into the implications of soil input data and the employment of different methods to upscale or downscale data, the researchers investigated how aggregating soil input data based on the majority of soil mapping units within an area affected spatially gridded simulations using the soil-vegetation model CoupModel. Yet in a similar vein, Strand *et al* [8] investigated the complexities involved in estimating areal averages, focusing on methodologies that involve dividing the entire area into regions, fitting a surface through the data points, and using physical model building techniques. Strand shed light on the significant challenges that come with scaling models, whether scaling up or down, with an emphasis on the effect on crop yield models.

Shelia *et al* [2] highlighted the limitations of different existing models for simulating crop growth in geospatial contexts and the development of CRAFT, a tool designed for yield forecasting, risk analysis, and climate change impact studies using gridded crop simulations powered by DSSAT, APSIM, and SARRA-H. Similarly, a study by Priya *et al* [9] explores the implementation of the Spatial-EPIC crop growth model in a GIS environment. It effectively combines high-resolution climatic data interpolation across large scales and robust datasets, providing location-specific and detailed insights into potential agricultural outcomes. This approach accentuates the value of multidimensional data in agricultural modeling and decision-making, despite challenges associated with data availability and quality in developing regions. In line with this, McNider *et al* [3] described GriDSSAT, an innovative modeling system that effectively merges DSSAT and gridded simulations. This integration facilitates a comprehensive analysis of the benefits and repercussions of irrigation, thereby underlining the practicality and value of such integrated, GIS-enabled modeling approaches.

In the context of employing web-based software to facilitate user-friendly and easy-to-use graphical interfaces, Sebben da Cunha [10] proposed the development of a new graphical interface for the DSSAT CSM. This initiative was designed to leverage web technologies, aiming to enhance user-friendliness and promote multiplatform compatibility.

Finally, as elucidated by Fachinello [5], the development of a GSSAT2 had already been a subject of discussion and prior endeavors had been executed. Regrettably, these initiatives were unsuccessful due to challenges encountered during the development period [5].

3. BACKGROUND

3.1 DECISION SUPPORT SYSTEM FOR AGROTECHNOLOGY TRANSFER

The Decision Support System for Agrotechnology Transfer (DSSAT) is an advanced computational platform that leverages crop simulation models for over 42 crops to simulate the dynamics of soil-plant-atmosphere interactions [11], being it one of the most important tool used for crop growth simulation [12]. Through years of dedicated research, DSSAT has been refined into a robust decision-making tool that, despite the growth in its application domain and expansion of modeling networks, has maintained remarkable stability, retaining much of its structure from decades ago [12, 13]. Fortran[1], its foundational programming language, continues to be utilized, underlining the system's enduring and reliable design.

As visualized in Figure 1, DSSAT is composed by a collection of support software packages, applications, the Crop System Model (CSM), the Shell (user interface) and a collection of databases [13].

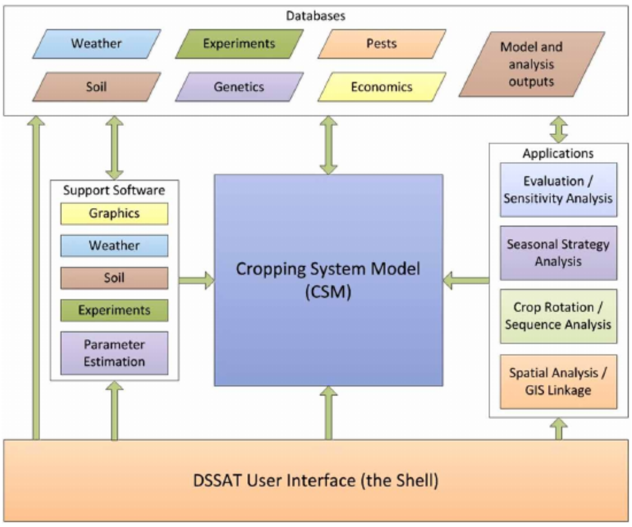

Figure 1. Architectural overview of the DSSAT toolkit, illustrating the integration between DSSAT components, such as the database, the support software package, auxiliary application modules and the main CSM. The figure shows how all the modules feed data to the CSM, and how they are all connected to the user interface at some point. Figure from Hoogenboom *et al* [13].

All input and output (I/O) files for DSSAT adhere to a stringent naming convention (see Figure 2) and are composed of plain ASCII text files, which consist of tables describing the I/O data [13]. This rigorous protocol has enabled the development of numerous tools that seamlessly integrate with DSSAT, such as the DSSAT-R package [14], jDSSAT [15], DSSAT Web [10], Pythia [16], CropTest [17], GSSAT and GSSAT2 itself.

[1] https://fortran-lang.org/

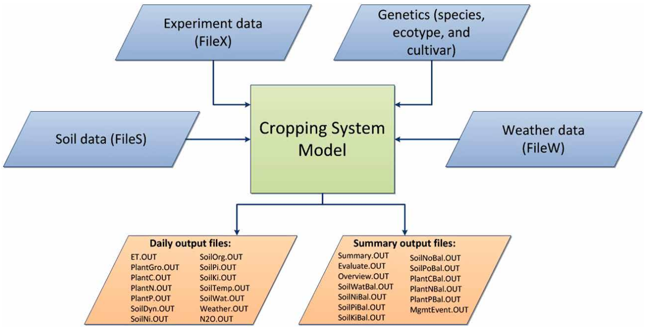

Figure 2. Overview of the DSSAT databases, that feed data into the CSM. The figure illustrates that files containing weather and soil data, as well as experiment and genetics parameters, are fed to the CSM, that produces daily output files and summary output files. Figure from Hoogenboom *et al* [13].

The Cropping System Model (CSM) is the main engine of the DSSAT ecosystem. Most users run the model through the DSSAT Shell, but it can also be run through a command line interface on several platforms [18, 13]. The CSM is a single executable that is capable to generically execute all the crop models available in DSSAT, each crop module shares the same routines for the simulation of most processes [13].

DSSAT can be used by a final user via its Graphical User Interface (available only for Windows), or via the direct execution of the CSM in the command-line in multiple operational system platforms [18].

Notably, since 2019, the DSSAT CSM has become an open-source project under the BSD-3-Clause license and is publicly available on GitHub (https://github.com/DSSAT/dssat-csm-os).

3.2 PYTHIA

Pythia is a tool developed by the University of Florida to simplify the usage and configuration process of the DSSAT [5]. Due to the high complexity associated with using and configuring DSSAT and the limitations of GSSAT, Pythia was designed to assist and simplify the execution process, particularly in cases where the chosen dataset needs formatting before use [5].

This Python-based tool can read specific datasets and divide them into a structure of folders and files accepted by DSSAT [5]. Additionally, Pythia creates the relationship between soil data, climate data, and spatial data for each execution, enhancing the simulation accuracy and efficiency [5, 13, 16].

Pythia is configured using a JSON file (Figure 3), which outlines relevant variables for the model's execution, file locations involved, and operations to be executed by DSSAT [5]. This method of configuration further simplifies the setup process for users.

```json
{
    "name": "example",
    "workDir": "work/unity",
    "templateDir": "/run/pythia/data/templates/",
    "weatherDir": "/run/pythia/data/weathers/",
    "cores": 12,
    "threads": 12,
    "sample": 10,
    "ghr_root": "/run/pythia/data/base/eGHR",
    "plugins": [],
    "default_setup": {
        "include": [
            "/run/pythia/data/includes/MZCER047.CUL"
        ]
    },
    "dssat": {
        "executable": "/opt/DSSAT/DSCSM047"
    },
    "runs": [
        {
            "name": "sorghum",
            "harvestArea": "raster::data/rasters/unity_spam_harvest_sorghum.tif"
        }
    ]
}
```

Figure 3. Example of a Pythia configuration file. This configuration defines fields like the path to the weather, and GHR databases, as well as the working directories, path to the raster file containing harvest statistics (further discussed in Section 4.8.2), the DSSAT executable file, and the amount of CPU cores and threads utilized to parallelize the simulations.

One of the key strengths of Pythia is its flexibility in managing diverse input data at different spatial resolutions, including crop masks, weather data, soil profiles, and crop management information [13]. It also demonstrates cross-platform compatibility, being able to run on various operating systems including Linux, Windows, and macOS [13].

Pythia is an open-source tool available via the AAR[2] license on GitHub at https://github.com/DSSAT/pythia.

3.2.1 Geographic Support System for Agrotechnology Transfer

The Global Spatial Simulation and Analysis Toolkit (GSSAT), developed by the International Fertilizer Development Center (IFDC), emerged as a pioneering tool in the field of agricultural decision support systems. As a climate information analysis simulation tool, GSSAT integrated GIS capabilities with the DSSAT's Cropping System Model, facilitating comprehensive, spatial agricultural simulations (seen in Figure 4) [5, 4]. The tool's capability to process both historical climatic data and stochastic datasets allowed for versatile and dynamic agricultural planning, catering to specific environmental and climatic nuances of different regions [5].

This tool revolutionized how crop management strategies could be simulated and analyzed. By incorporating a seasonal analysis tool, GSSAT facilitated the optimization of crop management decisions based on cost/price structures and climatic variations. This feature proved invaluable in enhancing the precision and efficiency of agricultural planning [5].

[2] All Rights Reserved

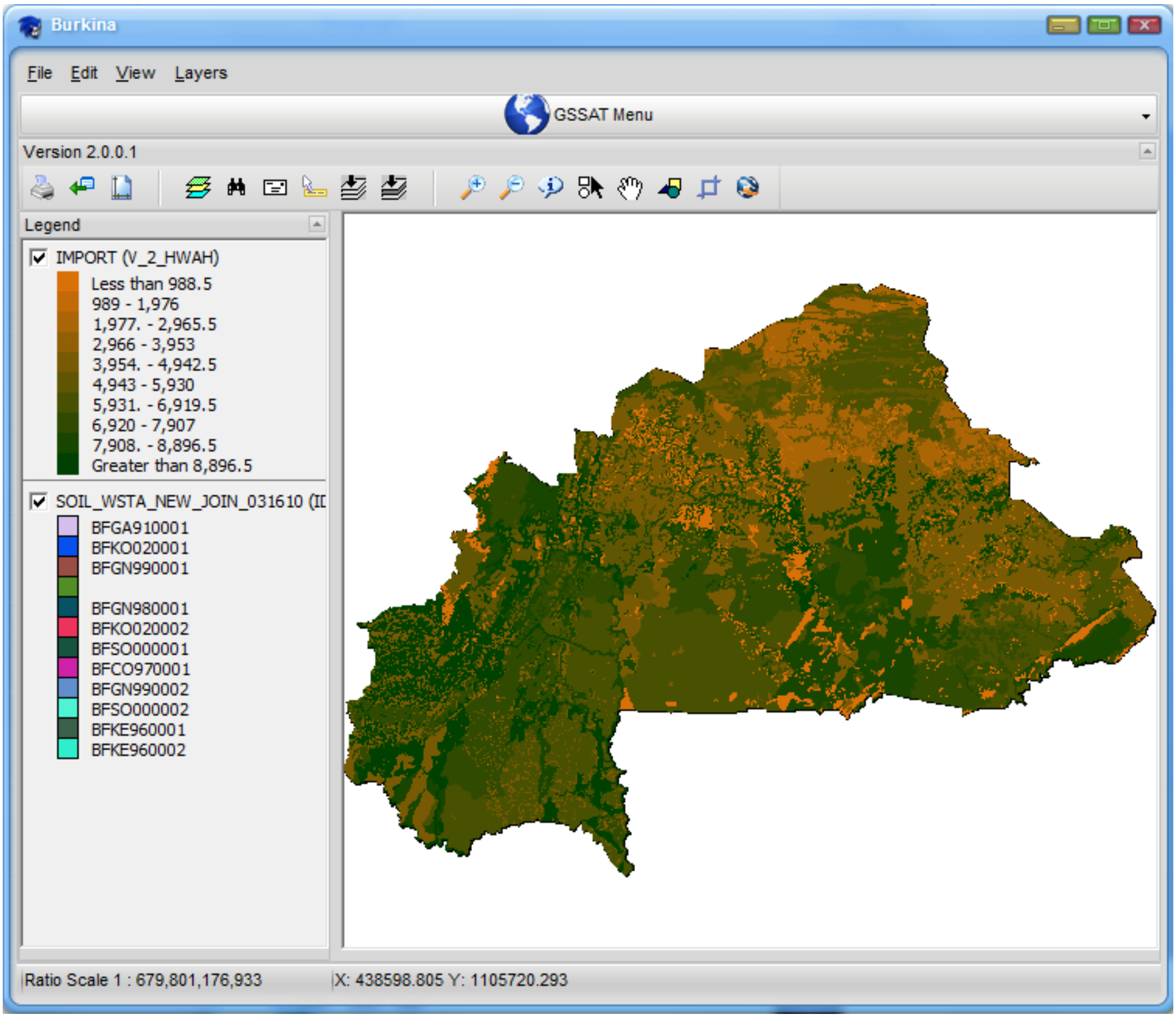

Figure 4. Legacy GSSAT's user interface, featuring GIS capabilities for comprehensive spatial simulations.

However, GSSAT faced several challenges that limited its long-term usability and development. Developed decades ago, the tool suffered from a lack of maintenance, resulting in compatibility issues with modern computing systems. This obsolescence not only affected its performance but also made it difficult to support or develop further. One significant limitation was the inflexibility in switching embedded datasets, which hindered the tool's adaptability to different regions of interest. Additionally, the scarcity of comprehensive documentation further compounded the challenges, making it difficult for new users to effectively utilize the tool.

The development of GSSAT2, therefore, was not just a technological upgrade but a necessary evolution to address these shortcomings. By incorporating modern computational tools and methodologies, GSSAT2 aims to retain the core functionalities of GSSAT while expanding its capabilities, user-friendliness, and accessibility to a wider range of users.

7. FINAL CONSIDERATIONS

7.1 SUMMARY OF KEY FINDINGS AND CONTRIBUTIONS

In this section, we aim to encapsulate the pivotal outcomes and significant contributions of the GSSAT2 project. In summary, GSSAT2 represents a critical advancement over its predecessor, the legacy GSSAT. Our investigation underlines GSSAT2's capability to address many of the previous version's limitations. Specifically, it now supports modern operating systems and boasts a more intuitive user interface.

Key contributions include the integration of cloud computing and web application frameworks, expanding both the tool's utility and user engagement. Additionally, GSSAT2 features enhanced, spatially-explicit crop growth simulations. These improvements serve to furnish a more dynamic and accurate tool for stakeholders such as researchers, farmers, and policymakers.

7.2 SIGNIFICANCE

In this section, the significance of GSSAT2 is discussed in the context of the broader field of GIS and its potential impact on various domains.

The significance of GSSAT2 extends beyond mere technological upgrades; it has implications for the broader field of GIS platforms and their applications in agriculture. By overcoming the legacy challenges of its predecessor, GSSAT2 sets a new standard in GIS-enabled decision-making for agricultural settings. Its ability to integrate complex crop simulations with real-world geographical data opens up avenues for nuanced agricultural planning at multiple scales—from local farms to regional and even national landscapes. Furthermore, the modular architecture of GSSAT2 enables it to be a part of a larger ecosystem of tools, making it adaptable and scalable to future agricultural challenges.

7.3 FUTURE DIRECTIONS

As we look ahead, the future for GSSAT2 is rife with potential. Based on the limitations highlighted earlier, a slew of enhancements and new features are under consideration (refer to Section 6.2 and Section 6.3). For example, the concept of developing complementary tools (such as the proposed Pythia substitute, or the *chirpsfetch* script) isn't confined solely to GSSAT2; we're exploring how these could be flexible enough to seamlessly integrate with other programs.

The opening of GSSAT2's source code is also being considered. This move could speed up the tool's development process and attract contributions from a wider range of experts. By doing so, GSSAT2 would not only enhance its own capabilities but also could become a cornerstone in a broader ecosystem of agricultural decision-making tools.

7.4 CLOSING REMARKS

In conclusion, the journey of developing GSSAT2 has been both challenging and rewarding. Its contributions are manifold—from its more intuitive interface to its cloud computing capabilities, to its enhanced, spatially-explicit crop growth simulations. These technological advancements elevate GSSAT2 from being merely an update to its predecessor into a comprehensive tool for modern agricultural decision-making. While we are excited about its potential, we recognize that it's a step in a longer journey. With future enhancements and community contributions, GSSAT2 is well-positioned to adapt and grow along with the ever-evolving landscape of GIS and agricultural science.

REFERENCES

[1] CHANG, K.-T. Geographic information system. 2019. http://dx.doi.org/10.1002/9781118786352.wbieg0152.pub2.

[2] SHELIA, V. et al. A multi-scale and multi-model gridded framework for forecasting crop production, risk analysis, and climate change impact studies. *Environmental Modelling and Software*, Elsevier Ltd, v. 115, p. 144–154, 5 2019. ISSN 13648152. http://dx.doi.org/10.1016/J.ENVSOFT.2019.02.006.

[3] MCNIDER, R. T. et al. An integrated crop and hydrologic modeling system to estimate hydrologic impacts of crop irrigation demands. *Environmental Modelling and Software*, Elsevier Ltd, v. 72, p. 341–355, 10 2015. ISSN 13648152. http://dx.doi.org/10.1016/j.envsoft.2014.10.009.

[4] SHELIA, V. et al. Spatial crop modeling and decision support tool. In: *Proceedings of ASA, CSSA and SSSA International Annual Meetings (2019)*. [S.l.]: ASA, CSSA and SSSA, 2019. https://scisoc.confex.com/scisoc/2019am/meetingapp.cgi/Paper/120210.

[5] FACHINELLO, R. M. Gssat2: uma proposta de ferramenta para organização e gerenciamento de dados geográficos. 2020.

[6] PASQUEL, D. et al. *A review of methods to evaluate crop model performance at multiple and changing spatial scales*. [S.l.]: Springer, 2022. 1489-1513 p. http://dx.doi.org/10.1007/s11119-022-09885-4.

[7] COUCHENEY, E. et al. Spatial aggregation for crop modelling at regional scales: the effects of soil variability. 1 2017. ISSN 11610301. http://dx.doi.org/10.1016/j.eja.2013.04.005.

[8] STRAND, B. W. *Spatial Scale of Crop-Yield Models A Review of the Relationship Between Scale of Models and Accuracy*. 1981. http://dx.doi.org/10.22004/ag.econ.321193.

[9] PRIYA, S.; SHIBASAKI, R.; OCHI, S. *Modeling spatial crop production: A GIS approach - Geospatial World*. 2009. Available at https://www.geospatialworld.net/article/modeling-spatial-crop-production-a-gis-approach/.

[10] CUNHA, A. S. da. Interface multiplataforma para simulação de sequência de cultivos. 2018.

[11] HOOGENBOOM, G. et al. *DSSAT Overview - DSSAT.net*. [S.l.]: DSSAT Foundation, 2023. Available at https://dssat.net/about/.

[12] FERNANDES, J. M. et al. Improving crop pest/disease modeling. In: ____. [S.l.]: Burleigh Dodds series in agricultural science, 2019. http://dx.doi.org/10.1201/9780429266591.

[13] HOOGENBOOM, G. et al. The dssat crop modeling ecosystem. In: ____. [S.l.]: Burleigh Dodds series in agricultural science, 2019. p. 173–216. http://dx.doi.org/10.19103/as.2019.0061.10.

[14] ALDERMAN, P. D. A comprehensive r interface for the dssat cropping systems model. *Computers and Electronics in Agriculture*, Elsevier B.V., v. 172, p. 105325, 5 2020. ISSN 01681699. http://dx.doi.org/10.1016/j.compag.2020.105325.

[15] RESENES, J. de A. et al. jdssat: A javascript module for dssat-csm integration. *SoftwareX*, Elsevier B.V., v. 10, p. 100271, 2019. ISSN 23527110. http://dx.doi.org/10.1016/j.softx.2019.100271.

[16] JOSHI, V. R. et al. *Pythia: A Gridded Modeling Framework for DSSAT-Cropping System Model for Multi-Spatial Scale Applications*. [S.l.]: ASA-CSSA-SSSA, 2021.

[17] NICOLAU, M.; 26160381881; HTTP://LATTES.CNPQ.BR/7175968064959899. Croptest : data-drive test automation for crop modeling systems. Universidade de Passo Fundo, 3 2018.

[18] HOOGENBOOM, G. et al. *For Power Users - DSSAT.net*. [S.l.]: DSSAT Foundation, 2023. Available at https://dssat.net/tools/tools-for-power-users/.

[19] RICHARDSON, C. *Microservices patterns: with examples in Java*. [S.l.]: Simon and Schuster, 2018. ISBN 978-1617294549.

[20] RAMAKRISHNAN, R.; GEHRKE, J. *Database Management Systems*. [S.l.: s.n.], 2002.

[21] FIREBASE Authentication. [S.l.]: Google LLC, 2023. Available at https://firebase.google.com/docs/auth.

[22] CLOUD Object Storage - Amazon S3 - Amazon Web Services. [S.l.]: Amazon Web Services, Inc. or its affiliates, 2023. Available at https://aws.amazon.com/s3/.

[23] LERNER, R. M. At the forge: 12-factor apps. *Linux Journal*, Belltown Media Houston, TX, v. 2014, p. 5, 2014. https://dl.acm.org/doi/10.5555/2682554.2682559.

[24] GARCéS, L. F. T-rex phaco: enabling paas application using twelve-factor app. 2018. Available at www.kth.se.

[25] KHAN, A. Key characteristics of a container orchestration platform to enable a modern application. *IEEE Cloud Computing*, Institute of Electrical and Electronics Engineers Inc., v. 4, p. 42–48, 9 2017. ISSN 23256095. http://dx.doi.org/10.1109/MCC.2017.4250933.

[26] NORMAN, M. G.; ZUREK, T.; THANISCH, P. Much ado about shared-nothing. *SIGMOD Rec.*, Association for Computing Machinery, New York, NY, USA, v. 25, n. 3, p. 16–21, sep 1996. ISSN 0163-5808. https://doi.org/10.1145/234889.234892.

[27] STACK Overflow Developer Survey 2022. [S.l.]: Stack Overflow, 2022. Available at https://survey.stackoverflow.co/2022.

[28] SPARKS, J. Enabling docker for hpc. *Concurrency and Computation: Practice and Experience*, v. 31, n. 16, p. e5018, 2019. https://onlinelibrary.wiley.com/doi/abs/10.1002/cpe.5018.

[29] DEVELOP with Docker Engine API | Docker Docs. [S.l.]: Docker Inc., 2023. Available at https://docs.docker.com/engine/api/.

[30] AGGARWAL, S. Modern web-development using reactjs. *International Journal of Recent Research Aspects*, v. 5, p. 133–137, 2018.

[31] CHU, S. Shopify upsell app: Using next. js, react. js to boost sale. 2020.

[32] PHAM, A. D. *Developing back-end of a web application with NestJS framework*. 2020.

[33] DOCUMENTATION | NestJS - A progressive Node.js framework. 2023. Available at https://docs.nestjs.com/.

[34] IHAKA, R.; GENTLEMAN, R. *R: A Language for Data Analysis and Graphics*. 1996. 299-314 p. http://dx.doi.org/10.1080/10618600.1996.10474713.

[35] CHAMBERS, J. M. *Software for Data Analysis: Programming with R*. [S.l.: s.n.], 2008. http://dx.doi.org/10.1007/978-0-387-75936-4. ISBN 978-0-387-75936-4.

[36] GINESTET, C. Ggplot2 : elegant graphics for data analysis. In: ____. [S.l.]: Springer, 2009. p. 245–245. ISBN 9780387981406. http://dx.doi.org/10.1080/15366367.2019.1565254.

[37] INTRODUCTION to Apollo Client - Apollo GraphQL Docs. 2023. Available at https://www.apollographql.com/docs/react/.

[38] HARTIG, O.; PéREZ, J. Semantics and complexity of graphql. *The Web Conference 2018 - Proceedings of the World Wide Web Conference, WWW 2018*, Association for Computing Machinery, Inc, p. 1155–1164, 4 2018. http://dx.doi.org/10.1145/3178876.3186014.

[39] TAELMAN, R.; SANDE, M. V.; VERBORGH, R. *GraphQLLD: Linked Data Querying with GraphQL*. 2018.

[40] GOKHALE, S. S.; YACOUB, S. Performability analysis of a pipeline software architecture. 2005. http://dx.doi.org/10.1109/COMPSAC.2005.120.

[41] DOBERKAT, E. E. Pipelines: Modelling a software architecture through relations. *Acta Informatica*, v. 40, p. 37–79, 9 2003. ISSN 00015903. http://dx.doi.org/10.1007/s00236-003-0121-z.

[42] GARLAN, D.; SHAW, M. *An introduction to software architecture*. [S.l.]: World Scientific, 1993. 1–39 p. http://dx.doi.org/10.1142/9789812798039_0001.

[43] WULF, C.; EHMKE, N. C.; HASSELBRING, W. *Toward a Generic and Concurrency-Aware Pipes Filters Framework*. 2014.

[44] CHEN, S. et al. Towards scalable and reliable in-memory storage system: A case study with redis. In: *2016 IEEE Trustcom/BigDataSE/ISPA*. [S.l.: s.n.], 2016. p. 1660–1667. http://dx.doi.org/10.1109/TrustCom.2016.0255.

[45] YU, H. et al. A cache framework for geographical feature store. In: . [S.l.: s.n.], 2012. ISBN 9781467311045. http://dx.doi.org/10.1109/Geoinformatics.2012.6270288.

[46] MACEDO, T.; OLIVEIRA, F. *Redis Cookbook*. [S.l.: s.n.], 2011. ISBN 978-1449305048.

[47] JI, Z. et al. A distributed redis framework for use in the ucww. In: . [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2014. p. 241–244. ISBN 9781479962358. http://dx.doi.org/10.1109/CyberC.2014.50.

[48] BRONSON, N. et al. *TAO: Facebook's Distributed Data Store for the Social Graph*. 2013. 49 p.

[49] CARLSON, J. L.; SANFILIPPO, S. *Redis in Action*. [S.l.: s.n.], 2013. ISBN 978-1617290855.

[50] NELSON, J. *Mastering Redis*. [S.l.]: Packt Publishing, 2016. ISBN 978-1783988181.

[51] WHAT is BullMQ - BullMQ. 2023. Available at https://docs.bullmq.io/.

[52] MAGNONI, L. Modern messaging for distributed sytems. In: . [S.l.]: Institute of Physics Publishing, 2015. v. 608, p. 012038. ISSN 17426596. http://dx.doi.org/10.1088/1742-6596/608/1/012038.

[53] JOHN, V.; LIU, X. A survey of distributed message broker queues. 4 2017. http://dx.doi.org/10.48550/arXiv.1704.00411.

[54] FIRST steps | NestJS - A progressive Node.js framework. 2023. Available at https://docs.nestjs.com/first-steps.

[55] RENDERING Strategies - Rendering and Ranking | Learn Next.js. 2023. Available at https://nextjs.org/learn/seo/rendering-and-ranking/rendering-strategies.

[56] THAKKAR, M. Next.js. In: ____. [S.l.]: Apress, 2020. p. 93–137. http://dx.doi.org/10.1007/978-1-4842-5869-9_3.

[57] DOCS | Next.js. 2023. Available at https://nextjs.org/docs.

[58] JADHAV, M. A.; SAWANT, B. R.; DESHMUKH, A. Single page application using angularjs. 2015. ISSN 0975-9646. Available at https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=4c272a54fad90a38e2a218c54653303f1203438d.

[59] JOSEPH, R. J. Single page application and canvas drawing. *International journal of Web Semantic Technology*, Academy and Industry Research Collaboration Center (AIRCC), v. 6, p. 29–37, 1 2015. ISSN 09762280. http://dx.doi.org/10.5121/ijwest.2015.6103.

[60] MOLIN, E. et al. Comparison of single-page application frameworks. 2016.

[61] KORNIENKO, D. V.; MISHINA, S. V.; MELNIKOV, M. O. The single page application architecture when developing secure web services. *Journal of Physics: Conference Series*, IOP Publishing Ltd, v. 2091, 12 2021. ISSN 17426596. http://dx.doi.org/10.1088/1742-6596/2091/1/012065.

[62] DEPLOYING: Static Exports | Next.js. 2023. Available at https://nextjs.org/docs/app/building-your-application/deploying/static-exports.

[63] JOBS | Kubernetes. 2023. Available at https://kubernetes.io/docs/concepts/workloads/controllers/job/.

[64] WOJCIECHOWSKI, J.; HOPKINS, A. M.; UPTON, R. N. Interactive pharmacometric applications using r and the shiny package. *CPT: Pharmacometrics Systems Pharmacology*, v. 4, p. 146–159, 2015. http://dx.doi.org/10.1002/psp4.21.

[65] JIA, L. et al. Development of interactive biological web applications with r/shiny. *Briefings in Bioinformatics*, v. 23, p. bbab415, 8 2021. ISSN 1477-4054. http://dx.doi.org/10.1093/bib/bbab415.

[66] YU, Y.; OUYANG, Y.; YAO, W. shinycircos: an r/shiny application for interactive creation of circos plot. *Bioinformatics*, v. 34, p. 1229–1231, 8 2017. ISSN 1367-4803. Url{https://doi.org/10.1093/bioinformatics/btx763.

[67] BOUNDARY. 2023. Available at https://education.nationalgeographic.org/resource/boundary/.

[68] DATABASE of Global Administrative Areas 3.6. 2018. Available at https://gadm.org/download_world36.html.

[69] SETIAWAN, A.; SEDIYONO, E. Area calculation based on gadm geographic information system database. *Telkomnika (Telecommunication Computing Electronics and Control)*, Universitas Ahmad Dahlan, v. 18, p. 1416–1421, 2020. ISSN 23029293. http://dx.doi.org/10.12928/TELKOMNIKA.v18i3.14901.

[70] BUTLER, H. et al. *The GeoJSON Format*. [S.l.]: RFC Editor, 2016. http://dx.doi.org/10.17487/RFC7946.

[71] BRAY, T. *The JavaScript Object Notation (JSON) Data Interchange Format*. [S.l.]: RFC Editor, 2014. http://dx.doi.org/10.17487/RFC7159.

[72] HARRISON, G.; HARRISON, M. *MongoDB Performance Tuning*. [S.l.]: Apress, 2021. http://dx.doi.org/10.1007/978-1-4842-6879-7.

[73] MONGODB Limits and Thresholds — MongoDB Manual. 2023. Available at https://www.mongodb.com/docs/manual/reference/limits/.

[74] GU, Y. et al. Analysis of data storage mechanism in nosql database mongodb. 2015 International Conference on Consumer Electronics-Taiwan (ICCE-TW), 2015. http://dx.doi.org/10.1109/ICCE-TW.2015.7217036.

[75] CURRIER, C. Protocol buffers. In: ____. [S.l.]: Springer International Publishing, 2022. p. 223–260. http://dx.doi.org/10.1007/978-3-030-98467-0.

[76] NASA POWER | Docs | Methodology | Data Sources - NASA POWER | Docs. 2023. Available at https://power.larc.nasa.gov/docs/methodology/data/sources/.

[77] ZHANG, T. et al. *A GLOBAL PERSPECTIVE: NASA's Prediction of Worldwide Energy Resources (POWER) Project*. 2017.

[78] SPARKS, A. *nasapower: A NASA POWER Global Meteorology, Surface Solar Energy and Climatology Data Client for R*. [S.l.]: The Open Journal, 2018. 1035 p. http://dx.doi.org/10.21105/joss.01035.

[79] DUARTE, Y. C.; SENTELHAS, P. C. Nasa/power and dailygridded weather datasets—how good they are for estimating maize yields in brazil? *International Journal of Biometeorology*, Springer, v. 64, p. 319–329, 3 2020. ISSN 14321254. http://dx.doi.org/10.1007/s00484-019-01810-1.

[80] HUNT, L. A. et al. *ICASA Version 1.0 Data Standards for Agricultural Research and Decision Support*. 2006. Available at www.icasa.net/weather_data.

[81] WHITE, J. W. et al. Integrated description of agricultural field experiments and production: The icasa version 2.0 data standards. *Computers and Electronics in Agriculture*, Elsevier B.V., v. 96, p. 1–12, 2013. ISSN 01681699. http://dx.doi.org/10.1016/j.compag.2013.04.003.

[82] DASADIA, C.; NAYAK, A. *MongoDB Cookbook : over 80 comprehensive recipes that will help you master the art of using and administering MongoDB 3*. [S.l.: s.n.], 2016. ISSN 2349-7688. ISBN 9781785289989.

[83] TTL Indexes — MongoDB Manual. 2023. Available at https://www.mongodb.com/docs/manual/core/index-ttl/.

[84] CLIMATE, I. R. I. for et al. *Global High-Resolution Soil Profile Database for Crop Modeling Applications*. [S.l.]: Harvard Dataverse, 2015. http://dx.doi.org/10.7910/DVN/1PEEY0.

[85] HAN, E.; INES, A.; KOO, J. *Global High-Resolution Soil Profile Database for Crop Modeling Applications*. [S.l.], 2015.

[86] QUEUES - BullMQ. 2023. Available at https://docs.bullmq.io/guide/queues.

[87] FLOWS - BullMQ. 2023. Available at https://docs.bullmq.io/guide/flows.

[88] YOU, L. et al. *Spatial Production Allocation Model (SPAM) 2010 V1r1*. 2014.

[89] TAYLOR, D. Work the shell: Working with stdin and stdout. *Linux J.*, Belltown Media, Houston, TX, v. 2012, n. 224, dec 2012. ISSN 1075-3583. https://dl.acm.org/doi/10.5555/2422325.2422330.

[90] ZOLKIFLI, N. N.; NGAH, A.; DERAMAN, A. Version control system: A review. In: . [S.l.]: Elsevier B.V., 2018. v. 135, p. 408–415. ISSN 18770509. http://dx.doi.org/10.1016/j.procs.2018.08.191.

[91] HASHIMOTO, N. *Amazon S3 cookbook*. [S.l.: s.n.], 2015. ISBN 9781785280702.

[92] JH, D. E.; UMAR, R.; RIADI, I. *Implementation of Cloudflare Hosting for Speeds and Protection on The Website*. 2019.

[93] DEZORDI, M. L. et al. *Sistema de auxílio à tomada de decisão da área agrícola DSSAT: automatizando o processo de integração de novas versões*. 2023.

[94] SHAHIN, M.; BABAR, M. A.; ZHU, L. *Continuous Integration, Delivery and Deployment: A Systematic Review on Approaches, Tools, Challenges and Practices*. [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2017. 3909-3943 p. http://dx.doi.org/10.1109/ACCESS.2017.2685629.

[95] CHANDRASEKARA, C.; HERATH, P. Introduction to github actions. In: ____. [S.l.]: Apress, 2021. p. 1–8. http://dx.doi.org/10.1007/978-1-4842-6464-5_1.

[96] KINSMAN, T. et al. How do software developers use github actions to automate their workflows? In: . [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2021. p. 420–431. ISBN 9781728187105. http://dx.doi.org/10.1109/MSR52588.2021.00054.

[97] DANIELSSON, P.; POSTEMA, T.; MUNIR, H. Heroku-based innovative platform for web-based deployment in product development at axis. *IEEE Access*, Institute of Electrical and Electronics Engineers Inc., v. 9, p. 10805–10819, 2021. ISSN 21693536. http://dx.doi.org/10.1109/ACCESS.2021.3050255.

[98] SOLHEIMJEFFERY. Web apps in the computer science curriculum. *Journal of Computing Sciences in Colleges*, Consortium for Computing Sciences in Colleges PUB305, 5 2015. http://dx.doi.org/10.5555/2752981.2753011.

[99] KEMP, C.; GYGER, B. *Professional Heroku Programming*. [S.l.]: John Wiley Sons, 2013. ISBN 978-1118508992.

[100] CRAIG, J. et al. Accessible rich internet applications (wai-aria) 1.0. *W3C Working Draft*, 2009.

[101] RILEY-HUFF, D. A. Supporting web accessibility with html5 and accessible rich internet applications: Insights for libraries. In: ____. [S.l.]: Emerald Group Publishing Limited, 2015. p. 143–167. ISBN 978-1-78560-653-3. http://dx.doi.org/10.1108/S0065-283020150000040016.

[102] SINHA, A. Web accessibility analysis on government of india websites based on wcag. In: . [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2020. ISBN 9781728196152. http://dx.doi.org/10.1109/IEMTRONICS51293.2020.9216445.

[103] DONNER, J.; GITAU, S. New paths: exploring mobile-centric internet use in south africa. In: . [S.l.: s.n.], 2009. p. 20–21.

[104] GITAU, S.; MARSDEN, G.; DONNER, J. After access - challenges facing mobile-only internet users in the developing world. In: . [S.l.]: ACM, 2010. v. 4, p. 2603–2606. ISBN 9781605589299. http://dx.doi.org/10.1145/1753326.1753720.

[105] SOUZA, J. de Lima de. Dssat lite: Uma nova interface para execução e gerenciamento dos modelos do dssat. 2016.

[106] ANDREWS, G. R.; SCHNEIDER, F. B. Concepts and notations for concurrent programming. *ACM Computing Surveys (CSUR)*, ACM PUB27 New York, NY, USA, v. 15, p. 3–43, 3 1983. ISSN 15577341. http://dx.doi.org/10.1145/356901.356903.

[107] SILVA, V. S. da et al. Smart resource allocation of concurrent execution of parallel applications. *Concurrency and Computation: Practice and Experience*, John Wiley and Sons Ltd, v. 35, p. e6600, 8 2023. ISSN 1532-0626. http://dx.doi.org/10.1002/cpe.6600.

[108] MATSAKIS, N. D.; KLOCK, F. S. The rust language. *ACM SIGAda Ada Letters*, Association for Computing Machinery (ACM), v. 34, p. 103–104, 11 2014. ISSN 1094-3641. http://dx.doi.org/10.1145/2692956.2663188.

[109] BUGDEN, W.; ALAHMAR, A. Rust: The programming language for safety and performance. *Igscong'22*, 6 2022. http://dx.doi.org/10.48550/arXiv.2206.05503.

[110] QIN, C.-Z.; ZHAN, L.-J.; ZHU, A.-X. How to apply the geospatial data abstraction library (gdal) properly to parallel geospatial raster i/o? *Transactions in GIS*, John Wiley Sons, Ltd, v. 18, p. 950–957, 12 2014. ISSN 13611682. http://dx.doi.org/10.1111/tgis.12068.

[111] FUNK, C. et al. The climate hazards infrared precipitation with stations - a new environmental record for monitoring extremes. *Scientific Data*, Nature Publishing Groups, v. 2, p. 1–21, 12 2015. ISSN 20524463. http://dx.doi.org/10.1038/sdata.2015.66.

[112] FUNK, C. et al. Algorithm and data improvements for version 2.1 of the climate hazards center's infrared precipitation with stations data set. In: ____. [S.l.]: Springer, 2020. v. 67, p. 409–427. http://dx.doi.org/10.1007/978-3-030-24568-9_23.

[113] SHUKLA, S. et al. *The Climate Hazards group InfraRed Precipitation with Stations (CHIRPS) dataset and its applications in drought risk management*. 2017. 2017-11498 p.

[114] PAREDES-TREJO, F. J.; BARBOSA, H. A.; KUMAR, T. V. L. Validating chirps-based satellite precipitation estimates in northeast brazil. *Journal of Arid Environments*, Academic Press, v. 139, p. 26–40, 4 2017. ISSN 1095922X. http://dx.doi.org/10.1016/j.jaridenv.2016.12.009.

[115] RIVERA, J. A.; MARIANETTI, G.; HINRICHS, S. Validation of chirps precipitation dataset along the central andes of argentina. *Atmospheric Research*, Elsevier Ltd, v. 213, p. 437–449, 11 2018. ISSN 01698095. http://dx.doi.org/10.1016/j.atmosres.2018.06.023.

[116] BAI, L. et al. Accuracy of chirps satellite-rainfall products over mainland china. *Remote Sensing*, MDPI AG, v. 10, p. 362, 2 2018. ISSN 2072-4292. http://dx.doi.org/10.3390/rs10030362.

[117] DINKU, T. et al. Validation of the chirps satellite rainfall estimates over eastern africa. *Quarterly Journal of the Royal Meteorological Society*, John Wiley and Sons Ltd, v. 144, p. 292–312, 11 2018. ISSN 0035-9009. http://dx.doi.org/10.1002/qj.3244.

[118] KATSANOS, D.; RETALIS, A.; MICHAELIDES, S. Validation of a high-resolution precipitation database (chirps) over cyprus for a 30-year period. *Atmospheric Research*, Elsevier Ltd, v. 169, p. 459–464, 3 2016. ISSN 01698095. http://dx.doi.org/10.1016/j.atmosres.2015.05.015.

[119] SHEN, Z. et al. Recent global performance of the climate hazards group infrared precipitation (chirp) with stations (chirps). *Journal of Hydrology*, Elsevier B.V., v. 591, p. 125284, 12 2020. ISSN 00221694. http://dx.doi.org/10.1016/j.jhydrol.2020.125284.

[120] AULIYANI, D.; WAHYUNINGRUM, N. Rainfall variability based on the climate hazards group infrared precipitation with station data (chirps) in lesti watershed, java island, indonesia. In: . [S.l.]: IOP Publishing Ltd, 2021. v. 874, p. 012003. ISSN 17551315. http://dx.doi.org/10.1088/1755-1315/874/1/012003.

[121] WAHYUNI, S.; SISINGGIH, D.; DEWI, I. A. Validation of climate hazard group infrared precipitation with station (chirps) data in wonorejo reservoir, indonesia. In: . [S.l.]: IOP Publishing Ltd, 2021. v. 930, p. 012042. ISSN 17551315. http://dx.doi.org/10.1088/1755-1315/930/1/012042.

[122] GELETA, C. D.; DERESSA, T. A. Evaluation of climate hazards group infrared precipitation station (chirps) <scp>satellite-based</scp> rainfall estimates over finchaa and neshe watersheds, ethiopia. *Engineering Reports*, John Wiley and Sons Inc, v. 3, p. e12338, 6 2021. ISSN 2577-8196. http://dx.doi.org/10.1002/eng2.12338.

[123] ALEJO, L. A.; ELLA, V. B.; SALUDES, R. B. Applicability of the climate hazards group infrared precipitation with stations as rainfall input for swat watershed modeling. *Water Resources*, Pleiades journals, v. 48, p. 925–935, 11 2021. ISSN 1608344X. http://dx.doi.org/10.1134/S0097807821060026.

[124] HARRISON, L.; FUNK, C.; PETERSON, P. Identifying changing precipitation extremes in sub-saharan africa with gauge and satellite products. *Environmental Research Letters*, Institute of Physics Publishing, v. 14, p. 085007, 7 2019. ISSN 17489326. http://dx.doi.org/10.1088/1748-9326/ab2cae.

[125] SOUčEK, B. Limits to growth to computerised measurements: software and algorithms. *Measurement*, Elsevier, v. 1, p. 95–104, 4 1983. ISSN 02632241. http://dx.doi.org/10.1016/S0263-2241(83)80018-9.

[126] LIANG, S. *The Java native interface: programmer's guide and specification*. Addison-Wesley Professional, 1999. https://dl.acm.org/doi/10.5555/520155. Available: <https://dl.acm.org/doi/10.5555/520155>.

[127] VINOSKI, S. Advanced message queuing protocol. *IEEE Internet Computing*, v. 10, p. 87–89, 11 2006. ISSN 10897801. http://dx.doi.org/10.1109/MIC.2006.116.

[128] HONG, X. J.; YANG, H. S.; KIM, Y. H. Performance analysis of restful api and rabbitmq for microservice web application. In: . [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2018. p. 257–259. ISBN 9781538650400. http://dx.doi.org/10.1109/ICTC.2018.8539409.

[129] CLIENTS Libraries and Developer Tools — RabbitMQ. 2023. Available at https://www.rabbitmq.com/devtools.html.

[130] KALYANASUNDARAM, J.; SIMMHAN, Y. *ARM Wrestling with Big Data: A Study of Commodity ARM64 Server for Big Data Workloads*. 2017. http://dx.doi.org/10.1109/HiPC.2017.00032.

[131] ALI, Z. et al. Reassessing the performance of arm vs x86 with recent technological shift of apple. In: . [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2022. ISBN 9781665489454. http://dx.doi.org/10.1109/ICIT56493.2022.9988933.

[132] JIANG, Q.; LEE, Y. C.; ZOMAYA, A. Y. The power of arm64 in public clouds. In: . [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2020. p. 459–468. ISBN 9781728160955. http://dx.doi.org/10.1109/CCGrid49817.2020.00-47.

[133] DOWNLOAD | Node.js. 2023. Available at https://nodejs.org/en/download.

[134] BERMúDEZ-ORTEGA, J. et al. Remote web-based control laboratory for mobile devices based on ejss, raspberry pi and node.js. In: . [S.l.]: Elsevier B.V., 2015. v. 48, p. 158–163. ISSN 24058963. http://dx.doi.org/10.1016/j.ifacol.2015.11.230.

[135] SOORYAVANSHI, P.; UPGANLAWAR, S.; BHOSLE, A. Implementation of node.js server on raspberry pi to control a remote vehicle for defense use. In: . [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2018. p. 816–819. ISBN 9781538619599. http://dx.doi.org/10.1109/ISS1.2017.8389290.

[136] DAVIDSON, C.; REZWANA, T.; HOQUE, M. A. Smart home security application enabled by iot:: Using arduino, raspberry pi, nodejs, and mongodb. In: . [S.l.]: Springer Verlag, 2019. v. 256, p. 46–56. ISBN 9783030059279. ISSN 18678211. http://dx.doi.org/10.1007/978-3-030-05928-6_5.

[137] KENYON, C.; CAPANO, C. Apple silicon performance in scientific computing. In: . [S.l.]: Institute of Electrical and Electronics Engineers Inc., 2022. ISBN 9781665497862. http://dx.doi.org/10.1109/HPEC55821.2022.9926315.

[138] PATHAK, T. B. et al. Use of global sensitivity analysis for cropgro cotton model development. *Transactions of the ASABE*, v. 50, p. 2295–2302, 2007. ISSN 0001-2351.

[139] SARKAR, R.; KAR, S. Evaluation of management strategies for sustainable rice-wheat cropping system, using dssat seasonal analysis. *Journal of Agricultural Science*, v. 144, p. 421–434, 10 2006. ISSN 00218596. http://dx.doi.org/10.1017/S0021859606006447.

[140] DZOTSI, K. A.; BASSO, B.; JONES, J. W. Development, uncertainty and sensitivity analysis of the simple salus crop model in dssat. *Ecological Modelling*, v. 260, p. 62–76, 7 2013. ISSN 03043800. http://dx.doi.org/10.1016/j.ecolmodel.2013.03.017.

[141] PIERRE, J. F.; PAVAN, W.; SINGH, U. Integrating dssat and gssat for precise agronomic modeling and site-specific recommendations for maize cultivation. 2023.

[142] WORTMANN, C. S. et al. Maize-nutrient response functions for eastern and southern africa. *Agronomy Journal*, Wiley Online Library, v. 110, p. 2070–2079, 2018. http://dx.doi.org/10.2134/agronj2018.04.0268.