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SeedSAGE (Seed System Analysis and Guidance Engine): Digitalizing Seed Systems Resilience Assessments

ARNAB GUPTA* AND ABISHKAR SUBEDI

Wageningen Centre for Development Innovation, Wageningen University and Research
Building 116 (Actio), Akkermaalsbos 12, 6708 WB Wageningen, The Netherlands
*arnab. gupta@wur. nl

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ABSTRACT: In protracted crisis situations, robust seed systems are vital for ensuring food security and mitigating the impacts of stressors such as conflict, climate change, and economic shocks. Traditional Seed Systems Resilience Assessment (SSRA) methods are extremely valuable, but often face challenges in data collection, analysis, and reporting, which hinder timely and effective interventions. This proposed digital SSRA suite, named SeedSAGE (Seed System Analysis and Guidance Engine) is an innovative plan by integrating offline data capture capabilities with robust analytical tools, specifically designed to address the unique challenges of remote and crisis-affected regions. The suite will comprise of three interconnected tools: the Crop Diversity Assessment Tool, the Resilience Analysis Tool, and the Seed Network Analysis Tool. These tools, combined with robust data processing capabilities, will generate tailored reports to empower governments and development agencies to make informed decisions and implement targeted interventions, using AI parsing. The development plan outlines key components, including user-friendly input modules designed for field use, secure cloud-based data storage, and a phased implementation timeline. The tool does not yet exist, but this document will enumerate intricate pathways for easy development. This digital transformation promises to improve data quality, enhance time efficiency, and broaden the reach of assessments. Ultimately, it aims to enhance decision-making processes, bolstering food security and resilience in vulnerable communities. We invite stakeholders, investors, and development agencies to partner with us in this transformative endeavor.

Keywords: SeedSAGE, Seed systems resilience, Seed system in crisis affected communities

INTRODUCTION

Under fragile and conflict-affected conditions, the resilience of seed systems is a cornerstone for ensuring food security and mitigating the devastating impacts of conflicts, environmental disasters, and socioeconomic disturbances. Disruptions to these complex networks can risk the availability, accessibility, and diversity of seeds, undermining agricultural productivity and threatening the livelihoods of vulnerable communities [1]. Recognizing this critical nexus, a range of methodological tools have been developed to assess the strengths, vulnerabilities, and adaptive capacity of seed systems. The Seed Systems Resilience Assessment (SSRA) toolkit, developed by the Wageningen Centre for Development Innovation (WCDI) [2], stands as a thorough framework for such evaluations. Encompassing assessments of crop diversity, climate resilience, and social seed networks, the SSRA toolkit provides valuable insights to policymakers, development agencies, and practitioners working to strengthen agricultural resilience and food security. However, traditional implementation, relying on household surveys and manual data processing, presents significant challenges in data accuracy, analysis bottlenecks, and reporting delays [3].

While several digital initiatives have emerged in the agricultural sector, these often focus on specific aspects like crop monitoring or market information systems [4]. The proposed digital SSRA suite distinguishes itself by offering an integrated approach to seed system resilience assessment. Furthermore, unlike platforms that predominantly rely on online connectivity, our suite will incorporate offline data capture capabilities, ensuring its utility in remote areas with limited internet access.

To overcome these limitations and utilize the potential of advanced technologies, we propose a *digitally transformed* version of the SSRA toolkit into an advanced software suite. This article aims to provide a clear plan that allows practitioners and policymakers to work with *digital developers* to create this customized tool. This tool will have the capabilities of offline data capture, cloud computing, advanced analytics, and automated reports

and insights generation to streamline the assessment process and deliver timely, actionable information to stakeholders. This set of tools were already deployed in South Sudan using a mix of online and offline tools and the reports thus prepared gives valuable insights on resilience assessment in post conflict areas [5]. By integrating large language models (LLMs) [6] and analytical platforms like GEPHI or UCINET, the suite will ensure robust data collection, processing, and analysis even in challenging environments [7].

However, this digital transformation is not without its challenges. Issues such as data security, user training, and the need for ongoing maintenance and updates must be carefully addressed. We are committed to developing a comprehensive plan that not only outlines the suite's key components and underlying technologies but also addresses these potential obstacles. The SeedSAGE, is planned to create tailored reports and visualizations will allow stakeholders to make informed decisions, allocate resources effectively, and design evidence-based strategies for enhancing the resilience of seed systems in vulnerable regions [8, 9].

This paper presents a comprehensive plan to transform SSRA by digitalizing an established toolkit [2] into an advanced software suite. We present a roadmap for this initiative and invite stakeholders, investors, and development agencies to join us in this effort. By channeling the power of data-driven insights and technological innovation, it will strengthen seed systems, sustain food security, and build resilience in crisis-affected communities.

DESCRIPTION OF THE SSRA TOOLS

Overview of the SSRA Framework by Wageningen Centre for Development Innovation (WCDI)

The Seed Systems Resilience Assessment (SSRA) framework, developed by the Wageningen Centre for Development Innovation (WCDI) of the Wageningen University & Research, is a comprehensive methodology designed to evaluate the resilience of seed systems, particularly in the contexts of protracted crises. The framework aims to identify vulnerabilities and strengths within seed systems, providing critical insights for enhancing their resilience. It integrates multiple dimensions of seed systems, including crop diversity, climate resilience, and social seed networks into a cohesive assessment tool. The SSRA framework is structured to facilitate detailed data collection, rigorous analysis, and the generation of actionable recommendations, making it an essential tool for policymakers, development agencies, and practitioners working in agricultural resilience and food security.

Detailed Description of Each SSRA Tool: Before we dive into the digitalization process, we must first understand a bit about the tools themselves and their capabilities. The Fig. 1 shows the different tools and the data flow and insights these tools will generate. Please note that the tools and reports have a prefix of "SRA" which is a short for systems resilience assessment.

1. Crop Diversity Assessment Tool

The Crop Diversity Assessment Tool (SRA 1) is designed to evaluate the diversity of crops within a seed system. This tool uses a combination of farmer surveys, plot observations, and genetic data to provide a comprehensive overview of crop diversity. It includes several sub-tools:

a) **Historical Timeline (SRA 1A):** This component maps the historical context of crop diversity, including the impact of major hazards such as conflicts and climate events on crop varieties. Furthermore, the coping mechanisms and the impact of the assistance provided by different humanitarian and development agencies are also analyzed against each hazard types. The first report, the Historical Timeline Report (SRA 1A), provides a detailed account of the historical changes and trends in crop diversity, offering insights into how crop diversity has evolved over time.

b) **Diversity Wheel (SRA 1B):** The diversity wheel categorizes crops and their varieties, based on their prevalence and distribution, providing insights into the diversity of crops grown within a community. It also enumerates the crops and varieties that are lost and no longer cultivated [10, 11]. The Diversity Wheel Report (SRA 1B) is generated here, which visually represents the current state of crop diversity, assessing the variety and distribution of crops across different areas.

c) **Preference Ranking (SRA 1C):** This sub-tool captures farmers' preferences for different crops and varieties, disaggregated by gender, to understand the socio-cultural factors influencing crop diversity. The Preference Ranking Report (SRA 1C) analyzes and ranks crops based on stakeholder preferences, helping to identify priority crops for conservation and

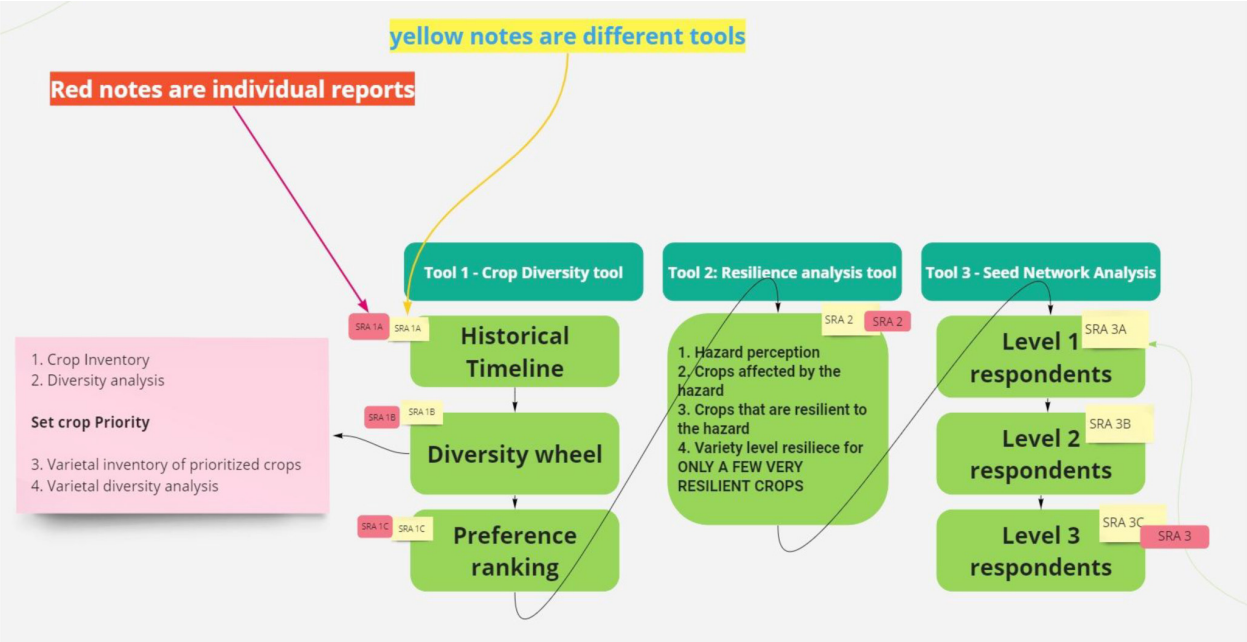

Figure 1. The SSRA tools, their sub-tools and the reports they generate

development efforts. Collectively, these reports enable stakeholders to understand the past and present landscape of crop diversity, facilitating strategic planning for future conservation and development initiatives.

2. Resilience Analysis Tool

The Resilience Analysis Tool focuses on evaluating how crops respond to various hazards, generating the Resilience Analysis Report (SRA 2), or how farmers perceive them do so. This report starts by assessing the perception of hazards affecting crops, identifying the specific crops that are impacted by these hazards. It then highlights crops that exhibit resilience, providing detailed information on variety-level resilience for the most resilient crops. This thorough analysis helps in understanding the resilience of different crops to environmental and socio-economic stressors, enabling stakeholders to prioritize and mainstream the cultivation of resilient crop varieties. The insights gained from this report are crucial for developing strategies to enhance crop resilience, ensuring food security, and supporting sustainable agricultural practices in the face of changing environmental conditions.

3. Seed Network Analysis Tool

The Social Seed Network Analysis Tool is crucial for understanding and managing the flow of genetic materials within farming communities. It identifies key farmers, known as nodal or bridging farmers, who facilitate the distribution and conservation of crop genetic diversity. This tool provides insights into network stability, seed exchange patterns, and social dynamics, enabling effective interventions to enhance seed system resilience and on-farm conservation of crop genetic resources [12]. The analysis includes:

- **Mapping Seed Networks:** The tool generates network diagrams that illustrate the flow of seeds within and between communities, highlighting key nodes and linkages.
- **Assessing Network Resilience:** By analyzing the structure of seed networks, this tool identifies potential vulnerabilities and strengths, providing insights into the robustness of seed systems.

Talking about the reports, The Level 1 Respondents Report (SRA 3A) details the interactions and seed exchanges among primary respondents, providing an in-depth analysis of the most direct level of the seed network. The Level 2 Respondents Report (SRA 3B) expands on this by examining the interactions and seed exchanges among secondary respondents, showing how seeds move through intermediary levels in the network. Finally, the Level 3 Respondents Report (SRA 3C) offers a comprehensive view of the entire seed network, focusing on tertiary respondents and identifying central actors and

potential weak links. These reports collectively enhance the understanding of seed system dynamics, highlighting key players and critical connections within the network. This information is vital for stakeholders aiming to strengthen seed networks, improve seed system resilience, and ensure the effective flow of genetic materials within and across farming.

Importance and Impact of These Tools in Assessing Seed Systems Resilience

The Seed System Resilience Assessment (SSRA) tools are vital for evaluating and improving seed system resilience. Each tool provides distinct and complementary data on various aspects of seed systems, forming a comprehensive assessment framework.

The Crop Diversity Assessment Tool quantifies genetic diversity, which is essential for adapting to environmental fluctuations and mitigating risks from pests and diseases. By identifying gaps in crop diversity, this tool aids in formulating strategies to promote the cultivation of diverse and resilient crop varieties. Also, the Resilience Analysis Tool measures the capacity of seed systems to withstand and recover from perturbations. Evaluating the resilience of specific crops and varieties to climate hazards enables the development of targeted interventions that enhance the overall resilience of agricultural systems. Furthermore, the Seed Network Analysis Tool provides insights into the social dynamics of seed exchange, which is fundamental for ensuring the availability and accessibility of diverse seed varieties.

By mapping and analyzing seed networks, this tool helps in identifying key actors and potential bottlenecks, facilitating the design of interventions that strengthen seed systems' social resilience. In a nutshell, the SSRA tools are instrumental in guiding development agencies, policymakers, and practitioners in designing and implementing effective strategies to enhance the resilience of seed systems, thereby contributing to food security and sustainable agricultural development in vulnerable regions.

1. Rationale for Digitalization and the research questions

While the SSRA toolkit offers invaluable insights, its implementation in fragile and conflict-affected regions faces significant hurdles. The transition from paper-based to digital methods, while promising, presents unique challenges (3). Digital tools must be robust and adaptable to function effectively in inaccessible and precarious environments. Current paper-based systems suffer from data loss, transcription errors, logistical complexities, and lack of real-time data validation. These issues impede timely decision-making and hinder effective interventions. Furthermore, the manual collation, cleaning, and analysis of data are time-consuming and prone to errors, further delaying crucial responses.

In many regions, unreliable internet connectivity necessitates offline capabilities for digital data collection tools. Embedding offline functionality, with synchronization upon connection availability, expands the reach of assessments to remote areas where seed systems are often most vulnerable.

To address these challenges, the SeedSAGE will be designed not only to facilitate data collection but also dynamically analyze and visualize the data. It will generate customized reports tailored to the specific needs of stakeholders. For instance, government agencies might require insights on vulnerable regions or threats to varietal diversity, while NGOs could benefit from information on crop-variety preferences or seed distribution bottlenecks. This tailored approach enables targeted interventions and evidence-based strategic planning.

Several technological and operational challenges must be addressed to realize the full potential of digitalization. These include ensuring data security and privacy, developing user-friendly interfaces suitable for diverse stakeholders, and providing adequate training and support for tool adoption. Furthermore, interoperability with existing data systems and long-term maintenance of the digital infrastructure are crucial considerations.

We believe that digitalization can severely impact various stakeholder groups. For farmers and seed producers, it could mean improved access to quality seeds and timely information on best practices. For researchers, it could facilitate data sharing and collaboration, accelerating the innovations pace. For policymakers, it could provide the evidence base needed for informed decision-making and resource allocation.

In the following sections, we delve deeper into these doting questions:

- How can this digitalization initiative enhance the efficiency, accuracy, and comprehensiveness of seed system resilience assessments in crisis-affected regions?

- What are the key technical and operational challenges in developing and implementing a digital suite for seed system resilience assessments, and how can they be addressed?
- How can the integration of advanced analytical techniques, such as large language models and network analysis, improve the insights derived from seed system resilience data?
- What is the specific information needs of different stakeholders (government agencies, NGOs, researchers) regarding seed system resilience, and how can the digital suite effectively cater to these varying needs through tailored reporting and visualization?

By addressing these questions, we aim to develop a digital SSRA suite that not only overcomes the limitations of current methods but also empowers stakeholders to build more resilient seed systems and safeguard food security in the face of adversity.

2. The Seed Sage design

The SeedSAGE will be designed to digitize and integrate the time-tested methodological tools that have been extensively field-validated by seed system experts over decades of research [2, 13]. At the core of the suite lies a modular design comprising five interconnected tools, each focused on a specific aspect of seed system resilience assessment. This modular architecture allows for comprehensive coverage of key seed system components, from crop biodiversity and climate resilience to market dynamics and social networks.

Primarily, this architecture will consist of three main tools (Fig. 1) under which there will be submodules. Now looking at Fig. 2, we see that the plan is to design all data collection modules under all these tools in a simple intuitive interface in mobile based architecture. Preferrable they will be loaded into android tablets since they are portable, low cost and have good battery backup. Additionally, they have GPS which enables geo tagging of respondent locations.

a) *Data Collection:* Field data will be collected through new forms that researchers can fill in on tablets, and later imported into the Data Repository; all instruments will be designed to work offline. Flexibility to gather the data even in remote areas having less internet connectivity. There will also be physical notebooks as a contingency during the piloting phase.

b) *Data Syncing and Storage:* All the local data will get synchronized on a cloud database when internet access is available. The data is secured and allows centralized accessibility for additional analysis. Field agents can gather data using mobile devices, even in areas with limited internet access, with subsequent synchronization to a secure, centralized cloud-database when connectivity is restored. This flexible approach ensures that data collection can occur seamlessly, despite of infrastructure limitations.

c) *Data Analysis:* Once the data is centralized, the suite utilizes a powerful combination of statistical analysis, social network analysis, and LLMs to process and derive insights from the collected information (Fig. 2, “Cloud Database” and the “Analytical tools”). Statistical techniques w used to identify trends, correlations, and patterns within the data, while network analysis techniques map the relationships influencing seed access and exchange [14]. Additionally, machine learning models can be trained on historical data to identify patterns, make projections, and support decision-making. The cloud database will be linked with analytical tools (e.g., UCINet for Social Network Analysis and Large Language Model APIs for semantic insights) to analyze these queries. Large language models (LLMs) are particularly useful for asking open-ended questions and gaining insights from qualitative data. They can recall contextual knowledge about the country, stakeholders, and relevant information to analyze responses from focus group discussions, diversity analyses, preference rankings, and other collected data. This allows for a broad understanding by combining contextual information about stakeholders and regions.

d) *Query Formulation:* The refined reports based on the requirement could allow researchers to make structured queries with filters like location, parameters, crops, season, year, and others. This flexibility provides analytic precision to focus on particular groups of data in the general collection.

e) *Report Generation:* A key innovation within this suite is its capacity to generate tailored reports that cater to the specific needs of diverse stakeholders, including government agencies, NGOs, and researchers. There will be preformatted, and relevant templates already loaded in the AI knowledge base, which will be filled in and generated

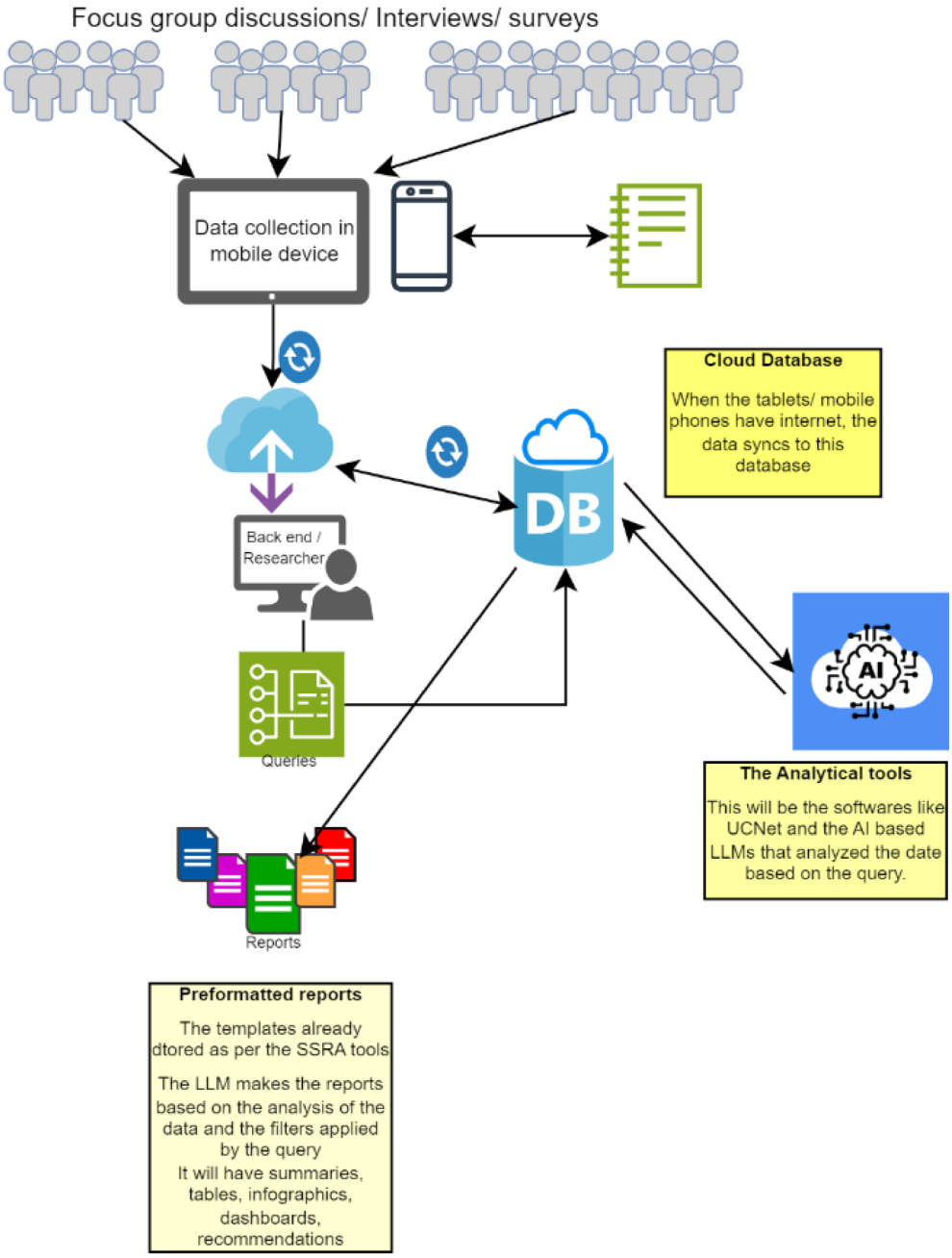

Figure 2. The data flow diagram of SeedSAGE

as output *based on the query/ filters* entered through the user interface by the scientist/ researcher/ stakeholder. By utilizing Natural Language Processing (NLP) techniques [6], the suite will produce reports ranging from concise summaries to in-depth analyses, presenting insights in a clear and actionable format already fed in the system. These templates or formats can be easily edited as per the over the years when any context changes. This will empower stakeholders with relevant, contextualized information, facilitating evidence-based decision-making and the development of targeted interventions.

3. Development and Implementation:

The digital suite's development will follow comprehensive guidelines to ensure its construction, integration, scalability, and adaptability across diverse contexts.

These guidelines will serve as a roadmap for developers, detailing best practices, recommended technologies, and step-by-step instructions for building the suite's components.

System Construction: The SeedSAGE will have a modular architecture, comprising five interconnected tools, will be built using detailed technical specifications for each tool, including data structures, user interfaces, and algorithms. Emphasis will be on seamless interoperability and data flow between tools to provide an integrated user experience.

Integration Strategies: The guidelines will outline strategies for integrating the digital suite with various data sources, platforms, and systems used by stakeholders in crisis-affected regions. This includes developing APIs, data connectors, and integration protocols to ensure interoperability with legacy systems, government databases, and third-party applications.

Scalability and Adaptability: The suite's modular design promotes scalability, allowing new tools or functionalities to be added without disrupting the entire system. Recommendations for scalable architectures, load balancing, and efficient data management strategies will be provided to handle increasing user bases and data volumes [15]. Additionally, the suite will be designed for adaptability, with features for localization, user preference settings, and region-specific data sources or algorithms.

Step-by-Step Guide: A comprehensive step-by-step guide will aid developers throughout the development lifecycle, from initial setup to deployment, testing, and maintenance. This guide will include instructions for setting up development environments, installing dependencies, and configuring tools and frameworks, along with coding standards and quality assurance measures to ensure robustness and reliability.

Connectivity Constraints: As mentioned earlier, the suite must function in areas with limited internet connectivity. While offline data collection capabilities are built into the design, the guidelines will provide recommendations for optimizing data synchronization and minimizing bandwidth requirements. This may involve techniques such as data compression [16], caching, and intelligent data prioritization [9].

Data Quality: Ensuring the accuracy and consistency of data collected from diverse sources is crucial for the suite's reliability. The guidelines will outline data validation strategies, including automated checks, human verification processes, and techniques for handling missing or inconsistent data [17]. Additionally, recommendations for data cleaning and normalization will be provided to maintain data integrity.

Capacity Building: Effective adoption and utilization of the digital suite will require extensive capacity building and training efforts for end-users, including government agencies, NGOs, and researchers. The guidelines will emphasize the importance of user-friendly interfaces, comprehensive documentation, and the development of training materials and resources. Strategies for ongoing user support, such as dedicated help desks or online communities, will also be outlined [18].

Adhering to these comprehensive development guidelines, the digital suite will be well-positioned for successful implementation and adoption across crisis-affected regions. The step-by-step guide will ensure consistent development practices, while the focus on scalability, adaptability, and addressing potential challenges will enable the suite to evolve and meet the ever-changing needs of stakeholders in these dynamic environments.

4. Target Audience and Stakeholder Benefits

The digital suite for seed system resilience assessments is designed to serve a diverse array of stakeholders working towards enhancing food security and agricultural sustainability in crisis-affected regions.

Government Agencies: National and regional government agencies responsible for agricultural policy, program implementation, and crisis response will be among the suite's key beneficiaries. These agencies often struggle with limited resources, competing priorities, and the need to make informed decisions that have far-reaching impacts on food security and livelihoods. The suite will arm these agencies by providing data-driven insights into the state of seed systems, crop diversity, climate resilience, inclusion, and market dynamics. Equipped with this information, policymakers can develop targeted interventions, allocate resources more effectively, and design evidence-based strategies for enhancing seed system resilience (McGuire & Sperling, 2016). For instance, the analysis of crop diversity and farmer preferences can guide the promotion of underutilized but climate-resilient varieties, while the seed production and sales data can inform policies aimed at improving seed availability and access. Furthermore, the suite's ability

to generate customized reports tailored to specific regions or contexts will enable agencies to develop localized solutions that address the unique challenges faced by different communities [19].

Non-Governmental Organizations (NGOs): NGOs and other Civil Society Organizations working on the ground zero of food security and agricultural development projects in crisis-affected regions will also greatly benefit from this. These organizations often operate with limited resources and face the daunting task of designing effective interventions amidst complex and rapidly evolving situations. The suite's comprehensive assessments and insights will enable NGOs to make informed decisions about program design, resource allocation, and implementation strategies. For example, the social seed network analysis can help identify key actors and entry points for strengthening informal seed exchange systems, while the seed sector landscape analysis can reveal opportunities for collaboration and coordination with other stakeholders (20). Moreover, the suite's ability to monitor and evaluate the impact of interventions over time will allow NGOs to adapt their strategies as needed, ensuring their efforts remain relevant and effective in the face of changing circumstances. This iterative approach, facilitated by the suite's analytical capabilities, can lead to more sustainable and impactful interventions that address the root causes of seed system vulnerabilities.

Researchers: For researchers studying seed systems, resilience, and food security in fragile contexts, the digital suite represents a powerful tool for advancing knowledge and informing future research directions. By providing access to comprehensive and granular data, the suite enables in-depth analyses and the exploration of novel research questions. Researchers can leverage the suite's data and algorithms to investigate the complex interplay between social, environmental, and economic factors that influence seed system resilience. For instance, they may explore the role of traditional knowledge and practices in promoting crop diversity or examine the impact of conflict and displacement on seed exchange networks (Kennedy *et al*. , 2022). Furthermore, the suite's modular design and adaptability allow researchers to integrate their own methodologies, data sources, or analytical techniques, fostering interdisciplinary collaboration and advancing the field of seed system resilience research.

Cross-Cutting Benefits: While the primary target audience comprises government agencies, NGOs, and researchers, the digital suite's benefits extend to various other stakeholders involved in enhancing food security and agricultural resilience in crisis-affected regions. International aid organizations and donor agencies can utilize the suite's insights to inform their funding priorities and ensure resources are directed toward the most critical interventions and regions. Agricultural extension services can leverage the suite's data and recommendations to provide tailored advisory services to farmers, promoting the adoption of resilient practices and crop varieties. Local community groups and farmer organizations can also benefit from the suite's outputs, as they can serve as a basis for community-driven initiatives, such as seed banks, participatory varietal selection, and the documentation of traditional knowledge. Ultimately, by empowering these diverse stakeholders with comprehensive, data-driven insights and decision support, the digital suite contributes to the overarching goal of fostering sustainable agricultural practices, improving food security, and enhancing the resilience of livelihoods in vulnerable regions.

Future Directions

The SeedSAGE will mark a crucial advancement in utilizing data and technology to tackle challenges in fragile and crisis-affected regions. However, when developed, it will ensue an ongoing process involving continuous refinement, expansion, and integration with other resilience-building efforts.

A. *Refinement of Algorithms*: As the suite will be used in diverse contexts, its algorithms will be refined and optimized through iterative feedback and new data sources. Enhanced data on climate patterns, crop performance, and farmer adaptation strategies will improve the suite's ability to identify climate-resilient crops and assess community resilience. Advances in natural language processing can further enhance its report generation and multimedia data analysis capabilities [22].

B. *Expansion of Data Sources*: Efforts will focus on integrating additional data sources, such as remote sensing platforms, citizen science projects, and crowdsourced data [23, 24]. This will enable more comprehensive and current assessments, capturing dynamics missed by traditional methods.

C. *Integration with Other Resilience Tools*: The suite is part of a broader ecosystem of resilience tools. Future integration with tools addressing water

security, nutrition, and climate change adaptation will facilitate seamless data exchange and synergistic analyses. This will highlight critical interdependencies and inform holistic interventions. The suite's modular design and open architecture will also allow the development of complementary tools and plugins, fostering an innovative and collaborative ecosystem.

D. *Advancing Seed System Resilience and Food Security*: The suite aims to advance seed system resilience and food security in vulnerable regions. By refining capabilities, expanding data sources, and integrating with complementary tools, it will support sustainable agricultural practices tailored to local contexts and resilient to climate change and other crises [25, 26].

To Sum up, this digital suite represents a significant leap forward in evaluating seed system resilience strategies in post-crisis situations. With tools like offline data capture, cloud computing, Big Data analytics, and automated reporting, this suite surpasses the limitations of traditional paper-based assessments. The modular design, featuring interconnected tools for crop diversity, resilience analysis, and seed network analysis, provides a comprehensive framework for improving robust seed systems.

The digital suite enhances the efficiency, accuracy, and completeness of seed system resilience assessments through various available technologies. Offline data capture allows for continual assessment even in rural areas with no connectivity, broadening the scope and insight of assessments. Data will be securely managed in a single cloud store, providing central access and collaborative analytics. Sophisticated analytical techniques such as statistical analysis, network analysis, and large language models (LLMs) help efficiently process data, generating rich insights from both qualitative and quantitative data. The reporting process is streamlined through automated report generation and customizable visualizations, enabling timely information dissemination to decision-makers.

With tailored reports and visualizations, the suite can provide stakeholders such as government agencies, NGOs, and researchers with the information needed to create targeted interventions, allocate resources more effectively, and design evidence-based strategies. This suite supports sustainable agricultural practices, ensures food security, and improves livelihoods for vulnerable communities through early warning and informed decision-making.

The development and implementation of the digital suite face challenges, including connectivity issues, ensuring data quality, building user capacity, and integrating with existing systems. However, strategies to address these challenges include focusing on offline capabilities, data validation schemes, user training and support, and developing APIs and integration protocols for seamless interoperability.

The suite's potential lies in its ability to evolve and grow over time. Algorithms are flexible and adaptable to specific deployment situations through feedback and new data sources, such as remote sensing platforms and citizen science initiatives. This approach allows for large-scale and up-to-date assessments, considering dynamics overlooked by conventional methods. Using advanced analytical methods such as LLMs combined with network analysis enhances understanding of seed system resilience data. LLMs can filter and analyze textual data, while network analysis provides means for describing and analyzing seed flow networks, highlighting central actors and weak links. These models can recognize patterns, predict trends, and facilitate data-based decision-making.

Integrating the suite with other tools that strengthen resilience in water security, nutrition, and climate change adaptation allows for seamless data exchange and synergistic analysis, identifying critical interdependencies and informing comprehensive interventions. The suite's modular design and open architecture enable extension with other innovative tools and plugins.

Finally, the digital suite for seed system resilience assessments marks a significant step forward in utilizing data and technology to address challenges in crisis-affected regions. By refining capabilities, broadening data sources, incorporating advanced analytical approaches, and linking with complementary tools, the suite supports sustainable agriculture tailored to local conditions and climate change adaptation. This leads to increased resilience in the seed system, higher food security, conservation of agricultural biodiversity, and support for vulnerable families in times of need.

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