Universität Hamburg

Towards Sustainable Food Security in Namibia: Agricultural Adaptation under Future Climate and Development Pathways

Dissertation

with the aim of achieving a doctoral degree

at the Faculty of Mathematics, Informatics and Natural Sciences

Department of Earth System Sciences at University of Hamburg

Research Unit Sustainability and Climate Risks

Submitted by

Jihye Jeong

Hamburg, 2025

Department of Earth Sciences

Date of Oral Defense:	12.12.2025
Reviewers:	Prof. Dr. Uwe A. Schneider Dr. Kerstin Jantke
Members of the examination commission:	Prof. Dr. Uwe A. Schneider Dr. Kerstin Jantke Prof. Dr. Jana Sillmann Prof. Dr. Jürgen Böhner Prof. Dr. Barbara Reinhold-Hurek
Chair of the Subject Doctoral Committee	
Earth System Science:	Prof. Dr. Hermann Held
Dean of Faculty MIN:	Prof. Dr. -Ing. Norbert Ritter

Eidesstattliche Versicherung | Declaration on Oath

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Sofern im Zuge der Erstellung der vorliegenden Dissertationsschrift generative Künstliche Intelligenz (gKI) basierte elektronische Hilfsmittel verwendet wurden, versichere ich, dass meine eigene Leistung im Vordergrund stand und dass eine vollständige Dokumentation aller verwendeten Hilfsmittel gemäß der Guten wissenschaftlichen Praxis vorliegt. Ich trage die Verantwortung für eventuell durch die gKI generierte fehlerhafte oder verzerrte Inhalte, fehlerhafte Referenzen, Verstöße gegen das Datenschutz- und Urheberrecht oder Plagiate.

I hereby declare and affirm that this doctoral dissertation is my own work and that I have not used any aids and sources other than those indicated.

If electronic resources based on generative artificial intelligence (gAI) were used in the course of writing this dissertation, I confirm that my own work was the main and value-adding contribution and that complete documentation of all resources used is available in accordance with good scientific practice. I am responsible for any erroneous or distorted content, incorrect references, violations of data protection and copyright law or plagiarism that may have been generated by the gAI.

Hamburg, 25. 09. 2025 Jihye Jeong

Acknowledgement

I dare say that this dissertation is a result of many years of scientific and emotional work involving many, very many people.

First and foremost, I deeply thank my Doktorvater, Prof. Dr. Uwe Schneider. He nurtured me with his academic and technical insights, being one-of-a-kind advisor. Countless conversations and repeated jokes filled many years of my life and they shall stay with me. I remember the moment of thinking – I would not mind to be a kind and genuine person just like him when my time comes – when I was not yet converted into a PhD candidate. Beside Uwe, there has always been Dr. Kerstin Jantke. Without her, there would have been far more unpaved road in the journey. She kept me sane with lots of emotional support and clear guidance. I knew I could always turn to her anytime when the challenges felt immense. To this day, I often think back to the family trip I had with my Doktoreltern, where I realized how wonderful it is to have scientist parents.

I would like to thank my panel chair, Prof. Dr. Jana Sillmann, and other co-authors for their collaborations. In particular, my partners in Namibia, Prof. Dr. David Uchezuba and Andreas Ngolo who enabled the field trip and shared invaluable insights into the region.

I am also grateful for financial, educational, and organizational support by CLICCS and SICSS community. More importantly, I have met numerous passionate people there who kept me inspired and motivated. This community gave me folks who now became deeply ingrained in my life. Together, we passed through the darkest part of the tunnel, and so the darkness was almost absurdly light. Thanks Alex, Clara, Eva and Paul.

Two amazing women, Lea and Nicole, whom I saw nearly every day in last four years, helped me push through hardships. Endless chats, gossips, chocolates, schnapps and tears that we had together gave me strength and made me stand up again on tough days when I was completely defeated. In my lowest moments, they looked after me and pulled me out of the swamp and set me back on track. Thanks to the strong women on the GB5 2nd floor.

The work was expansive, going beyond science. I am a lucky person to have strong support from loving friends. At this point of my life, they are my friends, my family, my therapists and more. They have been the safe bed I could fall back on, at any time, for any reason. When I could not appreciate myself, they trusted me and showered me with love. I cannot list down all the beautiful names here but each and every one of them has a special place in my heart.

Finally, I thank my family deeply: my grandma, my parents and my brother in Korea. They believed in me until the end although it was not always an easy journey to understand. 'You are the smartest person ever' as my grandma says. Thanks for all the love and support that build me to this day. Who could I have been otherwise. In memory of my grandpa, I thank him for passing on his interests he had and for the greatest unconditional love.

사랑하는 우리 가족, 길고 지리했던 여정동안 나를 믿고 기다려준 것에 대단히 감사합니다. '세상에서 제일 똑똑한게 우리 지혜아니가' 하는 할머니 말을 생각하면 어떤 일도 해낼 수 있을 것 같았거든요. 삼십년 넘는 시간 동안 내게 쏟아진 사랑과 정성으로 박사 과정을 무사히 마치게 되었습니다. 많이 고맙고 사랑합니다

Thanks a lot, to everyone, bearing me at all time.

Hamburg, 25.09.2025

Abstract

Namibia faces considerable food insecurity challenges exacerbated by an arid climate, low soil fertility, and socio-economic vulnerabilities, with approximately 58% of the population affected. Smallholder agriculture dominates but is characterized by low productivity and reliance on rainfed systems, making the country heavily dependent on food imports. This dissertation investigates the potential of cowpea—a climate-resilient and nutritionally rich legume—to enhance food security, support rural livelihoods, and improve child nutrition through Namibia's school feeding programs under current and future climate and socioeconomic scenarios. The research is structured into three integrated studies. The first study assesses cowpea production potentials using biophysical crop simulations combined with spatial optimization, focusing on the effects of rhizobial inoculation, irrigation, and fertilization on yields and resource use efficiency. Results demonstrate that inoculated cowpea yields nearly double those of uninoculated crops in northern Namibia, while irrigation further boosts productivity. Improved practices reduce land and water use intensity, highlighting opportunities for sustainable intensification despite scarce water resources. The study also reveals critical trade-offs between water and land usage that influence optimal production strategies in semi-arid conditions. The second study evaluates whether Namibia's domestic agriculture can sustainably meet the caloric and nutrient demands of the Home-Grown School Feeding Programme (HGSFP). Simulations show that northern regions can fulfill these demands with potential surpluses under improved management, whereas southern regions remain constrained by harsh biophysical conditions. Protein supply meets requirements nationally, especially with fertilization, although fat remains a limiting nutrient. These findings underscore the potential of domestic agriculture as a reliable supplier for the Namibia HGSFP. It highlights importance of improved farming managements and policy support to mitigate climate change impacts and regional disparities. The third study examines the nutritional and socioeconomic impact of integrating inoculated cowpea flour into the maize-based porridge served in schools. Cowpea fortification significantly enhances protein quality and micronutrient density while maintaining cultural acceptance. Linking local cowpea production with institutional demand strengthens smallholder markets, improves farmer incomes, and facilitates sustainable rural development. Together, these studies establish cowpea production, supported by inoculation and integrated water-nutrient management, as a promising strategy for nutritious and sustainable agriculture in Namibia. The research highlights the HGSFP's potential as a platform for improving child nutrition, enhancing food system resilience, and reducing import dependence. While offering robust technical insights, this thesis recognizes the need for further research on social and institutional factors to translate findings into effective policy and practice. Ultimately, it contributes key evidence to foster adaptive capacity, food security, and sustainable livelihoods in resource-constrained, semi-arid environments.

Zusammenfassung

Namibia steht vor erheblichen Herausforderungen im Bereich der Ernährungssicherheit, die durch ein trockenes Klima, geringe Bodenfruchtbarkeit und sozioökonomische Schwachstellen noch verschärft werden und von denen etwa 58 % der Bevölkerung betroffen sind. Die Landwirtschaft wird überwiegend von Kleinbauern betrieben, ist jedoch durch geringe Produktivität und Abhängigkeit von Regenbewässerungssystemen gekennzeichnet, wodurch das Land in hohem Maße von Nahrungsmittelimporten abhängig ist. Diese Dissertation untersucht das Potenzial von Augenbohnen – einer klimaresistenten und nährstoffreichen Hülsenfrucht – zur Verbesserung der Ernährungssicherheit, zur Unterstützung der ländlichen Lebensgrundlagen und zur Verbesserung der Ernährung von Kindern durch namibische Schulernährungsprogramme unter aktuellen und zukünftigen klimatischen und sozioökonomischen Szenarien. Die Forschung gliedert sich in drei integrierte Studien. Die erste Studie bewertet das Produktionspotenzial von Augenbohnen anhand biophysikalischer Pflanzenwachstumssimulationen in Kombination mit räumlicher Optimierung, wobei der Schwerpunkt auf den Auswirkungen von Rhizobien-Impfung, Bewässerung und Düngung auf Erträge und Ressourceneffizienz liegt. Die Ergebnisse zeigen, dass die Erträge von geimpften Augenbohnen in Nordnamibia fast doppelt so hoch sind wie die von nicht geimpften Pflanzen, während die Bewässerung die Produktivität weiter steigert. Verbesserte Anbaumethoden reduzieren den Flächen- und Wasserverbrauch und zeigen Möglichkeiten für eine nachhaltige Intensivierung trotz knapper Wasserressourcen auf. Die Studie zeigt auch kritische Kompromisse zwischen Wasser- und Landnutzung auf, die die optimalen Produktionsstrategien unter semiariden Bedingungen beeinflussen. Die zweite Studie bewertet, ob die heimische Landwirtschaft Namibias den Kalorien- und Nährstoffbedarf des Home-Grown School Feeding Programme (HGSFP) nachhaltig decken kann. Simulationen zeigen, dass die nördlichen Regionen diesen Bedarf unter verbesserten Bewirtschaftungsbedingungen mit potenziellen Überschüssen decken können, während die südlichen Regionen weiterhin durch schwierige agroökologische Bedingungen eingeschränkt sind. Die Proteinversorgung entspricht den nationalen Anforderungen, insbesondere bei Düngung, obwohl Fett nach wie vor ein limitierender Nährstoff ist. Diese Ergebnisse unterstreichen die Bedeutung einer Intensivierung des Managements und politischer Unterstützung, um die Auswirkungen des Klimawandels und regionale Ungleichheiten zu mildern. Die dritte Studie untersucht die ernährungsphysiologischen und sozioökonomischen Auswirkungen der Integration von geimpftem Cowpea-Mehl in den in Schulen servierten Maisbrei. Die Anreicherung mit Cowpea verbessert die Proteinqualität und die Mikronährstoffdichte erheblich, während die kulturelle Akzeptanz erhalten bleibt. Die Verknüpfung der lokalen Cowpea-Produktion mit der institutionellen Nachfrage stärkt die Märkte für Kleinbauern, verbessert die Einkommen der Landwirte und fördert eine nachhaltige ländliche Entwicklung. Zusammen belegen diese Studien, dass die Cowpea-Produktion, unterstützt durch Impfung und integriertes Wasser-Nährstoff-Management, eine vielversprechende Strategie für eine klimafreundliche, nährstoffreiche und nachhaltige Landwirtschaft in Namibia darstellt. Die Forschung unterstreicht das Potenzial des HGSFP als Plattform zur Verbesserung der Ernährung von Kindern, zur Stärkung der Widerstandsfähigkeit des Ernährungssystems und zur Verringerung der Importabhängigkeit. Diese Arbeit liefert zwar fundierte technische Erkenntnisse, erkennt jedoch auch die Notwendigkeit weiterer Forschung zu sozialen und institutionellen Faktoren, um die Ergebnisse in wirksame Politik und Praxis umzusetzen. Letztendlich liefert sie wichtige Erkenntnisse zur Förderung der Anpassungsfähigkeit, der Ernährungssicherheit und nachhaltiger Lebensgrundlagen in ressourcenarmen, semiariden Umgebungen.

List of included publications/essays

1. Jeong, J., Jantke, K., Rasche, L., Eschenbach, A., Uchezuba, D., Reinhold-Hurek, B., Schneider, U. A. (2025), *Managing Scarce Water and Land Resources: The Potentials of Cowpea Production in Namibia,* published in *Environmental Development* vol. 54 (101139) https://doi.org/10.1016/j.envdev.2025.101139.

2. Jeong, J., Jantke, K., Rasche, L., Uchezuba, D., Rieth, B., Nyambe, S., Taha, R., Kamwi, G., Schneider, U. A., *Assessing Namibia's Home-Grown School Feeding Program: Can Domestic Agriculture Meet and Sustain its Schoolchildren's Nutritional Needs?,* under review at *npj Sustainable Agriculture*

3. Jeong, J., Jantke, K., Rasche, L., Uchezuba, D., Reinhold-Hurek, B., Schneider, U. A., *Improved maize porridge for the Namibian school feeding programme: nutritional and socioeconomic potential of inoculated cowpea*

Contents

1. **INTRODUCTION** 1

1.1 BACKGROUND 2
1.2 STUDY AREA 8
1.3 OUTLINE OF THE THESIS 10

2. **MANAGING SCARCE WATER AND LAND RESOURCES: THE POTENTIALS OF COWPEA PRODUCTION IN NAMIBIA** 1

2.1 INTRODUCTION 15
2.2 STUDY AREA 18
2.3 DATA AND METHODS 19
2.4 RESULTS 27
2.5 DISCUSSION 34
2.6 CONCLUSIONS 37

3. **ASSESSING NAMIBIA'S HOME-GROWN SCHOOL FEEDING PROGRAM: CAN DOMESTIC AGRICULTURE MEET AND SUSTAIN ITS SCHOOLCHILDREN'S NUTRITIONAL NEEDS?** 39

3.1 INTRODUCTION 41
3.2 STUDY AREA 44
3.3 DATA AND METHODS 45
3.4 RESULTS 52
3.5 DISCUSSION 57
3.6 CONCLUSION 62

4. **IMPROVED MAIZE PORRIDGE FOR SCHOOL FEEDING PROGRAMME: NUTRITIONAL AND SOCIOECONOMIC BENEFITS OF INOCULATED COWPEA** 63

4.1 INTRODUCTION 65
4.2 DATA AND METHOD 70
4.3 RESULTS 73
4.4 DISCUSSION 77
4.5 CONCLUSION 79

5. **CONCLUSION AND OUTLOOK** 81

5.1 SUMMARY OF RESULTS 82
5.2 LIMITATION 84
5.3 OUTLOOK 85

6. **REFERENCES** 88

7. **APPENDIX** 107

List of figures

Figure 2.1 Distribution of cropland in the study region Namibia ... 18
Figure 2.2 Overview of the modeling approach.. ... 19
Figure 2.3 Illustration of scenario analysis ... 25
Figure 2.4 Cowpea productivity in Namibia [t/ha] ... 28
Figure 2.5 Nationally aggregated protein supply potentials for cowpeas ... 29
Figure 2.6 Land intensity under different farming system ... 30
Figure 2.7 Benefit in land intensity due to improved farming systems ... 31
Figure 2.8 Trade-off between land and water use under different food supply and inoculation scenarios ... 33
Figure 3.1 Flow of information through the modeling framework ... 45
Figure 3.2 Food demand shifts for Namibia ... 50
Figure 3.3 Overview of scenarios. ... 51
Figure 3.4 Regional food security potential under reference conditions ... 52
Figure 3.5 Present and future domestic supply potentials for crop-based caloric energy and macronutrients under alternative farm management ... 54
Figure 3.6 Present and future nutrient production in relative to future demand [%] under four farming practices ... 56
Figure 4.1 Overview of information through the modeling framework and analysis. ... 71
Figure 4.2 Overview of scenarios. ... 72
Figure 4.3 Cost-effectiveness of each management practices under different SSPs ... 75

List of tables

Table 3.1 Nutritional guidelines of school children 49
Table 4.1 Nutrient values of cowpea, maize and soybean 68
Table 4.2 Estimated future cowpea supply of Namibia for NSFP. 73

Abbreviations

CGLS	Copernicus Global Land Service
EPIC	Environmental Policy Integrated Climate model
FAO	Food and Agriculture Organization of the United Nations
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory Earth System Model 4
HGSFP	Home-Grown School Feeding Programme
HRU	Homogeneous Response Unit
IPSL-CM6A-LR	Institute Pierre-Simon Laplace Climate Model 6A, Low Resolution
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ISIMIP3BASD	ISIMIP Bias Adjustment Statistical Downscaling version 2.5
LAI	Leaf Area Index
MPI-ESM1-2-HR	Max Planck Institute Earth System Model 1.2, High Resolution
MRI-ESM2-0	Meteorological Research Institute Earth System Model 2.0
NAB	Namibian Agronomic Board
NSFP	Namibian School Feeding Programme
NPK	Nitrogen, Phosphorus, Potassium (fertilizer)
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SFP	School Feeding Programme
SHF	Smallholder Farmer
SPF	Social Protection Floor
SSA	Sub-Saharan Africa
SSP	Shared Socioeconomic Pathway
UKESM1-0-LL	United Kingdom Earth System Model 1.0, Low resolution
WFP	World Food Programme

1. Introduction

1.1 Background

1.1.1 Food security under future challenges

Food security is defined as a situation where all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and preferences for an active and healthy life (FAO, 2006; World Bank, 2024; WFP, 2025). This multidimensional concept encompasses food availability, accessibility, utilization, and stability, offering a comprehensive framework for understanding and addressing hunger and malnutrition both acutely and chronically (FAO, 2006; World Bank, 2024).

Ensuring the food security of schoolchildren holds particular significance. Childhood is a critical period for physical and cognitive development, and nutritional deprivation at this stage can have lasting impacts on health, learning capacity, and lifetime (Black et al., 2017; DiGirolamo et al., 2020; Gallegos et al., 2021; Jyoti et al., 2005; UNESCO et al., 2023). School feeding programs serve as vital safety nets for millions, improving attendance and learning while enhancing daily nutrition for vulnerable populations (Awojobi, 2019; Destaw et al., 2022; Mostert, 2021; Zenebe et al., 2018). Beyond their immediate educational and health benefits, these programs now serve as platforms for integrating nutrition, local food systems, and climate adaptation—especially where households face multidimensional threats from climate change, pandemics, and conflict (Bundy et al., 2018; Rahal & Elloumi, 2023; WFP, 2024). Globally, food security faces intensifying and intersecting challenges. Population growth, urbanization, persistent poverty, conflict, and market volatility drive present and future risks (Rahal & Elloumi, 2023; World Bank, 2024). Most notably, climate change and increasing frequency of extreme events will magnify vulnerabilities, especially for children, smallholder farmers, and low-income communities (Rahal & Elloumi, 2023).

1.1.2 Future challenges and adaptation potentials

Climate change presents unprecedented challenges for agriculture and food security, accelerating shifts in temperature, precipitation, and weather extremes. These disruptions are expected to be most severe in regions such as sub-Saharan Africa, affecting crop yields, livestock production, and food prices (IPCC, 2023; Chabwera et al., 2026; Ka, 2025).

Agriculture stands at the epicenter of resource scarcity and climate change, two of the most formidable threats to global food security and rural livelihoods in the 21st century. The sector is fundamentally dependent on natural resources—land, water, soil nutrients, and biodiversity—which are increasingly under pressure due to population growth, unsustainable land practices, urbanization, and mounting environmental degradation (IPCC, 2023; Molotoks et al., 2021; Pretty, 2008; FAO, 2021).

Land availability for agriculture is declining in many regions as arable land is degraded through soil erosion, nutrient depletion, and salinization (Shrivastava & Kumar, 2015). Water scarcity is intensifying, with agriculture consuming around 70% of all global freshwater withdrawals, yet facing growing competition from urban and industrial users (Dantas et al., 2021; Ingrao et al., 2023). Further, fertilizer and energy costs are volatile, and their extraction disrupts ecosystems and generates greenhouse gas emissions, perpetuating a cycle of environmental stress and resource depletion (AkdemirR et al., 2019; Khan et al., 2023). These constraints are especially acute for smallholder farmers, who often lack access to sufficient productive resources, credit, or modern agricultural technologies (Dhillon et al., 2023; Shitaye et al., 2024).

Climate change compounds these existing vulnerabilities. It brings increased average temperatures, erratic rainfall, prolonged droughts, more frequent floods, and growing pest and disease risks, all of which threaten the productivity and stability of global agriculture (IPCC, 2023). Recent comprehensive, data-driven modeling across over 12,000 regions and six major crops finds that—even with adaptation—climate change will drive global crop yields down by 8% by 2050 and as much as 24% by 2100 under high-emissions scenarios (Hultgren et al., 2025). Temperate regions may experience yield declines of up to 41%, while subsistence farming communities—especially in sub-Saharan Africa—can see losses approaching 28% by 2100 (Hultgren et al., 2025).

Adaptation strategies—such as changing crop varieties, planting and harvest dates, and input mixes—can offset up to one-third of climate-related losses, but the net impact on production remains negative (Habib-ur-Rahman et al., 2022). For most staples (wheat, maize, soybeans, cassava, and sorghum), the probability of yield losses by mid-century exceeds 70%, while rice is the exception, with some projections of modest gains under warming (Hultgren et al., 2022; L. Liu et al., 2022). Higher emissions will bring disproportionately larger losses, and uncertainty in future productivity persists due to the complex interplay of agronomic, economic, and climatic systems (Dhillon et al., 2023; Hultgren et al., 2022).

Rising input costs, shifting agroeconomic zones, and persistent market volatility exacerbate these physical threats. Climate-induced yield reductions are projected to raise commodity prices by up to 18% by 2050 and could push as many as 78 million additional people into chronic hunger, with the burden falling primarily on low- and middle-income countries (Campbell et al., 2014; IPCC, 2022; World Bank, 2025). The challenge is particularly acute for smallholders and rural communities with limited adaptive capacity, underscoring the urgency for substantial investment in agricultural research, water provision, value chains, and climate-resilient infrastructure (Oluwole et al., 2023; Sulser et al., 2021).

Addressing these threats requires transformative changes: embracing climate-smart agriculture, developing drought- and heat-tolerant crop varieties, investing in sustainable water management, and promoting practices that restore soil and ecosystem health. Only through coordinated adaptation and mitigation efforts can agriculture meet future food needs while stewarding finite resources and fostering rural resilience (de Pinto et al., 2020; Nguyen et al., 2021).

Smallholder farmers, who produce much of the world's food, often lack adequate access to inputs, climate-adapted technologies, extension services, and markets, limiting their adaptive capacity (Kamara et al., 2019; Pangapanga-Phiri & Mungatana, 2021; Sithole et al., 2024). Environmental degradation, biodiversity loss, and social or economic shocks further constrain productivity, amplifying risks for food insecurity (Erkal et al., 2025; Kwakwa et al., 2022; Slayi et al., 2024).

Resilience is best built through adaptation strategies, such as climate-smart agriculture, conservation farming, efficient water management, and adoption of agroecological practices that maintain productivity and ecosystem health (Baffour-Ata et al., 2023; KAMANDA, 2025; Shilomboleni et al., 2024). Home-Grown School Feeding Programs and the use of climate-resilient crops—such as cowpea—have demonstrated promise in linking nutrition, local production, farmer livelihoods, and climate adaptation (Liguori et al., 2024; Mekonnen et al., 2022; Sumberg & Sabates-Wheeler, 2011).

1.1.3 School feeding program

School feeding programmes (SFPs) have emerged as one of the most effective and widely implemented social protection mechanisms in developing countries. They serve as vital safety nets that simultaneously address food insecurity, support education, and contribute to broader development objectives (WFP, 2024). By providing regular meals to schoolchildren, SFPs not only improve nutritional and health outcomes but also foster higher school attendance and academic performance. At the same time, they hold the potential to strengthen local food systems and promote agricultural development, thereby linking multiple sectors including education, health, food security, and rural livelihoods (Awojobi, 2019; Destaw et al., 2022; Jomaa et al., 2011; Metwally et al., 2020; Mostert & Van Niekerk, 2021; Wall et al., 2022).

Recent studies have highlighted that SFPs improve school enrollment and attendance, while cost–benefit analyses suggest that investments in school feeding can generate significant multi-sectoral returns (Gelli et al., 2016a; Zenebe et al., 2018). For instance, Verguet et al. (2020) estimated that SFPs may provide at least nine dollars in benefits across health, education, social protection, and agriculture for every dollar invested.

In Namibia, the Namibia School Feeding Programme (NSFP) was first introduced by the World Food Programme (WFP) in 1991 following the country's independence and has since been managed by the national government (WFP, 2023). The programme typically provides a soft maize porridge (pap) to schoolchildren through a centralized procurement and distribution system. While the NSFP has played a critical role in ensuring that many children receive at least one meal per day, it faces persistent challenges. Maize used for the porridge is largely imported, and organizational problems such as delayed deliveries, limited regional procurement control, and inadequate storage facilities often disrupt the supply chain (Namibia Ministry of Education, 2012). Moreover, although the maize meal is fortified, it remains nutritionally insufficient, particularly for children who rely on it as their only daily meal (Mostert & Van Niekerk, 2021).

To address some of these limitations, Namibia introduced the Home-Grown School Feeding Programme (HGSFP) in 2021, with support from WFP Namibia. Unlike the centralized NSFP, the HGSFP aims to strengthen the link between local agricultural production and school feeding initiatives. Its dual objectives are to provide children with more balanced and diverse diets while simultaneously improving the livelihoods of smallholder farmers by offering them access to nearby markets. In doing so, the programme functions not only as a nutrition policy but also as an agricultural development policy, with the potential to stimulate local food production and promote the adoption of improved farming practices (Gelli et al., 2021; Galani et al., 2022).

Nevertheless, the HGSFP is still at an early stage and faces several structural and organizational barriers. Local agricultural production is often insufficient to meet school demand, and the absence of long-term supply contracts results in unstable procurement (Desalegn et al., 2022). Regional disparities further exacerbate these challenges, as only one percent of Namibia's land is arable, concentrated mainly in the north, whereas livestock farming—though more evenly distributed—cannot provide key plant-based nutrients such as vitamins and minerals (FAO & NAB, 2021). Organizational difficulties are also significant: the programme is run on a voluntary basis, making it difficult to secure consistent parental participation in meal preparation. Teachers are frequently burdened with additional responsibilities without compensation, and inadequate storage and cooking facilities limit the ability to preserve and prepare fresh ingredients (WFP, 2021).

Despite these challenges, SFPs in Namibia—both the NSFP and the HGSFP—offer clear benefits that extend beyond schools. Improved nutrition supports children's cognitive and physical development, which in turn enhances educational outcomes such as attendance, progression, and completion rates (Destaw et al., 2022; Mostert & Van Niekerk, 2021). Importantly, the positive effects may ripple into households: when children receive meals at school, families are relieved from allocating scarce food resources to them, freeing capacity for other household members (Verguet et al., 2020). Over time, this can contribute to greater household food security and resilience. Moreover, by stimulating local agricultural production, the HGSFP holds the potential to reinforce rural livelihoods and strengthen food systems, aligning directly with multiple Sustainable Development Goals (SDGs), including those related to hunger, education, and poverty reduction (United Nations, 2015).

The Namibian experience resonates with broader international practices, as school feeding initiatives have also been successfully implemented in countries such as Brazil and India. These global examples underscore the potential of school feeding programmes to act as multi-dimensional interventions that connect agriculture, education, health, and social protection (Bundy et al., 2018; WFP, 2023). In this sense, Namibia's evolving programmes contribute not only to immediate nutritional and educational improvements but also to the longer-term objective of building more resilient and inclusive food systems.

1.1.4 Cowpea and inoculation

Namibia's arid climate, low soil fertility, and recurrent droughts pose significant challenges to food security, making the diversification of crops and the efficient use of natural resources critical for sustainable agricultural production. Legumes, and cowpea (Vigna unguiculata) in particular, play a central role in this regard. As one of the most important food legumes in sub-Saharan Africa, cowpea is valued for its nutritional qualities, environmental resilience, and contribution to soil fertility. Its adaptability to harsh climatic conditions makes it a strategic crop for Namibia, where only one percent of the land is arable and most soils are sandy with low nitrogen and organic carbon levels (FAO, 2021; de Blécourt et al., 2019).

Cowpea is highly nutritious, providing 23–32% protein, essential amino acids, vitamins, and minerals while containing only about 1% fat (Singh et al., 2002; Phillips et al., 2003). It contributes significantly to household food security in rural Namibia, where it is often intercropped with pearl millet or sorghum, thereby ensuring both dietary diversity and ecological resilience (Dube & Fanadzo, 2013; Kyei-Boahen et al., 2017). In addition to its nutritional value, cowpea contributes to sustainable farming systems by improving soil fertility through nitrogen fixation and the incorporation of organic residues (Giller, 2013; Vanlauwe & Hungria, 2017). The crop's global importance is reflected in production trends: cowpea output in sub-Saharan Africa increased from about 9.8 million tons in 2020 and is projected to grow further in the coming decade (Boukar et al., 2019; FAOSTAT, 2022).

In Namibia, cowpea cultivation covers approximately 62,000 hectares, primarily in the north, where smallholder farmers rely on local, unimproved varieties (FAO & NAB, 2021). Despite its potential, productivity remains low due to limited access to improved seeds, inadequate inputs, and minimal adoption of yield-enhancing technologies (Horn & Shimelis, 2015). Climate variability further exacerbates production challenges. Nevertheless, studies have shown that cowpea exhibits remarkable tolerance to water stress, making it one of the few crops that can maintain productivity under prolonged drought conditions (Hall, 2012; Oluwole et al., 2020).

One promising strategy to enhance cowpea productivity in Namibia is the use of rhizobial inoculation. Through symbiotic association with rhizobia, cowpea can fix atmospheric nitrogen, thereby reducing dependence on synthetic fertilizers and improving both crop yields and soil health. Inoculation with effective rhizobial strains has been shown to significantly increase cowpea yields in several African contexts (Mohale et al., 2014; Jaiswal et al., 2016; Zahran, 2022; Rasche et al., 2023). Beyond yield gains, inoculated legumes contribute to more sustainable agricultural systems by lowering greenhouse gas emissions associated with fertilizer use and enhancing ecosystem services (Yadav et al., 2021; Becker et al., 2023). However, despite its potential, rhizobial inoculation technology is still underutilized in Namibia. At present, only one manufacturer in Africa (Kenya) produces commercial rhizobial inoculants for cowpea, severely limiting accessibility in southern Africa (Jefwa et al., 2022).

Expanding the adoption of inoculated cowpea in Namibia could yield multiple benefits. First, it would increase domestic food production by improving grain yields under low-input conditions. Second, it would reduce dependence on costly imports and synthetic fertilizers, aligning with the broader goals of climate-resilient and resource-efficient agriculture. Finally, cowpea inoculation could contribute to achieving Sustainable Development Goal 2 (Zero Hunger) by simultaneously improving food security, nutrition, and rural livelihoods (UN, 2015; Gelli et al., 2021). Scaling up this practice, however, requires coordinated efforts in research, extension services, input availability, and policy support to ensure that smallholder farmers can access both inoculants and improved cowpea varieties suited to local agro-ecological conditions.

From a broader agricultural perspective, the promotion of inoculated cowpea represents a viable pathway toward more sustainable domestic food production. Namibia's dependence on food imports—currently around 60% of national demand—leaves it highly vulnerable to regional price shocks and supply disruptions (WFP, 2017). Expanding cowpea production could help reduce this dependency, particularly if combined with inoculation technologies that boost productivity on resource-scarce soils. Inoculation avoids the need for expensive synthetic fertilizers, which are not only costly but also environmentally harmful. For smallholder farmers, this translates into lower input costs, greater resilience, and higher yields under drought-prone conditions.

Cowpea production also contributes to the sustainability of Namibian farming systems by enriching soils with nitrogen, reducing the need for external inputs, and improving the productivity of intercropped or subsequent cereal crops. This makes it especially relevant in dryland systems where soil fertility is a persistent constraint. At the same time, by increasing local production and encouraging market development, inoculated cowpea could provide smallholder farmers with new economic opportunities. While cowpea currently generates limited income due to poor access to markets, integrating it into institutional demand streams such as school feeding programmes could strengthen its market value, incentivizing greater production.

Cowpea holds significant potential for strengthening Namibia's school feeding initiatives, particularly the HGSFP, which emphasizes locally sourced and nutritionally balanced meals (WFP, 2021; Galani et al., 2022). Because cowpea is already culturally accepted and commonly consumed in rural communities, it represents an ideal candidate for integration into school meals. Its high protein content could address one of the major weaknesses of the current program, which primarily provides maize porridge that, despite fortification, remains nutritionally insufficient (Mostert & Van Niekerk, 2021). Introducing cowpea into the school feeding basket would not only enhance dietary diversity but also improve micronutrient intake among schoolchildren.

Inoculation further strengthens this link. By increasing cowpea yields without depleting natural resources, inoculation could make the crop more readily available and affordable for school procurement. If locally produced cowpea were systematically integrated into the HGSFP, it would simultaneously benefit schoolchildren, smallholder farmers, and local food systems. Farmers would gain access to a stable institutional market, while schools would secure a sustainable supply of nutritious food. This synergy illustrates how agricultural innovation at the farm level can directly enhance the success of nutrition-sensitive policies, expanding the impact of school feeding beyond education into household food security and rural livelihoods.

1.2 Study area

Namibia, located in southwestern Africa, is one of the most arid countries in sub-Saharan Africa, with only about 1% of its territory arable (WFP, 2017). The country gained independence from South Africa in 1990 after a protracted liberation struggle, establishing a constitutional democracy that remains relatively stable compared to many regional counterparts (Melber, 2019). Namibia's population is unevenly distributed due to its arid environment, with most people concentrated in the north-central and northeastern regions (Pendleton et al., 2014).

The societal structure is shaped by legacies of colonialism and apartheid, particularly unequal land ownership and access to resources (Werner, 2015). Despite being classified as an upper-middle-income country, Namibia exhibits one of the highest levels of income inequality worldwide (World Bank, 2021).

Food Security in Namibia

Namibia depends heavily on imports, with about 60% of its food sourced from abroad, primarily South Africa (WFP, 2017). Malnutrition remains widespread. Approximately 58% of the population is moderately or severely food insecure, and 17% are undernourished, largely due to poverty, unemployment, and climatic shocks (FAO et al., 2022). Namibia ranks 84th of 123 in the 2025 Global Hunger Index (Welthungerhilfe et al., 2025).

Future projections suggest increased challenges. By 2100, Namibia's population is expected to grow by 18–96% compared to 2010 levels (Riahi et al., 2017). Without improvements in agricultural productivity and resilience, this demographic growth may exacerbate malnutrition and food insecurity (Wudil et al., 2022).

Agriculture and Rural Livelihood in Namibia

Agriculture is the primary livelihood source for approximately 70% of the population, though it contributes only around 6% to the national GDP (Namibia Statistics Agency, 2024). The sector is dominated by smallholder farmers practicing subsistence farming, primarily on communal lands (Odero, 2017). These systems are characterized by low productivity, weak market integration, and minimal contribution to the formal economy (Namibia National Planning Commission, 2018).

Several factors explain the sector's limited performance. Farmers often lack access to markets, relying on informal or barter exchanges. High input costs and non-preferable biophysical conditions—such as sandy, nutrient-poor soils with low organic carbon and nitrogen—further constrain productivity (de Blécourt et al., 2019). Irrigation requires high initial investment and stresses scarce water resources, while fertilizer use is limited due to cost and risks of soil degradation (Holden, 2018; Mabhaudhi et al., 2018). These structural challenges leave smallholder farmers highly vulnerable to climate variability and economic shocks.

Climate in Namibia

Namibia's climate is predominantly hyper-arid to semi-arid, with highly variable and generally low rainfall (WB, 2021a). Extreme events such as droughts and floods have become increasingly frequent. Over the past decade, recurrent droughts left over 330,000 people acutely food insecure and an additional 447,000 moderately food insecure (Integrated Food Security Phase Classification, 2024).

Climate projections indicate worsening conditions. Between 2050 and 2074, average temperatures are expected to rise by 2–4 °C, with precipitation declining by up to 40%. By 2100, temperatures may rise by 4–6 °C (Niang et al., 2014; Trisos et al., 2022). These changes are projected to reduce crop yields by up to 40% across most sub-regions of Namibia (Knox et al., 2012), undermining national food production and rural livelihoods.

School Feeding Initiatives in Namibia

School feeding programmes (SFPs) represent one of the largest global safety nets, and Namibia has participated since the 1960s through the World Food Programme (WFP, 2023). In 2021, Namibia launched the pilot phase of the HGSFP, designed to source food directly from smallholder farmers. The pilot involved 29 schools across seven regions and supplied diversified meals including vegetables, meat, and fish (WFP, 2021).

Compared to the conventional fortified maize porridge model, the HGSFP provides more balanced and nutritious meals (Galani et al., 2022). In addition to improving child nutrition and school attendance (Mostert, 2021; Destaw et al., 2022), these initiatives strengthen rural livelihoods by providing reliable market access to smallholder farmers (Gelli et al., 2021). Cost-benefit analyses suggest that SFPs generate high socio-economic returns, with US$9 in benefits for every US$1 invested (Verguet et al., 2020).

However, the long-term sustainability of Namibia's HGSFP depends on addressing structural challenges in the agricultural sector, including limited arable land, low productivity, and climate-related risks. Effective scaling of this programme will therefore require targeted investments in agricultural innovation, resource management, and smallholder market integration.

1.3 Outline of the thesis

1.3.1 Objective of the thesis

This thesis aims to investigate effective agricultural adaptation strategies and supportive policy frameworks that can bolster food security, nutrition, and rural livelihoods in Namibia amid emerging socioeconomic and climate challenges. Given Namibia's arid environment, vulnerable smallholder farming sector, and dependency on food imports, the research focuses on the potential of climate-resilient crops such as cowpea—enhanced by sustainable management practices like rhizobial inoculation, irrigation, and fertilization—to strengthen local food systems and school feeding programs.

Specifically, the thesis addresses the following research questions (RQ):

RQ 1: How do irrigation and inoculation affect the resource demands, productivity, and trade-offs of scaling cowpea production in Namibia?

RQ 2: To what extent can Namibia's domestic crop production sustain the HGSFP's nutritional needs under current and future socio-economic, climatic, and management conditions?

RQ 3: What is the potential of cowpea to complement maize in Namibia's school feeding program under improved farming practices that ensure reliable domestic supply?

Through integrated biophysical modeling, economic analysis, and scenario evaluation, this research seeks to generate actionable insights for policy makers and development practitioners aiming to build adaptive capacity, ensure long-term food security, and foster resilient agricultural growth in Namibia.

1.3.2 Outline of the thesis

The thesis comprises three research articles that explores Namibia agriculture, food security, and adaptation pathways in the face of future challenges:

- **Agriculture**: Potential of agricultural production in Namibia
- **Food security**: Namibian schoolchildren's nutrition
- Potential **adaptation measures** to socioeconomic and climatic changes

Article I (Ch.2) investigates cowpea production under various future scenarios. This study analyzes effects of improved farming managements (inoculation, irrigation and fertilization) on cowpea production, while also assessing trade-offs between Namibia's two most constrained resources, land and water.

Article II (Ch.3) evaluates the technical feasibility on the Namibia HGSFP. The study It assesses the capacity of domestic agriculture to reliably supply the program and evaluates the implications of improved farming practices under alternative socioeconomic and climatic futures.

Article III (Ch.4) extends the preceding analyses by evaluating the prospective role of cowpea within the NSFP. Building on insights from Article I, it examines cowpea's capacity to complement conventional maize meal and thereby enhance the nutritional adequacy of school meals. The study further underscores the potential benefit of improving schoolchildren's nutrition while strengthening market integration for smallholder farmers.

2. Managing scarce water and land resources: The potentials of cowpea production in Namibia

Jihye Jeong [a, b], Kerstin Jantke [b], Livia Rasche [a, c], Annette Eschenbach [b, d], David Uchezuba [e], Barbara Reinhold-Hurek [f], Uwe Andreas Schneider [a, b]

[a] Research Unit Sustainability and Climate Risks, Universität Hamburg, Grindelberg 5, 20144 Hamburg, Germany

[b] Center for Earth System Research and Sustainability (CEN), Universität Hamburg, Grindelberg 5, 20144 Hamburg, Germany

[c] Department of Land Use Economics, Universität Hohenheim, Wollgrasweg 43, 70599 Stuttgart, Germany

[d] Institute of Soil Science, Universität Hamburg, Allende-Platz 2, 20146 Hamburg, Germany

[e] Department of Agricultural Science and Agribusiness, Namibia University of Science and Technology, Windhoek, Namibia

[f] Department of Microbe-Plant Interactions, CBIB Center for Biomolecular Interactions Bremen, Faculty of Biology and Chemistry, Universität Bremen, PO. Box 330440, 28334 Bremen, Germany

Abstract

Sub-Saharan countries such as Namibia face increasing food insecurity due to a combination of climatic and socio-economic challenges. Despite having limited arable land, agriculture remains crucial for rural livelihoods in the country. Cowpea, a legume known for its resilience to water and temperature stress, plays an important role in the livelihoods of smallholder farmers in Namibia. This study aims to explore the potential of cowpea cultivation in Namibia and its impact on resource use. To investigate the resource demand of cowpea production, to assess the impact of irrigation and inoculation on cowpea productivity, and to analyze trade-offs between water and land resources in cowpea production, we integrate crop growth simulations with resource allocation optimization. Field experiment data inform our simulations of cowpea production, covering both rainfed and irrigated systems for standard and inoculated cowpeas. Our results show that both irrigation and inoculation substantially enhance cowpea productivity in northern Namibia, with yields reaching a maximum of 5.73 tons per hectare. In particular, inoculation emerges as a promising strategy for improving yields and resource efficiency without exacerbating water stress, unlike irrigation. Our simulations indicate that inoculated cowpea cultivation alone has the potential to meet the protein needs of the entire Namibian population using 10% of the current cropland and water resources. Therefore, inoculation is a viable strategy for smallholder farmers in Namibia to sustainably increase yields and reduce food insecurity under resource scarcity. In conclusion, this study highlights the importance of exploring innovative agricultural practices to address food insecurity in sub-Saharan countries such as Namibia and emphasizes the role of cowpea cultivation in achieving sustainable food production in the region.

Keywords: Resource intensity, Inoculation, Cowpea, Namibia, Food security

Highlights

- Inoculation increases cowpea yield to a similar extent as the introduction of irrigation.
- Inoculated cowpea requires less land and water.
- With low implementation costs, and no stress on water resources, inoculation is an attractive strategy for smallholder farmers in Namibia to improve cowpea production.

2.1 Introduction

Namibia is one of the most arid countries in sub-Saharan Africa, with only 1% of its territory arable. Domestic food production does not meet the national nutritional needs, forcing Namibia to import 60% from other countries, particularly from South Africa (WFP, 2017). Efficient use of resources is a key to enhance production under resource scarce conditions.

Achieving the Sustainable Development Goal 2 of zero hunger means achieving food security, improving nutrition, and promoting sustainable agriculture (United Nations, 2015). Human population growth increasingly requires more efficient and sustainable food production, especially since in 2100 the Namibian population is expected to increase by 18-96% relative to its size in 2010 (Riahi et al., 2017). Food security in Sub-Saharan Africa is further burdened by multiple factors, including poor economic growth, gender inequality, high inflation, low crop productivity, low investment in irrigated agriculture and research, climate change, high population growth, poor policy frameworks, weak infrastructural development, and corruption (Wudil et al., 2022). Additionally, gender and income inequality exacerbate malnutrition, especially in the drylands of the global south (FAO et al., 2022).

Poverty is a major cause of food insecurity. Access to food is highly dependent on purchasing power, which is vulnerable to price fluctuations. According to the 2023 Global Hunger Index, Namibia ranks 78th out of 107 countries. The FAO dataset (FAO et al., 2022) shows that 58% of the Namibian population is moderately or severely food insecure and 17% suffer from undernourishment due to climatic shocks, price shocks, economic decline, and unemployment.

Unpredictable precipitation patterns under a changing climate pose a significant threat to food security in Namibia (Knox et al., 2012; Nickanor & Kazembe, 2016). In the last decade, a series of droughts have resulted in 330,000 people experiencing food insecurity, particularly in the north-western regions, with an additional 447,000 people facing moderate food insecurity (Integrated Food Security Phase Classification, 2024). Smallholder farming in Namibia is practiced on soils with a low fertility potential. The mostly sandy soils have low nutrient levels - especially nitrogen (N) - and show low organic carbon contents (de Blécourt et al., 2019). According to Knox et al., (2012), studies project that by 2050, there will be yield reductions of up to 40 % across all crop types and sub-regions in Namibia. Thus, effective and sustainable domestic food production in Namibia depends on the management of scarce cropland and water resources.

Legumes are a valuable source of protein and contribute significantly to diets in many regions. They promote food security, nutrition, health, and sustainable resource use, thus contributing to poverty reduction (Kebede, 2021). They are relatively cheap to obtain and grow, and are low in fat and cholesterol (Gerrano et al., 2017). Legumes enable biological N fixation from atmospheric dinitrogen (N_2) through their ability to form a mutualistic symbiosis with bacteria of the *Rhizobiaceae* family (Sugiyama & Yazaki, 2012). They can therefore enable higher yields, improve the growth of other crops through intercropping (NAB & FAO, 2021), and enhance soil improvement through N-enriched organic residues. Rhizobial inoculation enhances nitrogen fixation of legumes, so legumes inoculated with appropriate symbionts have higher yields (Becker et al., 2023).Rhizobial inoculants are considered as a solution to the intertwined problems of food security and environmental sustainability (Yadav et al., 2021)(Becker et al., 2023).

The cowpea *(Vigna unguiculata)* is a highly promoted legume grown in semi-arid regions of sub-Saharan Africa due to its nutritional and soil benefits and high resilience to arid climate (Dube & Fanadzo, 2013; Kyei-Boahen et al., 2017). Cowpea whole grains offer nutritional qualities similar to those of other legumes, featuring a high protein level (23-32%) and low fat content (1%) (Kirse & Karklina, 2015; Rodrigues Cruz et al., 2014). Cowpea production in sub-Saharan Africa is projected to increase from about 9.8 million tons in 2020 to nearly 12.3 million tons in 2030 (Boukar et al., 2019; FAOSTAT, 2022).

In Namibia, cowpea is grown on about 62,000 ha (NAB & FAO, 2021). Studies have shown that cowpea is highly adaptable to the harsh Namibian environmental conditions (NAB and FAO, 2021). 70% of farmers grow local, unimproved cowpea varieties. The main strategies for increasing smallholder cowpea production and productivity in the northern regions of Namibia are breeding for high grain yield and farmer-preferred traits as well as ensuring seed and production input availability(Horn et al., 2015). Studies in various arid regions have shown that cowpea is tolerant to significant water stress, not only surviving it but also remaining productive (Cavalcante Junior et al., 2016; S. M. Karanja et al., 2017). The use of rhizobial inoculants for higher nitrogen fixation has been shown to significantly increase cowpea yield (Luchen et al., 2018; Kanonge-Mafaune et al., 2018; Rasche et al., 2023; Zhao et al., 2022), however, inoculation technology is yet hardly applied in Namibia. At the moment, there is only one manufacturer in Africa (Kenya) producing rhizobial inoculants for cowpeas (Jefwa et al., 2022).

To increase sustainable domestic food production in Namibia, options include expanding the cultivation area of cowpea, increasing irrigation despite increasing water scarcity, and promoting the use of inoculated cowpeas adapted to local environmental conditions (Becker et al., 2023; Grönemeyer & Reinhold-Hurek, 2018). Previous studies have focused on specific options or solely on biophysical outcomes, ignoring the nexus between food production and scarce agricultural resources. The full potential of cowpea cultivation in Namibia, including possible resource trade-offs, has not been fully explored.

To address this research gap, this study aims to investigate and compare the potential of different agricultural management systems and their impact on resource use in cowpea cultivation. More specifically, the objectives of this study are:

(1) To investigate the resource demand of increased cowpea production in Namibia
(2) To assess the impact of irrigation and inoculation on cowpea productivity
(3) To analyze trade-offs between water and land resources in cowpea production

To address these questions, we integrate crop growth simulations with resource allocation optimization. National cowpea production is simulated based on data from field experiments.

2.2 Study area

Namibia, located in south-western Africa, has an extremely arid climate, making it one of the most vulnerable countries in the region. In the medium term (2050-2074), temperatures are projected to rise by 2-4 °C, while precipitation is expected to decrease by 40%. In the longer term (2075-2100), temperatures could increase by 4 to 6 °C. Projected climate change poses a threat to food production as floods become more frequent and droughts more likely (Niang et al., 2014; Trisos et al., 2022).

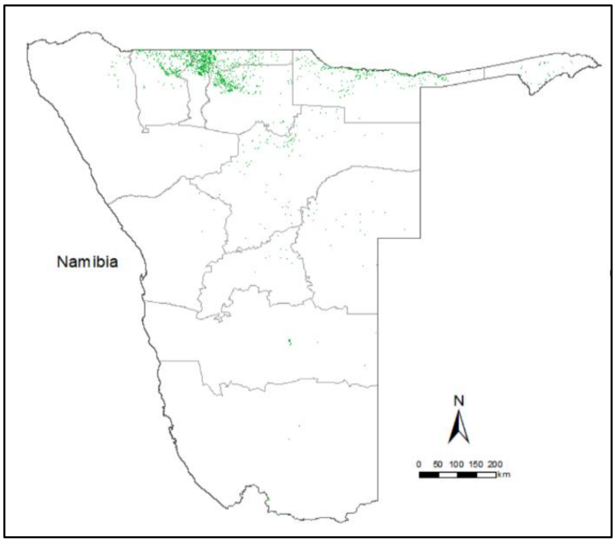

Figure 2.1 Distribution of cropland in the study region Namibia (modified from Buchhorn (2020)). Only 1% of Namibian territory is arable.

Water is a very scarce resource in Namibia, with agriculture being the largest user, accounting for up to 75% of total water withdrawal. Within agriculture, crop irrigation alone accounts for 60% of total water withdrawal (FAO: AQUASTAT, 2022). Due to the limited water resources, only 1% of the country's territory is suitable for crop production (Figure 1).

The country's reliance on rainfed agriculture and livestock increases its vulnerability to change and limits the capacity of poor households and communities to manage climate risks, increasing their vulnerability to climate-related shocks (WB 2021a. Namibia Climate Risk Profile).

2.3 Data and methods

This study integrates biophysical process simulations with mathematical programming. The biophysical simulations assess the potential productivity of cowpea cultivation across all suitable locations in Namibia, considering rainfed and irrigated production systems for standard and inoculated cowpeas. The outcomes of the biophysical modeling inform a mathematical programming model, which employs constrained optimization to delineate the production possibility frontier for cowpea within the constraints of limited cropland and water resources. Figure depicts the main components of the modeling framework and their interconnections. Details on the individual components are given in the following sub-sections.

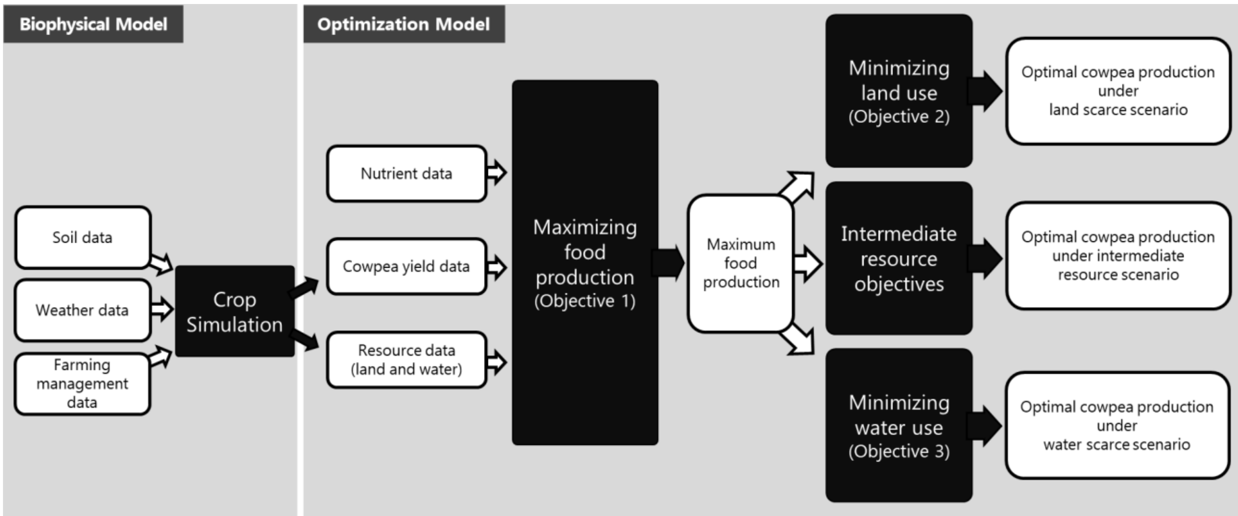

Figure 2.2 Overview of the modeling approach. Dark boxes show model runs, white boxes depict input and output data.

2.3.1 Data and spatial resolution

This study uses and integrates diverse data from different disciplines related to agricultural resources, land management options, and food demand in Namibia.

Land use data is from the Copernicus Global Land Service (CGLS) (Buchhorn et al., 2020). It provides a global land cover product at a spatial resolution of 100m for the reference years 2015 to 2019. Details on cowpea nutritional value are taken from Haytowitz et al., (2019).

We employ the Homogeneous response unit (HRU) classification system (Skalsky et al., 2012) to categorize the area for simulations. HRUs are landscape units which are similar in terms of altitude, slope, and soil texture. Altitude is divided into five classes: 1 (0 - 300m), 2 (300 - 600m), 3 (600 - 1100m), 4 (1100 - 2500m), 5 (> 2500m)). Slope is categorized into seven classes (degrees): 1 (0 - 3), 2 (3 - 6), 3 (6 - 10), 4 (10 - 15), 5 (15 - 30), 6 (30 - 50), 7 (>

50)). Soil composition is classified into five types: 1 (sandy), 2 (loamy), 3 (clay), 4 (stony), 5 (peat)) (Skalsky et al., 2012). In Namibia, the landscape is composed of eight different HRUs, seven of which contain cropland.

Field experiments located in Ogongo (Omusati region) and Mashare (north-eastern Kavango region) were carried out representing major agricultural regions in Northern Namibia. The sandy soils (sand content > 85% for both sites) reflect low nutrient (N 0.03% and 0.02%) and low soil organic carbon (0.3 and 0.2%) levels typical for the region (Becker et al. 2023). Comparable to the experiments with *V. unguiculata* variety `Lutembe` described by Rasche et al. (2023), experiments were carried out with the cowpea variety `Nakare`, the most cultivated cowpea variety in Namibia (NAB & FAO, 2021). In the treatments, the effect of inoculation with *Bradyrhizobium* sp. strain 1-7 is compared with non-inoculated cowpeas (for details see Rasche et al. 2023). This strain was previously isolated from nodules in the Kavango region, it nodulates cowpea and Bambara groundnut (Grönemeyer et al., 2014), and was found to increase cowpea grain yields by up to 100% (Luchen et al., 2018). With a growth range up to 35°C-38°C, it belongs to the relatively heat-tolerant Bradyrhizobium strains (Grönemeyer et al., 2014; Grönemeyer & Reinhold-Hurek, 2018) and is therefore likely to survive well in climate change scenarios.

2.3.2 Biophysical analysis of cowpea cultivation

We employed the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1988). A biophysical process-based model at the field level, EPIC can simulate various tillage and management practices, soil nutrient cycling, crop growth and crop yield. A distinct set of crop parameters, such as radiation use efficiency, maximum potential harvest index, base temperature, optimal temperature, maximum potential leaf area index (LAI), maximum stomatal conductance, maximum crop height and root depth, and nitrogen, phosphorous, and potassium uptake parameters, are used to characterize crops. The EPIC model simulates plant biophysical processes, which involve capturing photosynthetically active solar radiation based on LAI, transforming it into biomass using radiation use efficiency, and responding to crop growth stresses like nutrient and water availability, temperature. It also determines how daily biomass growth is distributed between root and aboveground biomass, and adjusts the harvest index in response to drought conditions (Williams et al., 2013). EPIC has a long history of being utilized in agricultural research to investigate various topics like yield gaps (Basukala & Rasche, 2022; Lu & Fan, 2013), climate change effects on crop yields (Schröder et al., 2024; Xiong et al., 2016), environmental impacts (J.

Liu et al., 2010; W. Liu et al., 2016), soil degradation (Balkovič et al., 2018), erosion (Schröder et al., 2024), and nutrient leaching (Bouraoui & Grizzetti, 2008).

The model was run on all HRUs for 100 years to generate data reflecting a variety of annual climatic conditions, utilizing long-term monthly means provided by the Tyndall Centre for Climate Change Research of University of East Anglia, Norwich, UK, with a resolution of 0.5°. The dataset includes historical time series of global weather for the period from 1901 – 2000 (Mitchel et al., 2004). Since we are examining the current potential of cowpea cultivation, we employed weather data that captures diverse conditions relevant to the present period. It is important to note that future climate change may lead to significant alterations in these weather patterns, potentially impacting cowpea yields and cultivation practices.

Management scenarios for each HRU include the cultivation of cowpeas with and without inoculant and cultivation, as well as cultivation with and without irrigation. Crop parameters for both crop variants were calibrated using results from field experiments. Irrigation was limited to a maximum amount of 100 mm per year. For fertilization, we simulated a rate of 15 kg of phosphorus fertilizer per hectare, corresponding to approximately 1.5 grams per square meter, based on the "pinch" added during field trials. Additionally, we included 3 kg of potassium fertilizer per hectare in our simulations. While many farmers may find it challenging to afford mineral P fertilizers, they commonly utilize manure, which contains at least 6 grams of P per kilogram, potentially covering the phosphorus requirements assumed in our study.

2.3.3 Optimization of cultivation system choice and resource allocation for cowpeas

To estimate production possibility frontiers for cowpea cultivation on a national scale, we develop a novel mathematical programming model. This model optimizes cowpea cultivation by considering 121 simulation units with limited land and water resources, as well as four cowpea cultivation systems with specific crop yields and water requirements. The four cultivation systems comprise rainfed and irrigated farming with and without inoculated cowpeas. The optimization model can operate in two principal modes to determine the nexus between food production, land, and water use. In the first mode, the model aims to maximize cowpea production subject to a given level of land and water resources. In the second mode, the model seeks to minimize the land or water resource use required to meet a given cowpea production level. The mathematical structure of the model contains nine structurally distinct equations, which are given below.

Maximize food supply $$F_t = \sum_n \left(v_n \cdot N_{t,n} \right) \qquad \forall t \qquad [2.1]$$

or Minimize land use $$L_t = \sum_{r,i,m} C_{t,r,i,m} \qquad \forall t \qquad [2.2]$$

or Minimize water use $$W_t = \sum_{r,i,m} \left(a_{t,r,i,m,'water'} \cdot C_{t,r,i,m} \right) \qquad \forall t \qquad [2.3]$$

subject to:

$$\sum_{i,m} \left(a_{t,r,i,m,j} \cdot C_{t,r,i,m} \right) \le b_{t,r,j} \qquad \forall t, r, j \qquad [2.4]$$

$$\sum_{r,i,m} \left(a_{t,r,i,m,j} \cdot C_{t,r,i,m} \right) \le z_{t,j} \qquad \forall t, j \qquad [2.5]$$

$$\sum_{i,m^{irr}} C_{t,r,i,m^{irr}} \le s^{irr} \qquad \forall t, r \qquad [2.6]$$

$$\sum_{r,i,m^{irr}} C_{t,r,i,m^{irr}} \le s^{irr} \qquad \forall t \qquad [2.7]$$

$$N_{t,n} = \sum_{r,i,m} \left(a_{t,r,i,m,n} \cdot C_{t,r,i,m} \right) \qquad \forall t, n \qquad [2.8]$$

$$N_{t,n} \ge f_{t,n}^{\min} \qquad \forall t, n \qquad [2.9]$$

All equations contain variables, parameters and indexes, which are defined as follows:

Indexes:

- The index *t* represents 30 years from an ensemble of generated weather under historical climate
- The index r represents all eligible homogeneous response units for cowpea cultivation.
- The index *i* includes options for inoculation: inoculated and non-inoculated.
- The index *m* encompasses alternative irrigation systems: subsistence farming and irrigation.
- The index j depicts resources for cowpea cultivation: cropland and water.
- The index *n* comprises nutritional elements: energy, protein, carbohydrates, fatty acids.

Variables:

- *F* represents cowpeas' domestic food supply contribution in caloric energy units.
- *L* represents the national land allocation to cowpeas.
- *W* depicts the national water use for irrigated cowpeas.
- *C* indicates the area in each HRU allocated to a specific cowpea cultivation system.
- *N* represents the total supply of nutrients from cowpea production including carbohydrates, protein, and fatty acids.

Data parameters:

- *a* contains technical data for all cultivation systems including cowpea yields and land and water requirements.
- *b* represents available cropland and water endowments for cowpea cultivation in each HRU.
- *z* denotes available cropland and water endowments for cowpea cultivation at national levels.
- *s* represents the maximum irrigation fraction for cowpeas either at HRU or national scale.
- *v* represents a value coefficient for nutritional elements in the objective function (usually set to 1 for caloric energy and 0 for all other elements).
- $f^{\min}$ represents the minimum total supply of nutrient n at time t from cowpea production.

The first three equations depict three alternative objectives. The first objective equation [2.1] maximizes the domestic food supply from cowpeas. The second [2.2] and third [2.3] objective equations minimize the use of land and water resources, respectively. Constraints [2.4] and [2.5] limit the land and water resources used for cowpea cultivation at HRU and national level, respectively. Constraints [2.6] and [2.7] limit the cowpea area under irrigation to specified bounds at HRU or national levels, respectively. The accounting equation [2.8] calculates the national food supply from cowpeas for major nutritional elements. Equation [2.9] enforces a domestic minimum supply of nutritional elements from cowpeas. Each model solution involves an assignment of data parameter values, a choice of objective, and a selection of constraining equations.

2.3.4 Scenario analysis

We perform a systematic scenario analysis to explore the food supply benefits and associated resource costs of cowpeas. Particularly, we vary whether inoculated cowpeas can be planted, how much cropland can be allocated to cowpeas, how much area can be irrigated, and how much water can be used for irrigation. For all regional (HRU) or national resource allocations, we use upper bounds to avoid insensible scenarios. First, we consider available land resources for cowpeas only in areas that are classified as cropland. These areas are located in the northern part of Namibia and represent about 1% of Namibia's national territory (Buchhorn et al., 2020). The total available water resource is defined as the sum of annual surface runoff and lateral subsurface flow. Second, we specify upper limits on available cropland and water resources for cowpea cultivation in each eligible production region. In particular, we assign a maximum cropland share of 25% for cowpeas. Regional maximum values for irrigation water are derived from regional water runoff volumes from precipitation. Particularly, we define 50% of the available water runoff in each HRU as an upper limit for water used for cowpea irrigation. Note that this water limit is based on the total HRU area, not just the cropland area with an HRU. The maximum share of irrigated cowpeas is 100 percent, and the irrigation efficiency equals 95%.

To determine the cowpea production opportunity space and substitution functions between land and water resources, we perform a sequence of optimizations for various assumptions of crucial model parameters (Figure 2.3). First, we maximize food production subject to scenario-specific assumptions about the availability of resources, cultivars, and management systems. From the resulting production opportunities, we construct a series of feasible production targets. We use these targets in a second step to determine the marginal rates of substitution between land and water resources. For a given production target, we start by minimizing the required cropland utilization under the highest water availability scenario. We then lower the water availability in small steps and repeat the land minimization process. We repeat this process until the available water endowments are zero.

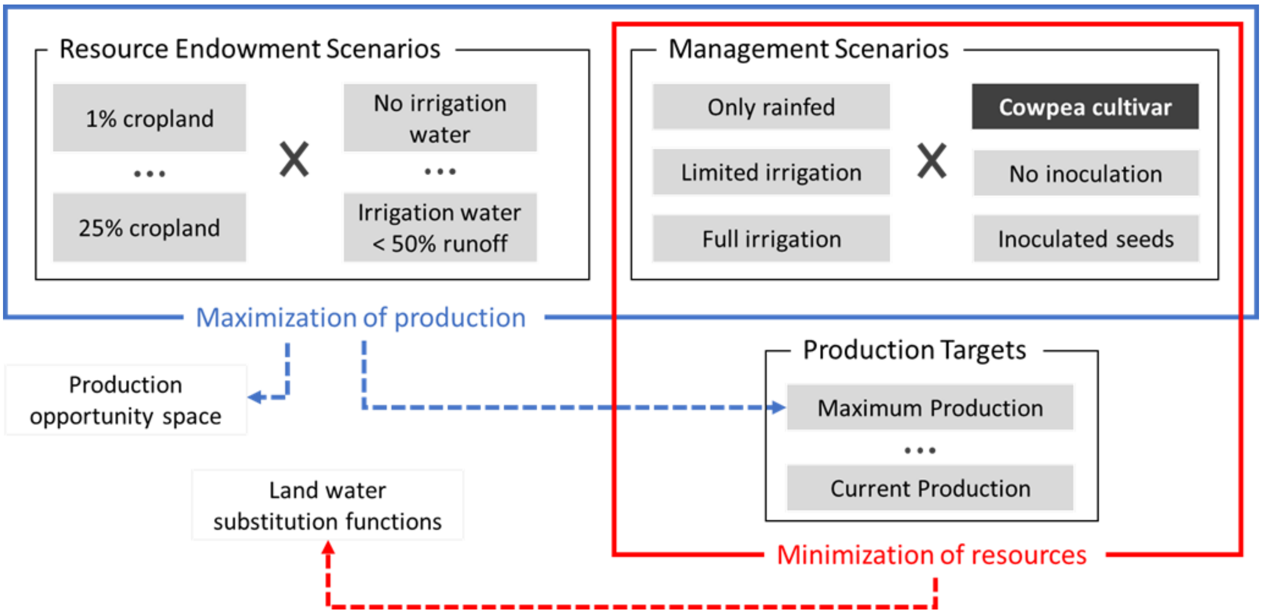

Figure 2.3 Illustration of scenario analysis. The production opportunity landscape is delineated across various resource endowments and assumptions about available cowpea management systems (illustrated through heatmaps in section 2.4.2). Subsequently, employing multiple attainable production targets, substitution functions for land and water resources are estimated.

2.3.5 Analysis of resource substitution elasticities

Resource substitution elasticities provide insights into how agricultural systems can adapt to environmental variability, such as precipitation patterns and fluctuations in water availability, thereby enhancing resilience. These elasticities aid in policy analysis, environmental assessment, economic studies, and interdisciplinary research. Here, we assess substitution elasticities (ε_{WL}) to calculate the trade-off between land (L) and water (W) resources used for cowpea cultivation. We employ an ordinary least square regression [11] to estimate the elasticity of water use with respect to land use. The regression coefficient β directly yields the elasticity ε_{WL} .

$$\varepsilon_{WL} = \frac{\partial W / W}{\partial L / L} \quad [2.10]$$

$$\ln(W) = \alpha + \beta \cdot \ln(L) \quad [2.11]$$

2.4 Results

2.4.1 *Cowpea productivity*

Biophysical simulations show that both irrigation and inoculation increase cowpea productivity in the cropland areas of northern Namibia (Figure 4). Without irrigation and inoculation (Fig. 4a), cowpea dry yields are on average 0.2 t/ha. Irrigation increases yields to 1.78 t/ha on average (Fig. 4b), and inoculation increases yields to 0.21 t/ha on average (Fig. 4c). When both irrigation and inoculation are adopted, cowpea yields increase to on average 2.2 t/ha (Fig. 4d). Productivity is highest in the north-west of Namibia, where most of the cropland is located. There, highest cowpea productivity with a maximum of 5.73 t/ha was simulated.

2.4.2 *National protein supply contribution from cowpea cultivation*

This section summarizes the estimated national protein supply capacity from cowpea cultivation for various assumptions of available cropland allocation and irrigation water usage. The heatmaps (Figure 2.5) show protein supply capacities for standard cowpeas (no inoculation, left panel) and for improved inoculated cowpeas (right panel). For ease of interpretation, we represent the land allocation (x-axis) in the percentage of cropland. As explained in section 3.4, we limit land resource for cowpeas to 25% of cropland. Similarly, on the vertical axis, we represent irrigation water as a percentage of regionally available runoff. Protein supply is quantified in daily per-capita grams and depicted through the color code. For the conversion of the national supply in tons of cowpeas to per-capita protein values, we used a population size of 3 million people and a protein content of cowpeas of 23 grams per 100 grams (according to FAOSTAT). Our results show that there is a considerable potential for cowpeas to meet contemporary protein demands.

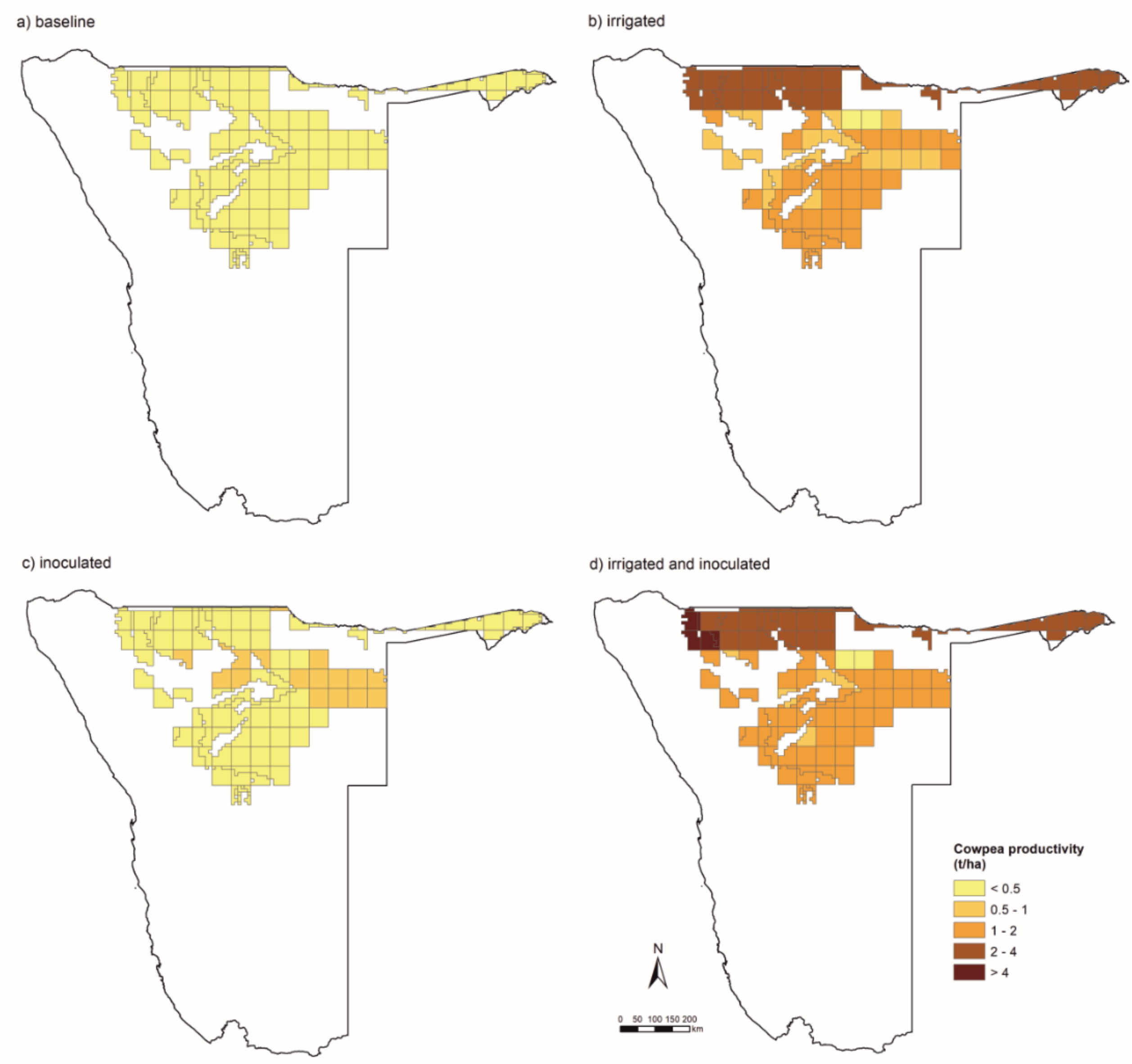

Figure 2.4 Cowpea productivity in Namibia [t/ha] under different farming systems. The maps show simulation results for maximum irrigation for regions containing cropland areas.

All supply values are calculated before accounting for losses incurred during harvesting, processing, distribution, and consumption, which inevitably would reduce these figures. Furthermore, the values are averages determined over the population size of Namibia in 2023. Prevalent income disparities and other factors prevent equal access to food, leading some individuals to consume less than the average amount.

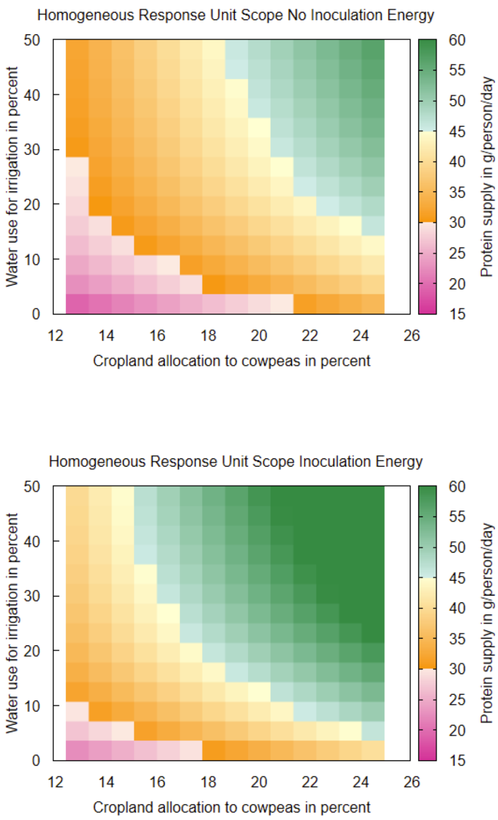

Figure 2.5 Nationally aggregated protein supply potentials for cow peas without inoculation (left panel) and with inoculation (right panel). The horizontal axis displays the allocation of cropland to cowpeas in each Hydrological Response Unit (HRU). On the vertical axis, the maximum irrigation level in each HRU is depicted as a percentage of the total area. The color gradient indicates the protein supply capacity in grams per person per day. Per-capita values were calculated based on a population size of 3 million people. Notably, all supply capacity figures reflect harvestable amounts and exclude losses incurred during processing, storage, and distribution.

2.4.3 *Land intensity under different farming systems*

Under basic farming systems (no inoculation, no irrigation), Namibia has the potential to produce up to 90,500t of cowpea using a maximum of 50% of the cropland (Figure 2.6). Adopting both inoculation and 100% irrigation, production increases by a factor of 3.5 (318,335t). Inoculation without irrigation increases the baseline production by14.4-32.2%. Irrigation at 10%, 50% and 100% increases yield by 24.0-31.2%, 95.2-125.7%, and 165.9-187.5%, respectively, compared to rainfed yields. Inoculation in combination with irrigation at 10%, 50%, and 100% increases production to 64.0%, 158.1%, and 251.6%, respectively. Irrigation has a higher effect for non-inoculated cases. In addition, inoculation has higher benefits in non-irrigated systems and is therefore particularly important for smallholder farmers who cannot afford or have no access to irrigation.

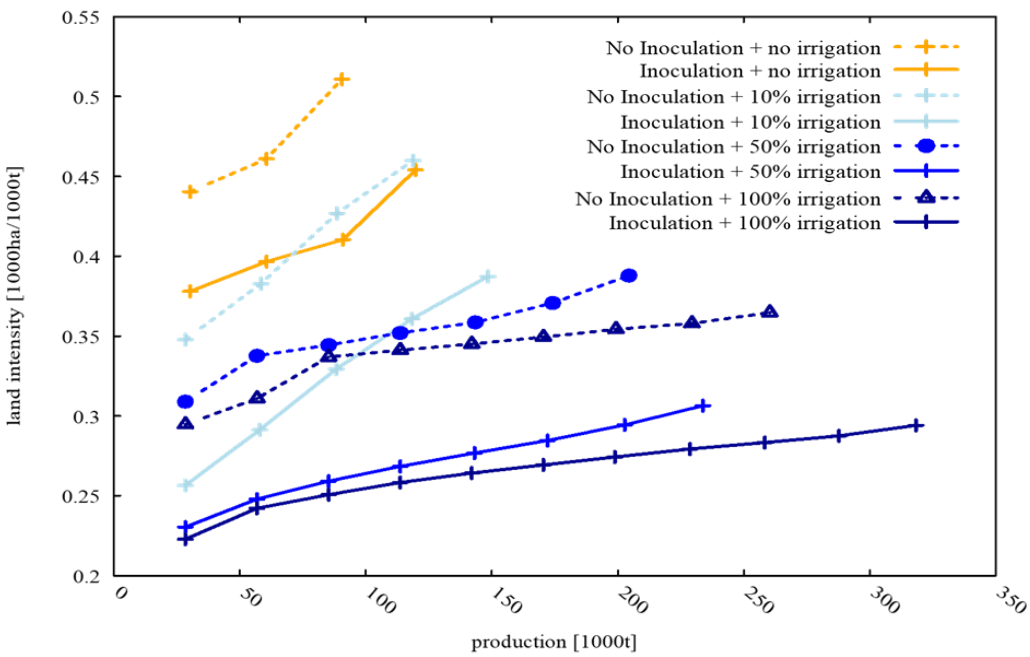

Figure 2.6 Land intensity under different farming system: inoculation and irrigation (no irrigation, 10%, and 100%). Dotted lines represent scenarios without inoculation. Solid lines depict inoculated scenarios. Each point is a different food supply scenario. Given 15 food supply scenarios, each production scenario has its own limit of production capacity. Therefore, scenarios with advanced farming managements show more food supply scenarios.

Resource intensity of land (= area/production [ha/t]) benefits from inoculation with an efficiency increase of 14.0-26.6% (average 22.7%). Irrigation increases land efficiency by 31.3% on average. Higher levels of irrigation make land more efficient, but the benefit to land efficiency decreases logarithmically with increasing levels of irrigation. Together with inoculation, the combination improves land intensity by 14.0-50.9% (average 31.17%). The higher the production, the higher the land intensity. As the optimization model uses more suitable land first, additional production requires more land to produce the same quantity. In the higher irrigation scenario, inoculation contributes more to land saving than irrigation (Figure 7).

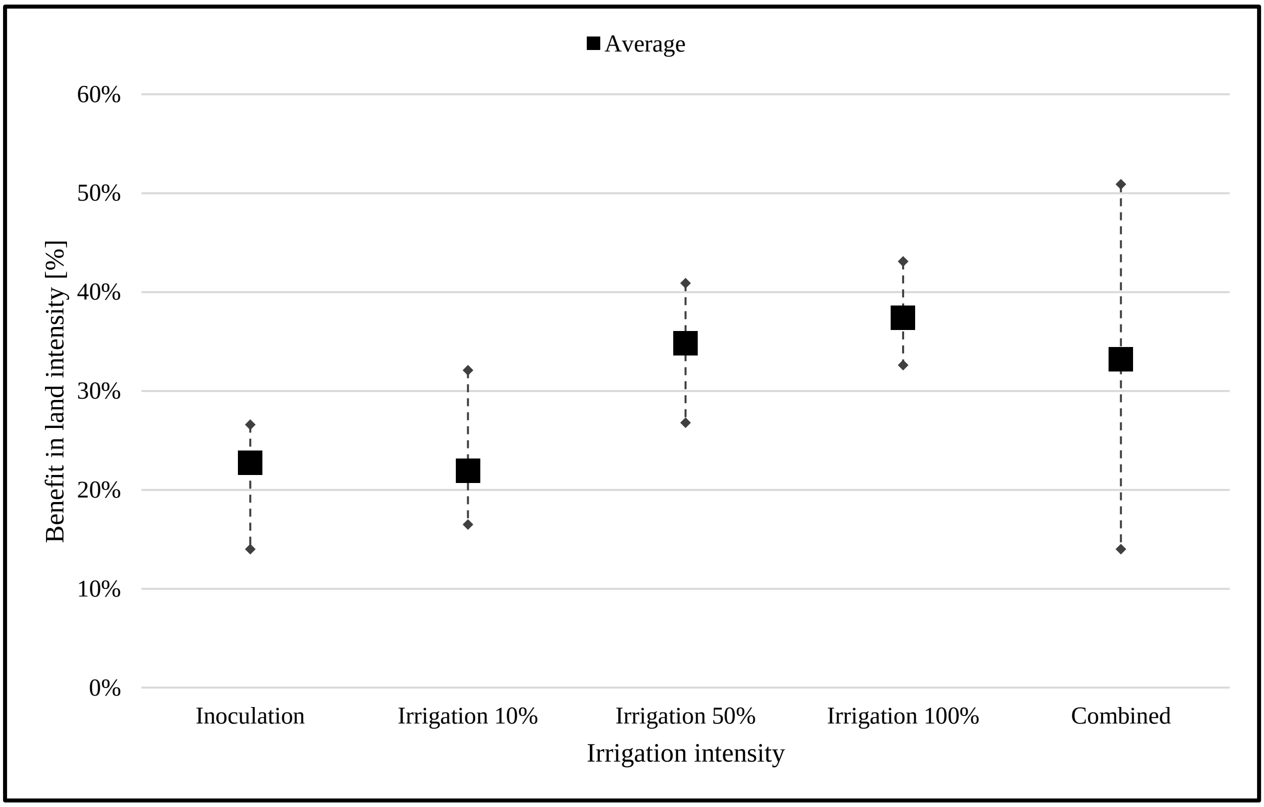

Figure 2.7 Benefit in land intensity due to improved farming systems: The box in the middle represents the average value over all production scenarios. High and low points are maximum and minimum respectively. Dotted line shows the range of increase in land efficiency under different scenarios.

2.4.4 *Water intensity under different farming systems*

Without inoculation and irrigation, Namibia has the potential to produce 118,600t of cowpea on 50% of the current cropland area. Adopting both inoculation and 100% irrigation, production increases by a factor of 2.7, to 322,153t, under the objective of minimizing water resource. Production increases by 14.4-32.2% with inoculation and by 24.1-31.0%, 97.6-128.4%, and 169.0-192.4% with 10%, 50%, and 100% irrigation, respectively. Irrigation has a higher impact for non-inoculated cases, same as in the land minimizing scenarios. Combined management improves production to 64.2%, 161.3%, and 255.8% (10%, 50%, and 100% of maximum irrigation respectively).

Inoculation decreases resource intensity of water (= water use/production [Million m^3/1000t]) to 86%. However, there is only one comparable scenario combination. Since the model minimizes water use, the benefit of 50% irrigation is still smaller than that of limiting water use. Therefore, only the 100% irrigation scenario uses irrigation, while the other scenarios favor rainfed agriculture.

2.4.5 ***Trade-off between land and water use***

Doubling production requires more than twice as many resources, both in terms of water and land. As water becomes scarcer, the utility of a unit of water increases. The relative increase in land use shows a decreasing trend in its change. Therefore, as water resources become scarcer, a unit of water can be replaced by more land than land scarce condition (Figure 2.8).

The estimated water uses elasticities with respect to land use range between -3.55 (high production with inoculation) and -4.58 (low production, without inoculation). This means that to compensate for a 1% decrease in land use, approximately 4% more water is required. With inoculation, less water is needed to offset the same reduction in land. However, under both high and low production scenarios, more land is necessary to compensate for the same amount of water. As the objective to minimize land use is given greater emphasis, any resulting shortfall must be compensated by using additional water resources. Consequently, the elasticity of water use with respect to land increases as the need for land conservation becomes more important, placing greater stress on water resources.

The high and low cowpea production points represent a satisfying 100% and 50% of total protein demand in Namibia, respectively (173.67 [1000t] and 87.54 [1000t]). L_1 and L_2 indicate 5% and 10% of total cropland (62000ha and 31000ha). Water demands at point L_1P_i and L_1P_b are 6% and 14% of total observed crop irrigation. Those of L_2P_i and L_2P_b are 17% and 36% of total crop irrigation, respectively. Regardless of production, inoculation has consistent impact in resource use. Given the same land, inoculation decreases water use to 53% (Figure 2.8).

Since food production is a result of optimization, food supply scenarios do not result in exactly the same amounts of production. However, in both scenarios, production shows 2.25-2.5 standard deviation which is 1-2.15% of the average.

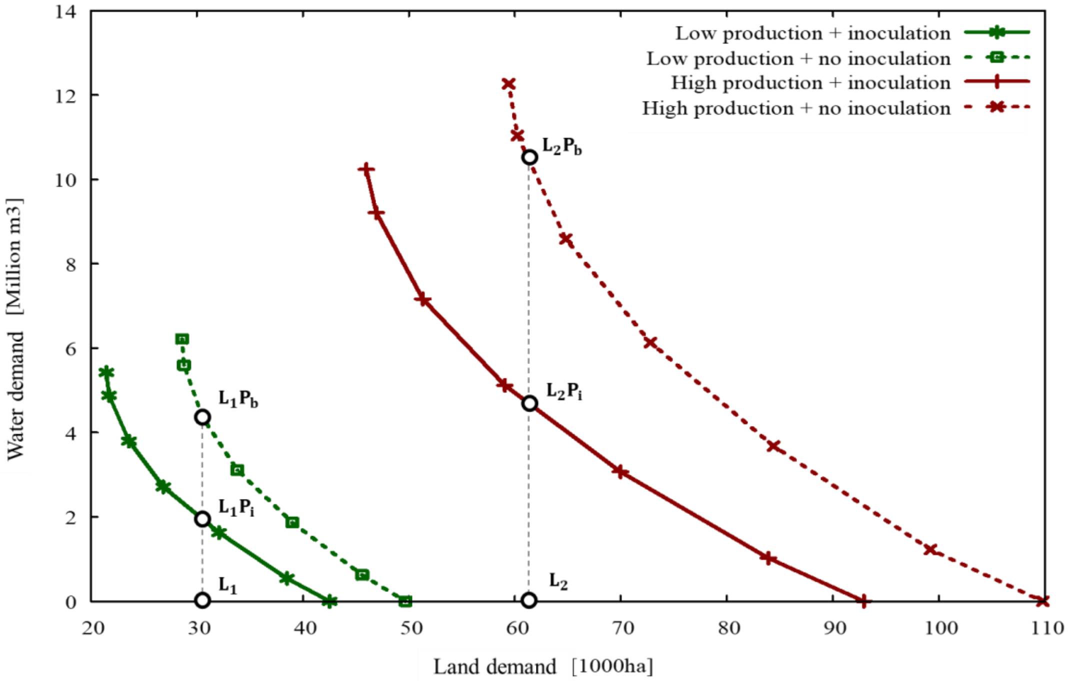

Figure 2.8 Trade-off between land and water use under different food supply and inoculation scenarios. Each point represents weighed objective scenario assuming 100% irrigation. Solid lines depict scenarios with inoculation and dashed lines depict ones without inoculation. High production indicates the quantity of cowpea that can satisfy protein demand of entire Namibian population (173.67 [1000t]). Low production meets 50% of total protein demand of population (87.54 [1000t]). $L_1$and L_2 is 5% (31 [1000ha]) and 10% (62 [1000ha]) of cropland respectively. $P_i$and $P_b$represents production with inoculation and without inoculation (base).

2.5 Discussion

2.5.1 Are cowpeas a reliable plant protein source for Namibia?

The growing poor population, low agricultural production, and climate change pose severe food insecurity challenges for Namibia. Considering the protein requirements for different population groups proposed by the World Health Organization (World Health Organization. et al., 2007), the Namibian population of currently 2.6 million people requires 39,900 tons of protein per year. Assuming that cowpea contains 23.5g of protein per 100g (Haytowitz et al., 2019), 169,649 tons of cowpea would meet the entire protein demand of the Namibian population. It is noteworthy that the current average diet in Namibia comprises approximately 60% plant-based protein and 40% animal-based protein, as per the author's calculation based on FAOSTAT data. The World Health Organization recommends a daily minimum protein intake per person of 41.3 grams. Despite the nutritional significance of pulses, the protein contribution from this food group, according to FAOSTAT, currently falls below 20%. Additionally, there is limited information available regarding the national extent of cowpea cultivation, and recorded yields for pulses remain relatively modest.

According to our simulations, inoculated cowpeas alone can meet the protein demand of the entire Namibian population on 10% of the current cropland (629,680 ha), using 10% of the total available water for crop irrigation (30 million m^3). This implies a huge potential for cowpeas as a major protein source, which is promising for a country with tough natural conditions and the prospect of future challenges due to climate change and population growth. Our research highlights the importance of resource management for unleashing this hitherto untapped potential in Namibian agriculture.

Our findings illustrate the significant benefits of inoculation and irrigation in cowpea production. Inoculation improves production by 32% in both land and water scarce scenarios, while maximum irrigation enhances cowpea production by up to 190%. Together with inoculation, cowpea production increases by 251% and 255% in the land and water scarce scenarios. Accordingly, inoculation saves 22.7% of land and 86% of water for the same amount of production. Although irrigation saves 31.3% of land, it imposes additional stress on the country’s scarcest resource. Elasticity analysis shows that a 10% reduction in land requires a 21.5% increase in water demand for irrigation with inoculation and a 29.6% increase in water without inoculation.

2.5.2 Resource efficiency and improved farming managements

Irrigation has a higher positive impact on land intensity, but may impose extra stress on water resources. Given that water is the scarcest resource in Namibia, and that agriculture already accounts for 70% of withdrawals, the implementation of irrigation has to be carefully assessed. In contrast, inoculation has no known negative impact on the environment. In addition, it has lower implementation cost, making it a realistic option for smallholder farmers despite the lower positive impact compared to irrigation. Rasche et al. (2023) found that inoculation has a lower positive impact on cowpea production under more severe future climate change scenarios characterized by hot and dry conditions. Therefore, the study suggests that a good combination of inoculation and irrigation can bring cowpea production to its potential under diverse climate change scenarios.

In Namibia, cowpea is predominantly intercropped with staple crops such as maize, pearl millet and sorghum (NAB & FAO, 2021). Intercropping with cowpea reduces the yield of cowpea itself due to lower biomass. Nonetheless, the nitrogen-rich soil resulting from cowpea cultivation extends the benefits of improved soil quality to intercropped staple crops. As a result, inoculated cowpeas enhance the land and water resource efficiency of cowpea itself, and also enables more efficient resource use in other intercropped crop productions.

2.5.3 Policy application

Inoculation benefits not only cowpea production but also soil quality and other crops through intercropping, with low implementation costs and positive impacts on water use. Smallholder farmers in Namibia struggle with a dry and hot climate and poor infrastructure, such as a lack of water supply systems. We conducted a simple cost-benefit analysis of cowpea inoculants for Namibian smallholder farmers: estimating the cost of cowpea cultivation in one hectare. Namibian Agronomic Board recommends to plant 20-25kg per hectare which we assumed 22.5kg/ha (NAB & FAO, 2021). The rhizobia inoculant that is the only one available in the African market costs US$ 7.46/0.15kg, the recommended amount for one hectare by the producer. In 2021, cowpeas cost around US$ 0.8 per kg (NAB & FAO, 2021). This analysis suggests that the yields only need to increase by 9.75kg per hectare to recover inoculation costs. Considering the attainable cowpea yield is 200kg/ha without inoculation and irrigation, and 2200kg/ha with both inoculation and irrigation, farmers can expect 5-23% increase in yield depending on the adoption of inoculation and irrigation. This combination makes inoculation an effective and affordable choice for smallholder farmers.

We quantify the benefits of inoculation and irrigation for cowpea production in Namibia, but there are inevitable limitations to our work. The assumption of maximum irrigation is not very realistic. However, the study explores the technical potential of different management systems. Therefore, it is still meaningful to assess the impact of irrigation on production and water resources. The biophysical simulations assumed phosphorus and potassium fertilization. As many Namibian smallholders cannot afford fertilizer, the yields may be too optimistic. For computational reasons, the study used crop simulation results from 2009, 1999, 1989. These years did not have any abnormal climatic conditions and the production performed close to the overall average of all years. Production does not consider loss of cowpea. Therefore, the protein production of cowpea may be too optimistic. The purpose of this study is to explore the technical potential of cowpea production. Therefore, the overestimated protein production has to be considered when interpreting the results.

Given that the majority of cowpea in Namibia is intercropped, with extensive positive impacts on soil and other staple crops, it is important to explore the impacts of cowpea on intercropping. This has an additional resource saving effect which is a long-lasting problem in Namibian agriculture.

2.6 Conclusions

Namibia faces major challenges in achieving food security due to climatic and socio-economic constraints. Despite these challenges, agriculture remains central to rural livelihoods, emphasizing the need for innovative strategies to increase productivity and resource efficiency. This study highlights the potential of cowpea, a resilient and adaptable crop, to mitigate water and temperature stress, making it an important staple for smallholder farmers in Namibia.

Our research shows the effectiveness of rhizobial inoculation in enhancing cowpea yields and resource efficiency. Inoculation increases yields by 32% while conserving land and water. It offers a sustainable alternative to large-scale irrigation, which is more productive but would considerably strain Namibia's scarce water resources. This resource benefit makes inoculation an accessible and environmentally friendly strategy that is particularly important in regions where water is heavily prioritized for other uses such as residential, industrial, and livestock farming.

In water-scarce areas, inoculation could significantly improve smallholder farming practices, providing a cost-effective means to enhance yields and address protein food security. Our findings indicate that cowpea production with inoculation could meet the protein needs of Namibia's population using only a fraction of current agricultural resources.

From a policy perspective, promoting inoculation techniques and integrating cowpea into intercropping systems can enhance soil quality and boost the productivity of other staple crops. This aligns with sustainable agricultural practices focused on resource conservation and food security, particularly in regions with limited water availability.

In conclusion, our study provides insights into how resource-efficient practices like inoculation can sustainably enhance agricultural productivity, addressing the complex trade-offs in water-scarce regions of Namibia.

3. Assessing Namibia's Home-Grown School Feeding Program: Can Domestic Agriculture Meet and Sustain its Schoolchildren's Nutritional Needs?

Jihye Jeong [a, b], Kerstin Jantke [b], Livia Rasche [a, c], David Uchezuba [d], Bridget Rieth [e], Salufu Nyambe [e], Rawan Taha [e], Gloria Kamwi [e], Uwe A. Schneider [a, b]

[a] Research Unit Sustainability and Climate Risks, Universität Hamburg, Grindelberg 5, 20144 Hamburg, Germany

[b] Center for Earth System Research and Sustainability (CEN), Universität Hamburg, Grindelberg 5, 20144 Hamburg, Germany

[c] Department of Land Use Economics, Universität Hohenheim, Wollgrasweg 43, 70599 Stuttgart, Germany

[d] Department of Agricultural Science and Agribusiness, Namibia University of Science and Technology, Windhoek, Namibia

[e] United Nations World Food Programme, Windhoek, Namibia

Abstract

Namibia's arid climate and sandy soils limit agricultural potential, making the country heavily dependent on food imports. Seventy percent of the population depends on subsistence farming, and severe food insecurity affects 58% of Namibians, with 17% undernourished. Climate change is expected to exacerbate these challenges, with temperatures projected to rise by 2-6°C and precipitation to decrease by up to 40% by the end of the century. In 2021, Namibia launched the Home-Grown School Feeding Program (HGSFP). This program aims to source school meals from local smallholder farmers, thereby improving nutrition for school children and providing market access for farmers. This study evaluates the technical potential of domestic agriculture to meet the nutritional needs of school children under the HGSFP under today and future climate. Using crop growth simulations and caloric production optimization, we analyzed the six most cultivated crops (maize, sorghum, cowpea, groundnut, pearl millet, and spring wheat) across different climate and management scenarios, including subsistence farming, irrigation, and fertilization. Results indicate that the northern regions of Namibia can fully meet the caloric demands of the HGSFP, with certain areas producing a surplus, while the southern part of the country cannot produce significant amounts of the assessed crops. Protein needs are met under all scenarios at the national scale, with fertilization significantly enhancing production, especially in the far future. We conclude that, with appropriate management practices, particularly fertilization, Namibia can meet the nutritional needs of schoolchildren through the HGSFP. The program has the potential to enhance food security for school children and their families, reduce dependence on imports, and improve the livelihoods of smallholder farmers in Namibia.

Keywords: School feeding programme, climate change, smallholder farmer, Food security

Highlights

- Northern Namibia can supply HGSFP nutritional needs, while the south remains limited.
- Fertilization substantially boosts future agricultural production.
- The HGSFP enhances child nutrition, reduces import reliance, and supports farmers' livelihoods.

3.1 Introduction

Since the 1960s, the World Food Programme (WFP) has been running School Feeding Programmes (SFPs). School meal programs represent one of the most extensive safety nets globally, benefiting 418 million children (World Food Programme, 2023). The White Paper on School Meals and Food Systems emphasizes that these programs can be structured to promote healthier diets, shorten and make more sustainable value chains, and foster more resilient food systems (World Food Programme, 2023). Furthermore, school food procurement policies can promote sustainable farming practices. Connecting smallholder farmers to school meal programs can enhance local agricultural and economic growth, strengthen community resilience, and streamline supply chains. Recently, the agricultural sector has become increasingly involved in supporting school feeding programs due to its potential to bolster local food systems and agricultural production, especially in sub-Saharan Africa. With approximately 400 million schoolchildren receiving meals daily, the global annual investment of US$48 billion in school meal programmes creates a large and predictable market for food (Global Child Nutrition Foundation, 2024; World Food Programme, 2023). Additionally, this investment offers an extraordinary opportunity to transform food systems and diets, and to respond proactively to the global food crisis (World Food Programme, 2023)

SFPs have the potential to benefit multiple major sectors. Many studies have shown positive impacts of school feeding programs on educational outcomes across diverse countries, including other African countries (Awojobi, 2019; Destaw et al., 2022; Jomaa et al., 2011; Maijo, 2018; Metwally et al., 2020; Mideksa et al., 2024; Mostert, 2021; Wall et al., 2022). Previous studies have also confirmed that the school feeding program improves attendance and enrollment among schoolchildren (Awojobi, 2019; Destaw et al., 2022; Mostert, 2021; Zenebe et al., 2018). Verguet et al., (2020) estimated the economic benefit of SPFs in four sectors, including health, education, social protection, and local agriculture, and conducted a cost-benefit analysis. The results suggest that SFPs can generate significant returns in all four sectors, providing at least US$9 in total benefits for every US$1 invested.

Improving the nutritional status of school children can lead to multiple positive chain reactions. Increased agricultural production can improve the livelihoods of SHFs (Gelli et al., 2021). Furthermore, more schoolchildren are likely to attend secondary schools. When schoolchildren are better nourished, each household may benefit from not having to set aside food for them. This frees up food capacity for other vulnerable family members. Therefore, the positive impact of Namibia's HGSFP on nutrition may not stop at schoolchildren but also propagate through individual households.

In 2021, the first pilot phase of the Namibia Home Grown School Feeding Program (HGSFP) took place under the initiative of the WFP Namibia. The Namibia HGSFP aims to channel the demand for school feeding food and services to smallholder farmers and other local stakeholders involved in the school feeding supply chain (Gelli et al., 2016b). The policy aims to provide more nutritious meals for schoolchildren and better livelihoods for smallholder farmers, with increased practical access to markets (Desalegn et al., 2022). During the first pilot phase in 2021, the Namibia HGSFP included 29 schools in 7 regions. Participating schools used their school gardens for agricultural education and also to supply the HGSFP (WFP, 2021).

The food provided to school children differs according to the region and production from local communities. In the first pilot phase of the Namibia HGSFP, schools served various vegetables grown in local communities, including onions, cabbage, beans, and mutete (a type of hibiscus traditionally cultivated in the Kavango and Zambezi regions of Namibia). Cow, sheep, and goat meat provide the protein needs of school children. Where available, fish is often included in the meal plan. Compared to conventional SFP (fortified maize porridge), the new program offers school children a nutritionally more diverse and balanced meal (Galani et al., 2022). However, stable agricultural production must be secured to ensure a continuous supply to the Namibia HGSFP.

Namibian agriculture faces both natural and socio-economic challenges, especially for smallholder farmers. The primarily sandy soils exhibit low amounts of organic carbon and low levels of nutrients, particularly nitrogen (N) (de Blécourt et al., 2019). Together with very low precipitation, only 1 percent of the total land area is regarded as suitable for rain-fed or irrigated arable farming. Food production is also seriously threatened by unpredictable precipitation patterns resulting from climate change (Knox et al., 2012; Nickanor & Kazembe, 2016). A series of droughts over the past decade has caused 330,000 people to be food insecure, particularly in the northwest of the country, and another 447,000 to be moderately food insecure (Integrated Food Security Phase Classification, 2024). Yield reductions of up to 40% are projected across all crop types and sub-regions in Namibia by 2050 (Knox et al., 2012). Therefore, achieving effective and sustainable domestic food production in Namibia depends on the prudent management of its scarce cropland and water resources (Jeong et al. 2025).

In addition to natural challenges, the Bank of Namibia (2017) points out several structural challenges. Given that only 1 percent of land is available for farming, the distribution of land ownership puts smallholder farmers in a difficult position. Approximately 52% of agricultural land is under commercial production, while 48% is allocated to communal land, which supports around 70% of the households. Moreover, Namibian agriculture, particularly among smallholder farmers, is characterized by low adoption of technologies, low input use, and low productivity.

The challenges in the agricultural sector contribute to Namibia's ranking of 78th out of 107 countries in the 2023 Global Hunger Index. According to the FAO dataset (FAO et al., 2022), 58% of Namibians are moderately or severely food insecure, and 17% are undernourished. Given the country's young population, with 22% aged 5-14 years (Namibia Statistics Agency, 2023), addressing these agricultural and food security issues is crucial for ensuring nutritional security during childhood, a factor linked to long-term societal benefits.

The core benefit of Namibia HGSFP is to link local agricultural production with nutritional support for schoolchildren, potentially boosting the local economy and reducing poverty. Given that only a small proportion of Namibia's land is arable, the question arises whether and under what conditions domestic production can fulfill the food demands for Namibia's HGSFP now and under future climatic and socio-economic scenarios. This includes the question of effectively using limited land and water resources, as well as employing different practices such as irrigation and fertilization. As the Namibian HGSFP is currently still in a pilot phase, there is a lack of quantitative evaluation. To address the knowledge gap, this study aims to answer the following questions:

(1) To what extent can Namibia's domestic crop production meet the current nutritional needs of schoolchildren through the HGSFP?
(2) How will the capacity be impacted under future socio-economic and climatic changes?
(3) How much could irrigation and fertilization improve the supply to Namibia's HGSFP?

To address these questions, we integrate crop growth simulations with production optimization.

3.2 Study area

Namibia, located in southwestern Africa, has an extremely arid climate, making it the most vulnerable country in the region. In the medium term (2050-2074), temperatures are projected to rise by 2-4°C, and precipitation is projected to decrease by 40%. In the longer term (2075-2100), temperatures are expected to increase by 4 to 6 °C. Projected climate change poses a threat to food production as floods become more frequent and droughts more likely (Niang et al., 2014; Trisos et al., 2022).

Due to the climate and the old and sandy soil, only 1% of the territory is suitable for agriculture. Most of the arable land is located in the northwest of the country, creating large regional disparities in agricultural production. Domestic food production does not meet the country's national nutritional needs, forcing Namibia to import 60% of its food from other countries, particularly from South Africa (WFP, 2017). Nevertheless, 70% of the population depends on agriculture for their livelihoods, which is predominantly subsistence farming (Odero, 2017). Despite its high dependence on agriculture, the sector contributes only 6% to the country's GDP (Namibia Statistics Agency, 2024).

Namibia is a highly centralized country with many functions concentrated in the capital Windhoek. The vast majority of the country is rural, and most of the rural population are smallholder farmers (SHFs).

Lack of market access has often been a challenge in rural communities (Namibia National Planning Commission, 2018). Products are traded in irregular street markets or are bartered within the community. As a result, SHFs have less motivation to improve productivity and need additional sources s

In order to bring about structural reform, economic transformation, and long-term food security, the present national development plan promotes increasing agricultural productivity. Namibia's Fifth National Development Plan (NDP5) specifically aims to raise food output to a cumulative 30 percent rise over the course of the five-year plan term (NDP5, 2017).

3.3 Data and methods

The study integrates spatially explicit biophysical crop simulations and optimization of production and resource allocation. The biophysical simulations project production opportunities and capacities for Namibia's six most cultivated crops (maize, pearl millet, soft wheat, groundnut, cowpea, and sorghum) under different climate and farm management scenarios. The results of the biophysical simulation inform a production and resource optimization model. This mathematical programming model maximizes caloric food energy output subject to cropland, water resources, and crop mix constraints. Figure 3.1 shows the main components of the modeling framework and their interconnections. Details of each component are given in the following subsections.

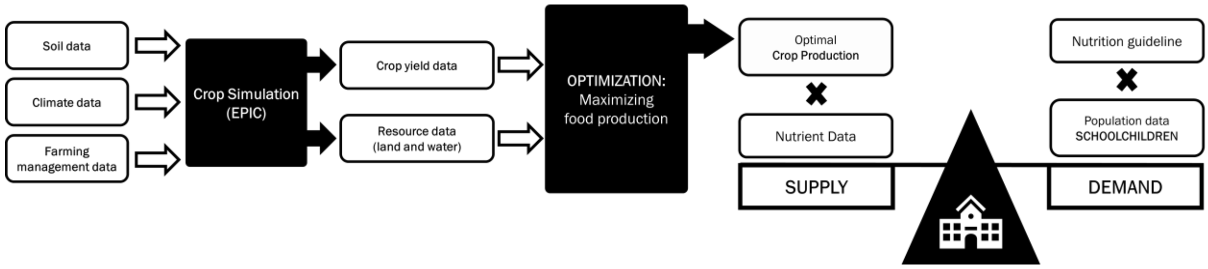

Figure 3.1 Flow of information through the modeling framework. Black boxes represent modeling tools; white boxes depict input and output data.

3.3.1 Data

This study integrates spatial data on weather and climate, soil and water resources, land use and management, and food demand.

We classify the cropland area based on stable biophysical parameters using the Homogeneous Response Ut (HRU) classification system (Skalsky et al., 2012). HRUs are landscape units characterized by homogeneous soil texture, slope, and elevation. Five classes are used to categorize altitude: 1 (0 - 300m), 2 (300 - 600m), 3 (600 - 1100m), 4 (1100 - 2500m), and 5 (> 2500m). The seven classes (degrees) of slope are as follows: 1 (0 - 3), 2 (3 - 6), 3 (6 - 10), 4 (10 - 15), 5 (15 - 30), 6 (30 - 50), and 7 (> 45). There are five different types of soil composition: 1 (sandy), 2 (loamy), 3 (clay), 4 (stony), and 5 (peat). Eight distinct HRUs make up Namibia's geography, seven of which include cropland.

We used climate data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) database with a spatial resolution of 0.5°. The ISIMIP3b data are based on the output of phase 6 of the Coupled Model Intercomparison Project (Eyring et al., 2016) and include the five general circulation models GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL. The projections of future climate conditions were driven by the three combinations ssp126, ssp370, and ssp585 of relative concentration pathway

(RCP) and shared socio-economic pathway (SSP) scenarios. We used the bias-corrected climate data provided in ISIMIP3BASD v2.5 (Lange, 2019).

Land use data are derived from the Copernicus Global Land Service (CGLS) (Buchhorn et al., 2020). It provides a global land cover product at a spatial resolution of 100m for the reference years 2015 to 2019.

Schoolchildren aged 5-14 years make up 22% of the total population. We calculated the caloric demand of school children by multiplying the population by the caloric energy requirement from FAO et al. (2001), with respect to their sex and age segments. As a result, the total caloric demand of school children accounts for 19% of Namibia's entire population's total caloric demand. Therefore, we assume in our model that 19% of Namibia's cropland area and 19% of its water resources are utilized for the HGSFP.

3.3.2 Biophysical simulation of crop production

Subsistence fertilization is based on a survey of Namibian subsistence farmers (Rasche et al. 2025). In this scenario, maize is fertilized with 200 kg/ha of manure per year, and pearl millet is fertilized with 50 kg/ha of NPK fertilizer. The other crops are not fertilized at all. Improved fertilization assumes a maximum of 250 kg of nitrogen per hectare and year, with multiple applications of 50 kg each, triggered by a nutrient stress value of 0.7 (only 70% of potential daily growth can be realized due to nitrogen stress) and a minimum interval of 30 days between consecutive applications. Irrigation options include rainfed management (no irrigation) and a rule-based irrigation system with an irrigation maximum of 1000 mm per year, 50 to 150 mm at a time, and intervals of at least 10 days between two consecutive irrigation applications.

3.3.3 Resource optimization for food production

We design and implement a spatially and temporally resolved mathematical programming model that maximizes caloric energy production. The model optimizes the allocation of crops in each HRU. Production is restricted by cropland and water resource limits.

Equations:

Maximize $$F_{t,r,m} = \sum_{c} \left(y_{t,r,c,m} \cdot C_{t,r,c,m} \right) \qquad \forall t,r,m \qquad [3.1]$$

subject to:

$$\sum_{c,m} \left(a_{t,r,c,m,i} \cdot C_{r,c,m,i} \right) \leq b_{t,r,i}^{\max} \qquad \forall t,r,i \qquad [3.2]$$

$$\sum_{m} C_{t,r,c,m} \leq \sum_{o} \left(h_{c,o} \cdot M_{t,r,o} \right) \qquad \forall t,r,c \qquad [3.3]$$

$$\sum_{m} C_{t,r,c,m} \leq s_c \cdot \sum_{\tilde{c},m} C_{t,r,\tilde{c},m} \qquad \forall t,r,c \qquad [3.4]$$

The objective equation [3.1] maximizes the supply of food from domestic crop production measured in caloric energy. Constraints [2.2] limit the land and water resources used for crop production to available endowments in each HRU. The crop mix constraints [3.3] restrict regional crop mixes to a combination of historically observed crop areas based on FAOSTAT. For crops where historical areas are not reported (cowpeas), crop shares are restricted to agronomically sensible maximum values [3.4].

All equations contain variables, parameters and indexes, which are defined as follows:

Indexes:

- The index t identifies the simulation years, ranging from 2020 to 2100.
- The index r distinguishes 737 homogeneous response units for crop production.
- The index c contains the simulated crops: maize, sorghum, cowpea, groundnut, pearl millet, and spring wheat.
- The index m depicts four alternative farming practices, including subsistence farming, fertilization, irrigation, and a combination of fertilization and irrigation.
- The index i includes the agricultural resources cropland and water
- The index o spans annual observations ranging from 1960 to 2020.

Variables:

- F represents crop production in kcal.
- C indicates the area in each HRU allocated to a specific crop, and farming practice in 1000 ha.

Data parameters:

- y denotes crop yields measured in caloric energy units.
- a denotes the resource requirements for crop production activities
- b contains endowments for cropland and water resources.

3.3.4 Scenarios

The current demand for Namibia's HGSFP considers one meal per school day (i.e., 198 days in 2020), the number of schoolchildren aged 5-14 (535,312 in year 2021) (Namibia Statistics Agency, 2023), and the nutrition guidelines suggested by the World Health Organization and Food and Agricultural Organization (FAO et al., 2001; FAO & WHO, 2004) (Table 3.1).

Table 3.1 Nutritional guidelines of school children according to their age and gender suggested by FAO et al., 2001; FAO & WHO, 2004

Age Cohort		5-9		10-14	
Sex		Female	Male	Female	Male
	Energy [kcal/day]	1554	1692	2212.5	2450
	Protein [g/day]	21.2	21.5	41	40.5
	Carbohydrate [g/day]	237.8	260.5	327.7	367.8
	Fat [g/day]	57.5	62.7	81.9	90.7
Minerals	Calcium [mg/day]	650	650	1300	1300
	Magnesium [mg/day]	88	88	220	230
	Zinc [mg/day]	5.2	5.2	7.2	8.6
	Iron [mg/day]	15.2	15.2	28	29.2
	Selenium [µg/day]	21	21	26	32
Vitamins	Vitamin A [µg/day]	475	475	600	600
	Vitamin D [µg/day]	5	5	5	5
	Vitamin E [mg/day]	6	6	7.5	10
	Vitamin K [µg/day]	22.5	22.5	45	45
	Vitamin C [mg/day]	32.5	32.5	40	40
	Vitamin B12 [µg/day]	1.5	1.5	2.4	2.4
	Folate [µg/day]	250	250	400	400
	Thiamin [mg/day]	0.75	0.75	1.1	1.2
	Riboflavin [mg/day]	0.75	0.75	1	1.3
	Niacin [mg/day]	10	10	16	16
	Vitamin B6 [mg/day]	0.8	0.8	1.2	1.3

Future demand projections are calculated relative to current food demand for alternative Shared Socio-economic Pathways (SSPs) (Riahi et al., 2017) (Figure 3.2). Projected demand shifts are proportional to population growth and Engel curve-based translations of income developments (see Appendix S1 section 2.2 in Habel et al., 2019). We explicitly consider only the contribution to crop products for food supply.

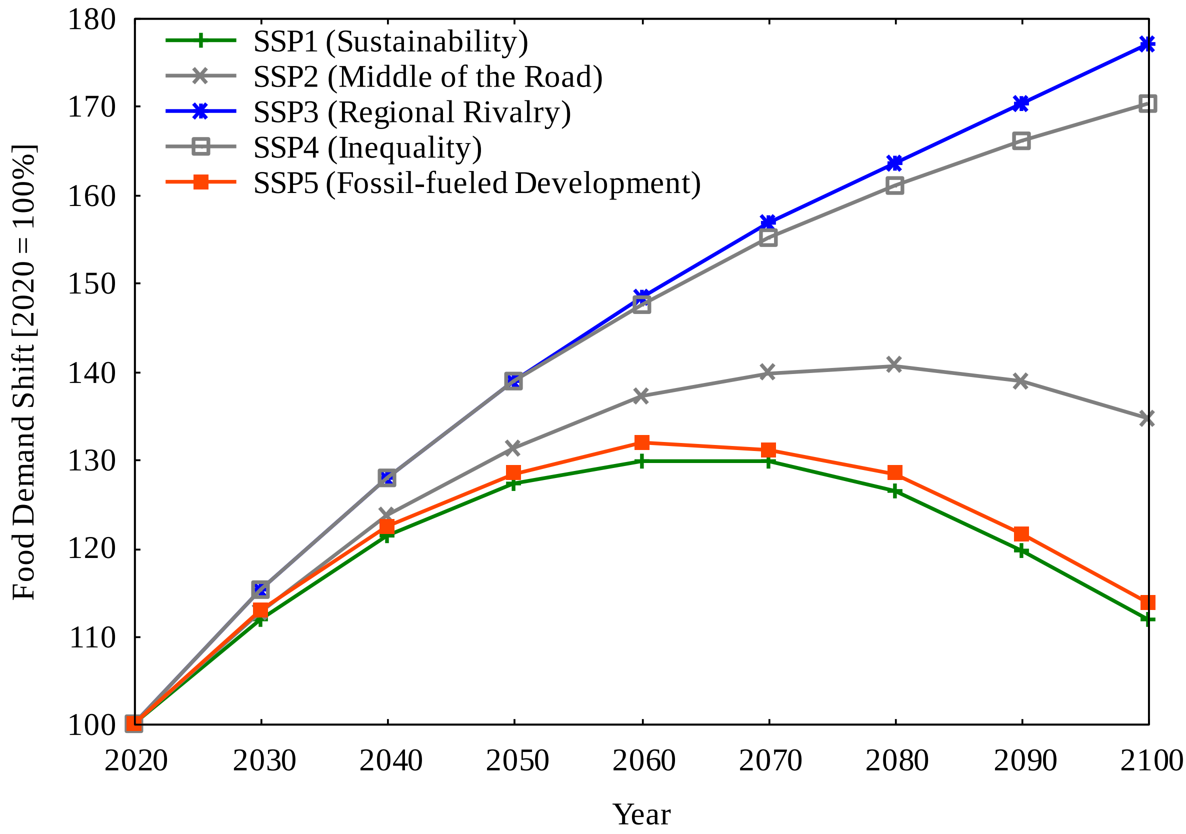

Figure 3.2 Food demand shifts for Namibia considering population and income growth projections (Riahi et al., 2017). for five shared socio-economic pathways (SSP). Demand increases proportionally to population growth. The impact of income growth on food demand is computed using statistically estimated Engel curves (see Appendix S1, Section 2.2 in Habel et al., 2019).

To explore the feasibility of Namibia's HGSFP, future climate and socio-economic scenarios are considered together with four different farming management options as production scenarios (Figure 3.3).

To project future production opportunities, we considered three future climate and socio-economic scenarios defined in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (IPCC, 2023). The SSPs are combined with CMIP Phase 6. In this study, we considered SSP1-2.6 (SSP126), SSP3-7.0 (SSP370), and SSP5-8.5 (SSP585). The reference situation is defined by the average crop simulation results between 2020 – 2025 under SSP126.

Farm management options span subsistence farming and alternative levels of fertilization and irrigation. Different combinations of fertilization and irrigation scenarios are considered as farming management scenarios; SS: subsistence farming (rainfed + subsistence fertilization), IR: irrigation, FR: improved fertilization, IR+FR: irrigation + improved fertilization.

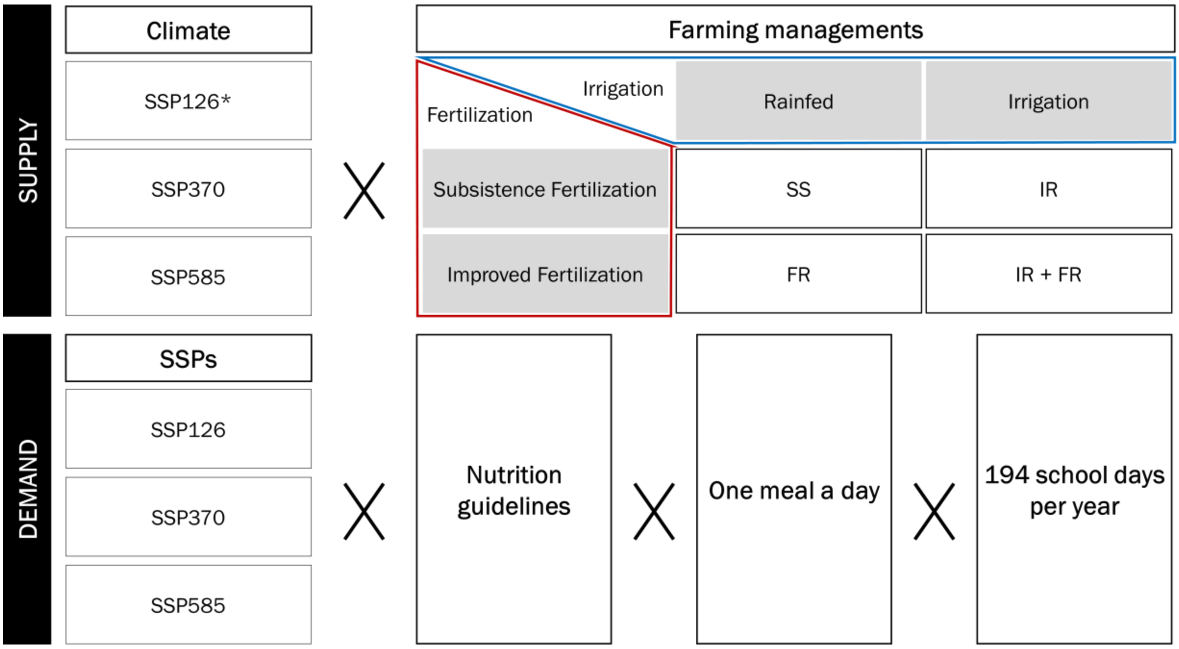

Figure 3.3 Overview of scenarios. (* Current scenario refers to average simulation result in 2020-2025, under SSP126)

3.4 Results

3.4.1 Current production in relative to demand

The concentration of agricultural production in the north results in regional disparity of access to agricultural production (Figure 4). Agricultural production in the regions Ohangwena, Omusati, Oshana, and Oshikoto can fully provide the current regional caloric needs of Namibia's HGSFP. In particular, Oshana and Oshikoto produce more than twice the regional caloric demand. The regions Hardap and Karas, on the other hand, have very low agricultural production due to their extremely arid environment. Fortunately, they are the least populated regions of Namibia.

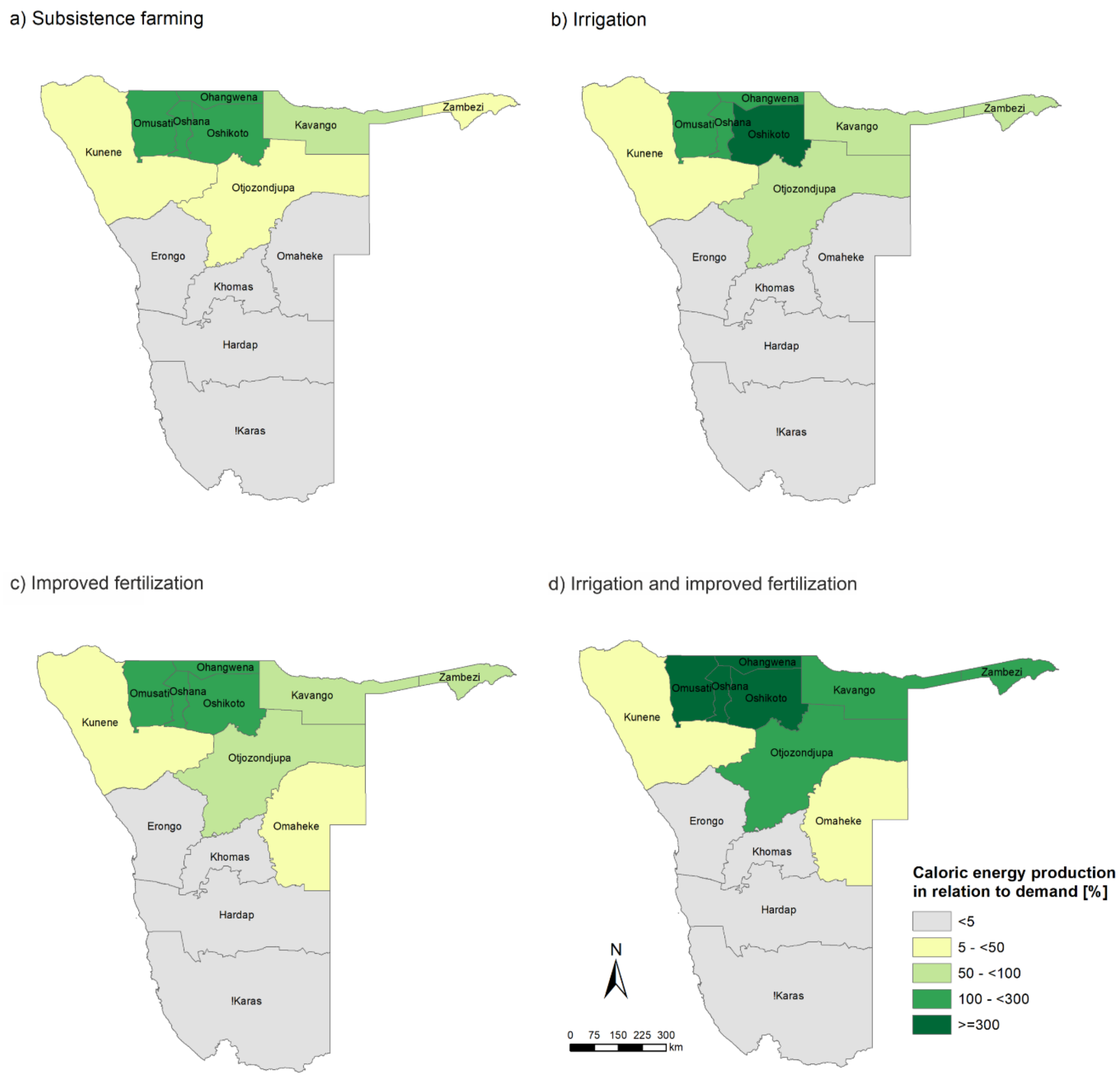

Figure 3.4 Regional food security potential under reference conditions (2020). The values show the ratio of caloric energy produced within a region relative to its current demand for alternative farm management scenarios (panels a-d).

3.4.2 Domestic supply potentials for crop-based macronutrients in the near and far future

Caloric energy and macronutrient supply potentials are simulated in different time period (Present: 2020 – 2025, Near future: 2030 – 2060, Far future: 2070 – 2100) under different climate and socio-economic scenarios (SSP126, SSP370, and SSP585). In the absence of fertilization, there are fairly small productivity benefits from irrigation. On the other hand, improved fertilization increases macronutrient supply substantially, with and without irrigation. Whereas fertilization triples the production in the near future, nutrient production benefits from irrigation by 8-10% in the near future. In the far future, the benefits of fertilization are even higher. Production with fertilization is projected to be up to 5 times higher than that of subsistence farming. In contrast, the benefit of irrigation is lower by 3-4% in the far future. In comparison to irrigation, fertilization has a higher impact on adaptation. When both irrigation and fertilization are adopted, there is a synergy, so that the increase in production is higher than the sum of the individual impacts when adopted separately (Figure 3.5).

Fertilization affects the supply of protein less than the supply of other macronutrients. However, protein supply varies more across climate scenarios. While food energy and fat supply decreases by at most 10%, protein supply decreases by 15.5% under SSP585 compared to SSP126.

Decreases in domestic macronutrient supply are projected under all climate scenarios in the far future (2070-2100), specifically for the management scenarios without improved fertilization (SS and IR). Protein supply is projected to decrease by 47% on average across all SSP scenarios. This can be explained by a decreased production of protein-rich crops (groundnuts and cowpeas). Under FT, the domestic macronutrient supply is estimated to increase by 3-4% in the far future compared to the near future.

Subsistence farming will be least affected by future climate. In some cases (energy: SSP585-SS, fat: SSP370-SS), production even increases by 2-3.3%. It should be noted that subsistence agricultural systems have the lowest baseline yields. Management with improved fertilization has higher baseline yields and, therefore, is more affected by climate scenarios. Overall, projected differences in production across SSPs are smaller than those resulting from changes in farming practices.

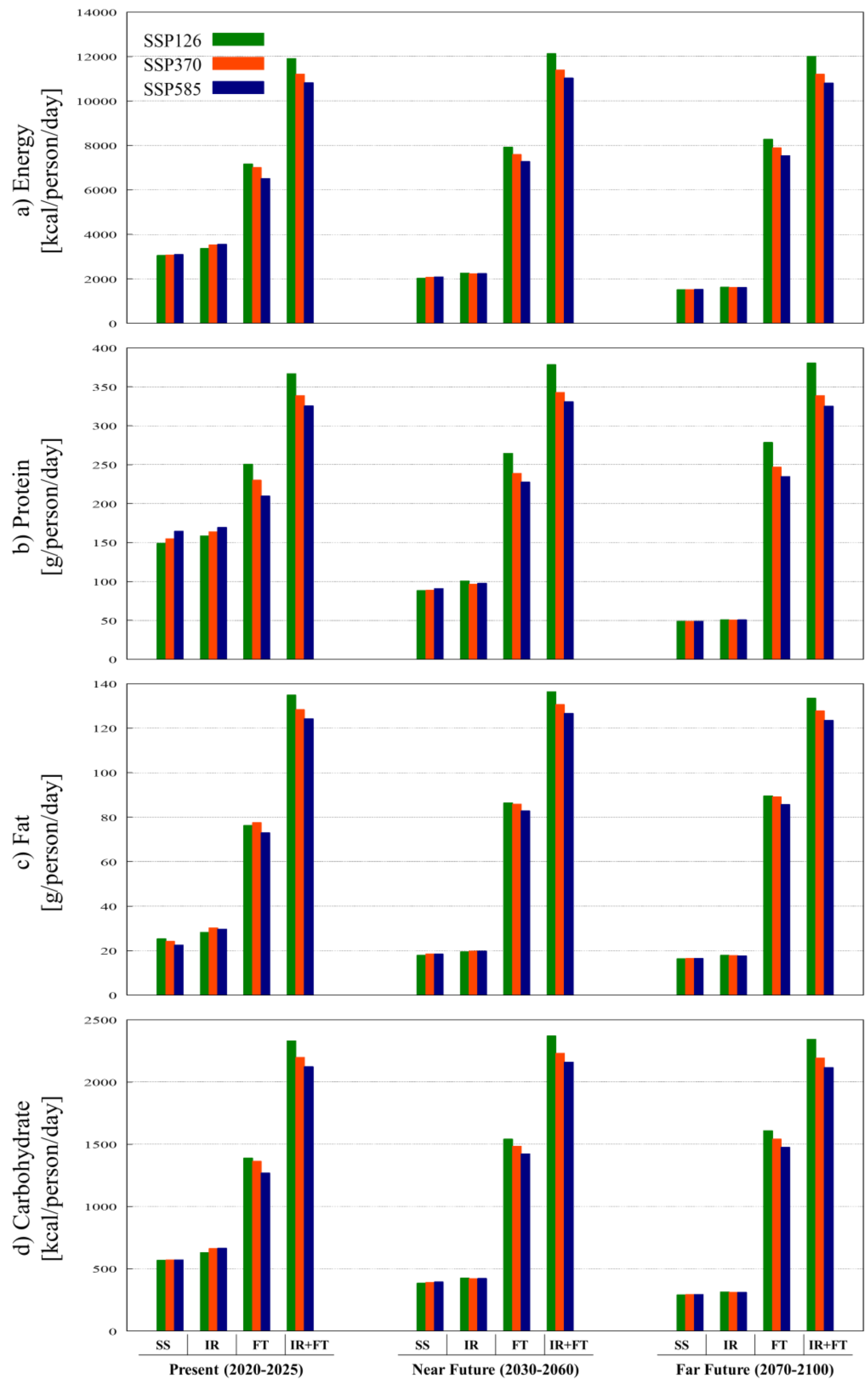

Figure 3.5 Present and future domestic supply potentials for crop-based caloric energy (panel a) and macronutrients (protein, fat, and carbohydrates, panels b-d) under alternative farm management (SS: subsistence farming, IR: irrigation, FT: improved fertilization, and IR+FT: irrigation and improved fertilization) and climate scenarios (SSP126, SSP370, and SSP585). Present refers to the average potentials between 2020 – 2025. Near and far futures refer to the average potentials between 2030 – 2060 and 2070 – 2100, respectively.

3.4.3 Production sufficiency to school children's nutritional demand

With improved fertilization, domestic agricultural production can meet the caloric needs of schoolchildren. However, without fertilization, food production will remain at 32-36% of their caloric needs in the near future and 15-24% in the far future. The combination of improved irrigation and fertilization yields a surplus of up to 39% in the near future and 49% in the far future. In both cases, production under SSP126 satisfies the nutrition needs best of the three SSPs.

In the near future, Namibian agriculture could supply sufficient protein for its HGSFP under all considered climate and management scenarios. Cowpea contributes to a high protein supply. In the far future, the domestic protein supply will be insufficient without improved fertilization. With improved fertilization, the production increases 3 to 4.6 times. While fertilization improves production under all assessed conditions, it provides the highest benefits in the far future across all nutrients.

Fat is the least produced of all nutrients. Crop products do not have a high fat content; therefore, it is mostly provided by animal products. Alongside crop farming, livestock farming plays a major role in Namibian agriculture. Particularly in regions with little or no arable land, livestock farming is prevalent, and naturally, more animal products are consumed. With the exception of fat, Namibian crops are able to meet the nutritional requirements of its HGSFP for all nutrients.

		SS			IR			FT			IR+FT		
		SSP126	SSP370	SSP585	SSP126	SSP370	SSP585	SSP126	SSP370	SSP585	SSP126	SSP370	SSP585
Energy	PR	82	75	74	108	114	119	118	113	110	280	264	261
	NF	34	32	35	38	34	38	133	116	125	190	162	175
	FF	26	18	26	28	19	27	142	95	132	194	126	178
Protein	PR	308	280	272	387	420	439	364	274	241	570	527	504
	NF	101	94	106	110	101	114	293	231	247	380	315	338
	FF	57	40	57	59	41	60	327	195	268	390	252	350
Mineral	PR	211	192	187	265	288	300	256	200	180	427	395	381
	NF	70	65	73	77	71	79	215	173	185	288	240	258
	FF	41	28	41	43	29	43	239	145	200	295	191	266
Carbohydrate	PR	99	91	89	131	138	143	147	144	141	362	340	338
	NF	43	39	44	47	43	47	171	150	161	246	211	228
	FF	33	23	33	36	24	35	181	122	170	251	164	230
Vitamin	PR	125	113	111	156	170	178	143	102	88	202	186	175
	NF	39	37	41	43	40	45	107	81	87	133	109	117
	FF	21	15	21	21	15	22	121	70	95	137	88	122
Fat	PR	14	13	13	20	21	21	26	31	33	85	80	81
	NF	8	7	8	9	8	8	38	36	38	58	50	54
	FF	7	5	7	8	5	8	39	28	40	59	38	54

[%]
Min.
100
Max.

Figure 3.6 Present and future nutrient production in relative to future demand [%] under four farming practices (SS: subsistence farming, IR: irrigation, FT: improved fertilization, IR+FT: irrigation and fertilization) and three future climate and socio-economic scenarios (SSP126, SSP370, and SSP585). Caloric energy, protein, fat, carbohydrate, mineral, and vitamin are considered as nutrient categories. (PR: Present (2020-2050), NF: Near future (2030-2060), FF: Far future (2070-2100))

3.5 Discussion

3.5.1 Prospect of Namibia HGSFP

The nutritional needs of schoolchildren in Namibia are currently far from being met. To address this deficiency and to provide more incentives to attend school regularly, Namibia has initiated the HGSFP in 2021. As a first step, this study assessed the technical potential of Namibian agriculture as a provider of the Namibian HGSFP. In addition, estimating future food and nutrition demand of school children is essential for the investment in the policy and its application.

Our results suggest that Namibian crop production has good potential to meet the nutritional demands of school children, with differences in nutrient levels, but only if adequate farming management practices are adopted. In particular, protein demand can already be met by subsistence farming under all assessed climate scenarios. Fertilization increases the degree of food self-sufficiency the most, regardless of the climate scenarios considered.

However, the overall outlook for agriculture in Namibia in the near future is not positive. According to Namibia Statistics Agency (2024), the agricultural sector is expected to shrink by 5.1% compared to the previous year's growth of 2.6% in 2025, primarily due to the multiple episodes of dry spells and erratic rainfalls in the past decade (2014, 2016, 2019, 2021 and 2024). The outlook for agriculture remains subdued, as the recovery of the agricultural sector from the drought is projected to be prolonged (Cottrell et al., 2019; He et al., 2019; Orimoloye, 2022). Considering that over 70% of Namibia's population relies on agriculture for their livelihoods, repetitive climate induced episodes threatens the country's welfare significantly. Thus, adequate adoption of farming practices is crucial for domestic agriculture to supply the nutrition policy.

3.5.2 Huge regional disparity

A key feature that distinguishes Namibia HGSFP from other nutrition policies is its high level of decentralization. Each school is responsible for food procurement and finding cooks, and supply depends solely on the community's production. As a result, many of the disadvantages associated with a centralized organization are avoided, such as delays in procurement and uniform implementation across diverse cultures and regions. However, the decentralized organization of Namibia HGSFP also means that each regional implementation is shaped by the natural and socio-economic conditions of the region.

The analysis reveals significant regional disparities in Namibia's agricultural production capacity and its implications for national food security. The northern regions, Ohangwena, Omusati, Oshana, and Oshikoto, demonstrate notably higher agricultural productivity, with these regions capable of fully meeting their caloric needs. More specifically, Oshana and Oshikoto produce more than twice the regional demand. This concentration of agricultural production in the northern regions positions them as potential surplus zones, integral to supporting national food security initiatives through interregional trades.

In contrast, the southern regions, particularly Hardap and Karas, show minimal crop production due to their extremely arid conditions, not to mention that livestock farming consists agricultural landscape in the south. While these areas are sparsely populated, their inability to meet even a fraction of their nutritional needs emphasizes the structural and geographical imbalances in access to agricultural resources. These disparities between the north and south suggest a critical issue of unequal food production capacity within the country, which may have long-term implications for both food security and regional development.

Martin (2017) stresses leveraging opportunities presented by trade is essential for progress, as trade can generate income gains both within and between countries, especially given differences in resources and economic structures. When assessing the impact of trade reforms on nutrition, it is crucial to consider both income and substitution effects. For example, a rise in food prices that reduces the real incomes of vulnerable groups, such as wage workers, can lead to significant changes in consumption patterns, potentially worsening nutritional outcomes. These dynamics are also relevant when evaluating trade policies including Namibia HGSFP that encompasses schoolchildren's nutrition and economic livelihood of smallholder farmers.

In conclusion, while Namibia's northern regions have the potential to serve as surplus producers of food, addressing regional disparities requires a multi-faceted approach that combines domestic agricultural development with enhanced regional cooperation and international trade. Without targeted interventions and broader policy frameworks that support regional exchanges, the gaps in agricultural productivity and nutritional access are likely to persist, undermining national food security and equity.

3.5.3 Stronger impacts of management practices than climate scenarios

Our results show that management adaptations can have a greater impact on yields than projected climate change. Adoption of fertilization compensates for the negative impact associated with future climate scenarios on domestic nutritional sufficiency. In the case of energy, fertilization enables higher sufficiency than under the baseline scenario (present, SSP126, and subsistence farming) despite stronger climate change. With the addition of irrigation, protein sufficiency can meet or even exceed baseline levels, despite stronger climate change impacts.

Fertilization has the advantage that it does not put extra stress on the country's scarcest resource, water. However, unrestricted use of fertilizer can have other negative impacts on the farmers livelihood and environment. Fertilizer is one the major reason for credit in communal agriculture in Namibia, putting financial burden on smallholder farmers (Fortunato & Enciso, 2023). The second disadvantage is that overuse of fertilizer may lead to adverse environmental consequences. Nonetheless, Namibia (14.9kg/ha in 2022) consumes significantly less fertilizer compared to the global average (134.2kg/ha in 2022) (FAO, 2024). Yet, a possible introduction of fertilizers has to be carefully assessed in advance.

In summary, Namibian farmers have the opportunity to build resilience to future changes. Under all examined SSP scenarios, adopting different farming practices can sustain the domestic supply to meet Namibia's HGSFP demand.

3.5.4 Strong performance in protein production

Of all the nutrients, protein has a particularly high potential to be produced in sufficient quantities. In an arid climate, legumes, especially cowpea, show robust performance (Rasche et al., 2023). According to FAOSTAT, two-thirds of the protein intake of Namibians is plant-based. Considering that the poorer population has limited access to meat products, plant-based protein has socio-economic significance in the Namibians' diet. We have only considered crop products in the study; however, livestock farming is another major pillar of Namibian agriculture, providing the other one-third of protein intake. Together with animal-based protein, our study suggests that Namibia has significant potential for protein production.

In contrast, fat production, being the most limited of all nutrients in plant-based food, underscores the critical role of animal products in providing essential nutrients. Livestock farming is particularly important in arid regions, where crop-based production is limited. However, while livestock farming can offset some of the shortfalls in fat supply, it does not fully resolve the nutritional gaps in these regions, and access to animal products remains unequal across different regions.

The production of protein emerges as particularly sensitive to climate change and management practices. While the supply of protein meets national needs in the near future under most climate scenarios, protein availability is projected to decline substantially in the far future, especially under scenarios without improved fertilization. This is largely due to the reduced production of key protein-rich crops such as cowpeas and groundnuts. Fertilization, while improving protein production, does so to a lesser extent than it does for other macronutrients. This highlights the vulnerability of certain nutritional components to climate variability, which may disproportionately affect regions that are already disadvantaged in terms of agricultural input access.

3.5.5 Policy suggestions

The HGSFP policy may have a positive impact on the country's food security and local livelihoods. Although the country cannot be fully self-sufficient, the policy reduces its dependency on imports from neighboring countries, making Namibia more resilient against abrupt changes in the external food market. The policy also improves the livelihoods of smallholder farmers in rural communities. With possible access to a nearby market, the policy is expected to increase the motivation of smallholder farmers to improve their farming practices for higher and more efficient production.

3.5.6 Limitations

We have estimated the potential of domestic agriculture in Namibia to contribute to a new school feeding program; however, our analysis has several limitations. First, the nutritional information is based on the raw product. Since most agricultural products are processed before consumption, and parts are lost, we may overestimate the potential. However, the study aims to analyze the technical potential of Namibian agriculture as a major supplier of Namibia's HGSFP. Moreover, diverse processes are carried out in different regions and households. Thus, we decided to use the nutritional value of the raw products.

Second, we assume that 19% of Namibia's agricultural area is used for the production of supplies for the HGSFP. While we aim to analyze the technical potential of Namibian agriculture as a major supplier of the HGSFP, we likely overestimate the true potential. Considering practical components such as smallholder farmers' willingness to participate, the organization of each school, and funding for infrastructure, a realistic estimate of potential supply might look different.

Third, we considered only the six most cultivated crops in Namibia in the crop simulation. These happened to be mainly cereals and legumes. While vitamins and minerals are abundant in other vegetables which are not considered in the study, vitamin and mineral production might have been underestimated by only considering cereals and legumes. The same applies to fat. Cereals and legumes do not contain much fat and the analysis does not consider any oil or animal products.

Extreme climate events have a significant impact on agricultural production (Vogel et al., 2019; Zhu & Troy, 2018). Namibia, being one of the most arid countries, has experienced frequent and severe droughts, particularly over the last decade (X. Liu et al., 2021). Current biophysical models often fail to adequately capture the effects extreme events, partly due to limitations in the quality of climate projections. Harrison et al (2016) suggest that forecasting extreme climatic events using global circulation models has limitations, which makes the use of this data in agricultural modeling prone to errors. Therefore, the impacts of future climate scenarios on crop production may be underestimated.

3.6 Conclusion

This study provides a comprehensive assessment of Namibia's domestic crop production capacity to meet the nutritional needs of schoolchildren through the Namibia HGSFP, both currently and under future climatic and socio-economic scenarios. Integrating spatially explicit crop growth simulations with a resource optimization model, the analysis demonstrates that Namibia's limited arable land resources, poor soil quality, and high climate vulnerability challenge the sustainability and scalability of local food supply for school feeding initiatives, that challenge the sustainability and scalability of local food supply for school feeding initiatives.

Under current conditions, domestic crop production cannot fully meet the caloric requirements of the HGSFP. Given the projected impacts of climate change, including rising temperatures and declining precipitation, future scenarios indicate that these challenges will intensify, with substantial yield reductions estimated across all major crops.

However, improved fertilization emerged as the most impactful management practice, significantly enhancing agricultural yields and nutritional sufficiency, even under severe climate change. Irrigation, on the other hand, improved potential yields less and could only be used to a small extent anyway due to the scarcity of Namibia's water resources. Importantly, management interventions influenced production more than projected changes in climate, indicating that agricultural adaptation – driven by policy measures and investments in inputs – could offset the adverse climate change impacts and enhance the resilience of agricultural systems.

The Namibia HGSFP offers opportunities to strengthen local food systems, support the livelihoods of smallholder farmers, and improve the nutritional status of Namibian schoolchildren. Linking school feeding demand to local agricultural production can generate multiple benefits which increase the resilience of rural communities.

4. Improved maize porridge for school feeding programme: nutritional and socioeconomic benefits of inoculated cowpea

Jihye Jeong [a, b], Kerstin Jantke [b], Livia Rasche [a, c], David Uchezuba [d], Bridget Rieth [e], Salufu Nyambe [e], Rawan Taha [e], Gloria Kamwi [e], Barbara Reinhold-Hurek [f], Uwe A. Schneider [a, b]

[a] Research Unit Sustainability and Climate Risks, Universität Hamburg, Grindelberg 5, 20144 Hamburg, Germany

[b] Center for Earth System Research and Sustainability (CEN), Universität Hamburg, Grindelberg 5, 20144 Hamburg, Germany

[c] Department of Land Use Economics, Universität Hohenheim, Wollgrasweg 43, 70599 Stuttgart, Germany

[d] Department of Agricultural Science and Agribusiness, Namibia University of Science and Technology, Windhoek, Namibia

[e] United Nations World Food Programme, Windhoek, Namibia

[f] Department of Microbe-Plant Interactions, CBIB Center for Biomolecular Interactions Bremen, Faculty of Biology and Chemistry, Universität Bremen, PO. Box 330440, 28334 Bremen, Germany

Abstract

Food insecurity and malnutrition remain persistent challenges for children in sub-Saharan Africa, including Namibia, where the School Feeding Programme (NSFP) provides a critical daily fortified maize porridge meal. However, reliance on imported soybean for protein fortification raises concerns about sustainability and cost. This study explores the potential of locally produced cowpea, a nutrient-dense, drought-tolerant legume, as a sustainable alternative to improve the nutritional quality of school meals and support local agriculture. Using a biophysical crop simulation integrated with spatial optimization and cost-effectiveness analysis, cowpea production scenarios were assessed under multiple climate pathways and farm management practices, including rhizobial inoculation, irrigation, and phosphorus fertilization. Results reveal that traditional subsistence farming cannot meet escalating demand from NSFP, particularly under moderate to high emission scenarios. However, moderate interventions such as inoculation and fertilization achieve significant yield gains at relatively low cost, especially under low-emission futures, making them attractive options for smallholder farmers. Combined irrigation and fertilization further increase yields but diminish cost-efficiency. Cowpea fortification improves protein quality and micronutrient density in maize porridge while preserving cultural acceptability at substitution levels up to 30%. Linking cowpea production to NSFP creates stable market opportunities for smallholder farmers, fostering rural livelihoods, reducing import dependence, and enhancing food system resilience. The integration of affordable, climate-smart agronomic practices with institutional procurement strategies is essential to scale cowpea fortification effectively. This work demonstrates the promise of cowpea as a climate-resilient, nutritionally impactful crop to strengthen child nutrition and sustainable food systems in Namibia and similar semi-arid regions.

Keywords: Food security, Cowpea, School feeding programme, Smallholder farmers

Highlights

- Cowpea is a sustainable, nutrient-rich alternative to imported soybean in school meals.
- Low-cost interventions significantly increase cowpea yields.
- Cowpea integration strengthens nutrition, farmer livelihoods, and food system resilience.

4.1 Introduction

Food security in sub-Saharan Africa (SSA) remains a pressing challenge, with millions of households facing chronic undernutrition, micronutrient deficiencies, and limited dietary diversity (FAO et al., 2023). Despite recent improvements in agricultural productivity, food security continues to be threatened by population growth, climate variability, low agricultural yields, and economic instability (Headey & Jayne, 2014). Children are particularly vulnerable to these challenges, as inadequate diets compromise not only their immediate health but also their long-term educational attainment and productivity (UNICEF, 2021).

Under future changes, food security in SSA is expected to face additional challenges. Climate change, soil degradation, and water scarcity are projected to exacerbate yield gaps in staple crops (Serdeczny et al., 2017). At the same time, rapid urbanization and demographic growth will intensify demand for affordable, nutritious foods, further straining food systems (Barrett, 2021). These factors put the importance on social protection measures that can both alleviate nutritional deficits and strengthen the resilience of local food systems.

4.1.1 School feeding programme

Since the World Food Programme (WFP) initiated School Feeding Programmes (SFPs) in the 1960s, SFPs provide one of the most extensive safety nets globally (World Food Programme, 2025). By reaching approximately 466 million children globally, SFPs address the intersection of education, health, and food security (Global Child Nutrition Foundation, 2024). Likewise, in SSA, SFPs have emerged as one of the most widely implemented social protection nets, providing a source of nutrition for schoolchildren while stimulating local agricultural markets (World Food Programme [WFP], 2023).

SFPs have potential benefits across multiple major sectors. Previous studies confirm that the school feeding program improves attendance and enrolment of schoolchildren (Awojobi, 2019; Destaw et al., 2022; Mostert, 2021; Zenebe et al., 2018). Many studies have shown positive impacts of school feeding program on educational outcome across diverse countries including other African countries (Awojobi, 2019; Destaw et al., 2022; Jomaa et al., 2011; Maijo, 2018; Metwally et al., 2020; Mideksa et al., 2024; Mostert, 2021; Wall et al., 2022). Verguet et al., (2020) estimated economic benefit of SPFs in four sectors including health, education, social protection and local agriculture and conducted a cost-benefit analysis. The results suggest that SFPs can generate significant returns in all four sectors, providing at least US$7 in total benefits for every US$1 invested.

In addition to educational benefit, SFPs plays a significant role in improving local food systems. The White Paper on School Meals and Food Systems demonstrates that these programs encourage healthier diets, create shorter and more sustainable value chains, and foster more resilient food systems (World Food Programme, 2023). Furthermore, school food procurement policies can promote sustainable farming practices. Connecting smallholder farmers to school meal programs can enhance local agricultural and economic growth, strengthen community resilience, and streamline supply chains. The global annual investment of US$48 billion in SFPs creates a huge and predictable market for food (Global Child Nutrition Foundation, 2024; World Food Programme, 2023).

4.1.2 Maize blend and its potential improvement

In many SSA countries, including Namibia, school meals are typically provided in the form of fortified maize porridge (Namibia Ministry of Education, 2013). Maize porridge is widely consumed for its affordability, familiarity, and cultural acceptance. However, traditional maize porridge is limited by low protein content and poor amino acid balance, especially in lysine and tryptophan, which are essential for child growth and cognitive development. (Namibia Ministry of Education, 2013).

The current Namibian School Feeding Programme (NSFP) maize blend ration (125 grams/child/day) provides about 478 kcal, 15% protein and 6% of fat. The standard food ration is a meal of hot porridge made from a fortified maize blend consisting of 63% maize meal and a protein blend (soybean 25%, sugar 10.8%, salt 1.2%). This meets approximately 1/3 of the Namibian schoolchildren's daily nutrient requirement. Currently, Namibia does not produce soybean nor sugar. Hence, the majority of protein sources in maize blend is imported (Namibia Ministry of Education, 2012).

Several studies have explored strategies to improve the nutritional quality and sensory properties of maize-based porridges by incorporating legumes and other nutrient-dense crops. Govender et al., 2022 showed that adding Bambara groundnut to provitamin A-biofortified maize porridge increased protein, mineral content, and physical quality without compromising consumer acceptance. Likewise, Oladeji et al., 2016 confirmed that legume-fortified porridges were both nutritionally superior and generally well-received. Additional approaches include technological processing and non-legume fortification. Rombo et al., 2001 demonstrated that irradiation and cooking of maize–kidney bean flours improved porridge viscosity and starch digestibility, while Dessta & Terefe, 2024 developed an instant porridge blend with sweet lupine, orange-fleshed sweet potato, and moringa that substantially improved micronutrient density.

Amongst previous studies, some of them highlighted high potential of legumes in improving fortified maize blend considering its nutritional quality and already established accessibility. Ngoma et al. (2018) demonstrated that cowpea flour processing can increase protein quality while maintaining favorable sensory attributes, with porridges containing 20–30% cowpea flour showing both enhanced amino acid profiles and good acceptability. Similarly, Ejigui et al., 2007 found that combining maize with legumes and using traditional fermentation techniques improved the protein content and nutrient density of yellow maize porridge, offering a culturally appropriate approach to complementary feeding. Other legumes, such as soybeans, have also been shown to improve protein quality. Nwankwo et al., 2015 reported that soybean fortification enhanced the amino acid balance and protein efficiency ratio of maize porridge, while Nnam & Baiyeri, 2008 demonstrated that maize–soybean–plantain mix not only improved nutrient composition but were also acceptable to caregivers and children.

Acceptance studies further indicate that fortified porridges remain culturally and perceptually acceptable when substitution levels are carefully managed. Sensory trials typically report acceptance up to 30% substitution with cowpea or soybean flour, beyond which bean-like flavors and darker coloration may reduce preference (Ngoma et al., 2021; Katola et al., 2023). Collectively, this evidence suggests that legume fortification of maize porridges is a cost-effective and feasible strategy to address protein–energy malnutrition and micronutrient deficiencies, particularly in the context of SFPs. When paired with local sourcing and improvements in legume production, such formulations not only improve child nutrition but also strengthen food systems and community resilience.

4.1.3 Cowpea and its inoculation

Due to its benefit on human nutrition and soil condition, cowpea (Vigna unguiculata L. Walp.) is a highly promoted legume cultivated in semi-arid climate of SSA (Dube & Fanadzo, 2013; Kyei-Boahen et al., 2017). Importantly, cowpea is already cultivated by many smallholder farmers in Namibia, particularly in semi-arid regions where it thrives even under low-input conditions (Namibia Agronomic Board, 2021; Rasche et al., 2025).

With its nutritional quality and affordability, cowpea is a highly complementary ingredient to maize-based diets in semi-arid regions. Cowpea addresses this gap, providing 23–32% protein, essential amino acids, dietary fiber, and minerals, while remaining low in fat (1%) (Kirse & Karklina, 2015; Rodrigues Cruz et al., 2014; USDA, 2019). On a dry-weight basis, cowpea seeds contain 23–25 g protein per 100 g, compared to 8–10 g in maize meal and only 2–4 g in cooked maize porridge. Although it is lower in protein compared to soybeans, its availability and affordability in Namibia compensates (Table 4.1). Their inclusion in fortified maize meals therefore has strong potential to improve dietary quality, supporting child growth, cognitive development, and food security.

Table 4.1 Nutrient values of cowpea, maize and soybean (USDA, 2019)

	Cowpea	Maize	Soybean
Energy (kcal/100g)	343	365	446
Protein (g/100g)	23.8	9.4	36
Fat (g/100g)	2	4.7	20

Beyond its nutritional quality, cowpea is especially valued in northern regions for its adaptability to heat, drought, and poor soils (Horn et al., 2015). In fact, it is cultivated in approximately 62,000 hectares. About 70% of farmers still grow unimproved local varieties, but interest is growing in higher-yielding cultivars that meet both household's needs and market demand. Expanding cowpea production could generate income opportunities for smallholders (NAB & FAO, 2021).

Moreover, cowpea supports sustainable farming systems as a nitrogen-fixing legume, improving soil fertility and reducing dependence on synthetic fertilizers (Becker et al., 2023; Sugiyama & Yazaki, 2012). Despite its potential, average cowpea yields in Namibia remain relatively low due to limited adoption of improved agronomic practices (NAB & FAO, 2021). Recent studies demonstrate substantial productivity gains when inoculation, irrigation, and phosphorus fertilization are applied together (Jeong et al., 2025; Rasche et al., 2023).

Inoculation: Across multi-year trials, inoculated cowpea plants produced on average 1.0 t/ha, nearly double the yield of uninoculated plants (0.5 t/ha). Yield benefits varied with climate: in wetter, cooler years, inoculation increased yields by more than 1 t/ha, while in very dry years (<200 mm rainfall), gains dropped to just 0.1 t/ha (Rasche et al., 2023).

Irrigation: In northern Namibia, combining inoculation with irrigation raised yields to 5.73 t/ha, compared to typical rainfed yields of around 1.0 t/ha (Jeong et al., 2025). This demonstrates the strong responsiveness of cowpea to water availability when supported by microbial symbiosis.

Phosphorus fertilization: In phosphorus-deficient soils, inoculation alone did not significantly increase yields unless combined with phosphorus application. Trials showed that inoculation plus phosphorus raised yields substantially above inoculation-only treatments, confirming that soil fertility constraints must be addressed for consistent productivity (Rasche et al., 2023).

Despite strong technical potential, adoption depends on farmer capacity and market support. Surveys in Namibia's Kavango region revealed that while nearly all farmers expressed willingness to grow inoculated cowpea, many were reluctant to expand production due to labor-intensive harvesting (Rasche et al., 2025). Additional barriers include pest pressure, limited storage facilities, and weak market demand. The limited availability of commercial inoculants remains as a major constraint for implementation (Jefwa et al., 2022; Jeong et al., 2025).

Specifically, it explores the nutritional, agronomic, and programmatic implications of cowpea–maize porridge formulations within school feeding programs, with the goal of identifying strategies that can enhance both child nutrition and local food system sustainability. This study answers following research questions:

(1) What is the nutritional and socioeconomic potential of cowpea in complementing the conventional maize-based NSFP blend?
(2) Which improved farming management practices can strengthen cowpea yield and contribute to making domestic production a reliable supplier for the NSFP?

To address the questions, a biophysical crop model and an optimization modelling are employed, followed by cost-effective analysis.

4.2 Data and Method

4.2.1 Study area

Namibia, located in south-western Africa, has an arid climate, making it the country vulnerable to future climate change. Temperatures are projected to rise by 2–4 °C between 2050 and 2074, with precipitation expected to decrease by 40%. From 2075 to 2100, temperatures could increase further, by 4 to 6 °C. Climate change also threatens food production as floods become more frequent and droughts more likely (Niang et al., 2014; Trisos et al., 2022).

Due to the climate and the old and sandy soil, only about 1% of the territory is suitable for agriculture. Most of the arable land is located in the north-west of the country, creating large regional disparities in agricultural production. Domestic food production does not meet the national nutritional needs, forcing Namibia to import 60% from other countries, particularly from South Africa (WFP, 2017). Nevertheless, 70% of the population depends on agriculture for their livelihoods, which is predominantly subsistence farming (Odero, 2017). Despite its high dependence on agriculture, the agriculture sector contributes only 6% to the country's GDP (Namibia Statistics Agency, 2024).

Access to market is often a challenge to rural communities (Namibia National Planning Commission, 2018). Products are traded in informal street markets or are exchanged within the community. As a result, SHFs have less motivation to improve productivity and need additional sources of income (NAMIBIA CENSUS OF AGRICULTURE 2013/2014, 2013).

Namibia's Sixth National Development Plan (NDP6) aims to produce 80% of its national food demand from 60% by 2030. This increase is intended to drive structural reform, economic transformation, and long-term food security (Namibia National Planning Commission, 2025).

Since the country's independence in 1991, the Namibia School Feeding Program (NSFP) has been implemented throughout the country, with over 96% of schools participating. In 1997, the Namibian ministry of education, art and culture took over the operation from the WFP Namibia who initiated the policy. As of 2024, the NSFP fed 518,829 children between 5-14 (Global Child Nutrition Foundation (GCNF), 2024). The NSFP offers one meal a day in schools, which consists of fortified maize porridge (a soft porridge called pap).

4.2.2 Data and Method

This study integrates biophysical crop simulations with an optimization model to assess the nutritional and socioeconomic potential of improved maize porridge enriched with cowpea in NSFP (Figure 4.1). Potential cowpea production is estimated as the result of modelling framework. It is assumed that cowpea blend will take up to 30% of school meal, maize meal being the rest as it is currently.

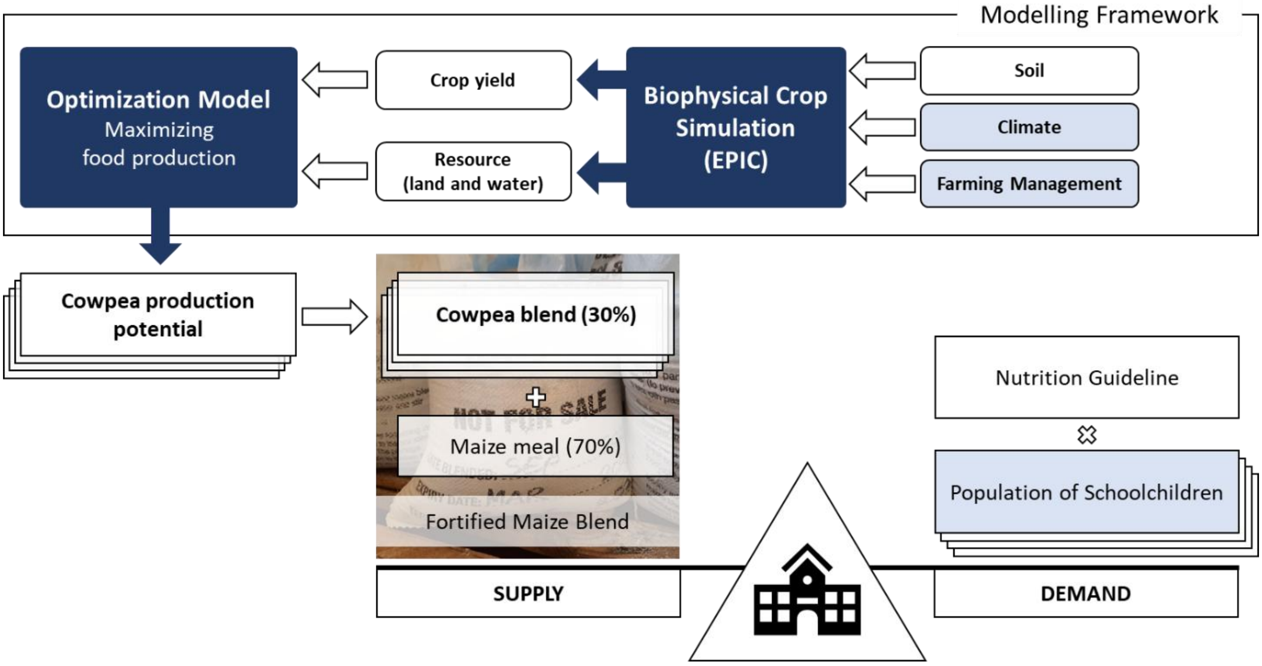

Figure 4.1 Overview of information through the modeling framework and analysis. Dark blue boxes represent employed modeling tools; rounded boxes depict input and output data; light blue boxes illustrate factors representing scenarios.

The analysis draws on spatial datasets of climate, soil, water resources, land use, and food demand. Cropland was stratified using the Homogeneous Response Unit (HRU) classification system, distinguishing zones by altitude, slope, and soil type. Climate inputs were taken from the ISIMIP3b database, driven by five CMIP6 general circulation models under three SSP-RCP combinations (SSP126, SSP370, SSP585). Land use information was derived from the Copernicus Global Land Service (2015–2019).

Caloric and nutrient requirements for Namibian schoolchildren (aged 5–14) were based on FAO/WHO guidelines. Their share of national caloric demand was estimated at 19%, and this proportion of cropland and water resources was allocated to the NSFP within the model.

Crop production potentials were simulated for Namibia's six major crops (maize, pearl millet, soft wheat, groundnut, cowpea, sorghum) under varying climate conditions and farming management scenarios. Management scenarios included:

- Subsistence (SS): rainfed + minimal fertilization based on farmer practices.
- Inoculation (IN): rhizobial inoculation
- Irrigation (IR): rule-based irrigation up to 1000 mm/year.
- Combined inoculation and irrigation (IN+IR): inoculation plus irrigation.
- Improved fertilization (FT): up to 250 kg N/ha/year with adaptive applications.
- Combined irrigation and improved fertilization (IR+FT): irrigation plus improved fertilization.

School feeding demand was estimated based on one school meal per child per day (198 days/year), aligned with WHO/FAO nutrient guidelines. Future projections incorporated population growth and income dynamics under SSP scenarios, combining climate projections (CMIP6) with socioeconomic pathways (SSP126, SSP370, SSP585) (Figure 4.2).

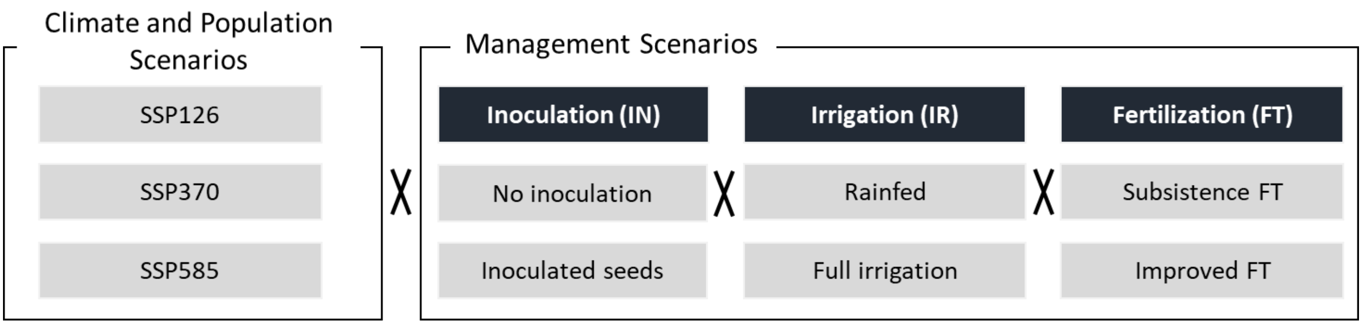

Figure 4.2 Overview of scenarios.

A spatially explicit mathematical programming model was developed to maximize caloric energy supply from domestic crop production. The model allocates crops across HRUs subject to constraints on cropland, water availability, and historically observed crop mixes. For crops lacking historical area data (e.g., cowpea), agronomic upper bounds were applied (see method in Jeong et al., 2025).

Cost assumptions were derived from local and regional agronomic studies, with inoculation estimated at approximately US$20/ha (Jefwa et al., 2022; Rasche et al., 2023), irrigation at US$400/ha (Jeong et al., 2025), and improved fertilization at US$300/ha (FAO, 2023).

Together, the simulation–optimization framework evaluates the feasibility of integrating inoculated cowpea into maize-based porridge for the NSFP, highlighting both nutritional adequacy and efficient resource use under alternative climate and management futures.

4.3 Results

4.3.1 Sufficiency of domestic cowpea production

The domestic cowpea production is projected to have variety of pathways depending on the biophysical and socioeconomic scenarios (Table 4.2). Table 4.2 shows how much percentage of domestic cowpea production is needed to fulfill the NSFP cowpea demand. Under subsistence management (SS), school feeding demand placed a high burden on domestic production. For example, under SSP370, supplying the NSFP would require 128% of total national production, meaning that even if the entire harvest were diverted, it would still fall short of meeting demand. These findings underscore that reliance on traditional farming practices is incompatible with sustaining a nationwide school feeding scheme without large imports.

		% of NSFP cowpea in total production		
		Present	Near Future	Far Future
SSP126	SS	7	16	95
	IN	6	12	72
	IR	8	14	120
	IN+IR	2	5	27
	FT	13	15	14
	FT+IR	28	22	18
SSP370	SS	7	17	100
	IN	5	13	76
	IR	7	15	128
	IN+IR	2	5	29
	FT	22	32	33
	FT+IR	84	127	68
SSP585	SS	7	16	101
	IN	5	12	77
	IR	7	15	118
	IN+IR	2	4	29
	FT	33	43	42
	FT+IR	199	268	133

Min. – Max.

Table 4.2 Estimated future cowpea supply of Namibia for Namibia School Feeding Programme (NSFP) under alternative farm management (SS: subsistence farming, IN: inoculation, IR: irrigation, IN+IR: inoculation and irrigation, FT: improved fertilization, and IR+FT: irrigation and improved fertilization) and climate scenarios (SSP126, SSP370, and SSP585). Present refers to the average potentials between 2020 – 2025. Near and far futures refer to the average potentials between 2030 – 2060 and 2070 – 2100, respectively.

Improvements in management practices sharply reduced the proportion of production required. Especially with inoculation (IN), demand accounted for 12–17% of total cowpea production under all SSPs. Irrigation (IR) further eased the pressure, requiring 13–15% of national production in all SSPs.

When inoculation and irrigation were combined (IN+IR), the share dropped even further, stabilizing between 2-29% across all climate pathways, at any time in the near (2030-2060) or far future (2070-2100). This suggests that integrated but relatively low-cost management improvements could make the NSFP more sustainable by leaving two-thirds or more of national production available for household consumption and markets.

When irrigation and fertilization is implemented together under SSP126, only 18–28% of production would be required to supply the NSFP, however in the near future under SSP370, the share increases to 127%. Under SSP585, with IR+FT national cowpea production cannot fulfil the total demand of NSFP alone. With fertilization together with irrigation, cowpea production decreases since the benefit of legume is reduced resulting in other crops winning in overall optimal production.

The results indicate three key trends:

- Climate impacts – Yields decline under SSP585 compared to SSP126 and SSP370, even with advanced management, highlighting the risks of high-emission futures.
- Management effects – Irrigation and fertilization, particularly in combination, provide the greatest yield benefits, while inoculation alone offers limited but consistent improvements.
- Synergies – The integration of water and nutrient management (IN+IR) yields the most robust outcomes, though its effectiveness is constrained under severe climate change (SSP585).

These findings suggest that future cowpea production for school feeding programs in Namibia will depend heavily on adopting improved farming practices to buffer against climate change.

4.3.2 Cost-Effectiveness Analysis of Management Practices

To assess the economic feasibility of different cowpea management practices, we evaluated projected yield gains relative to the associated costs under the farming management and climate scenarios (Figure 4.3).

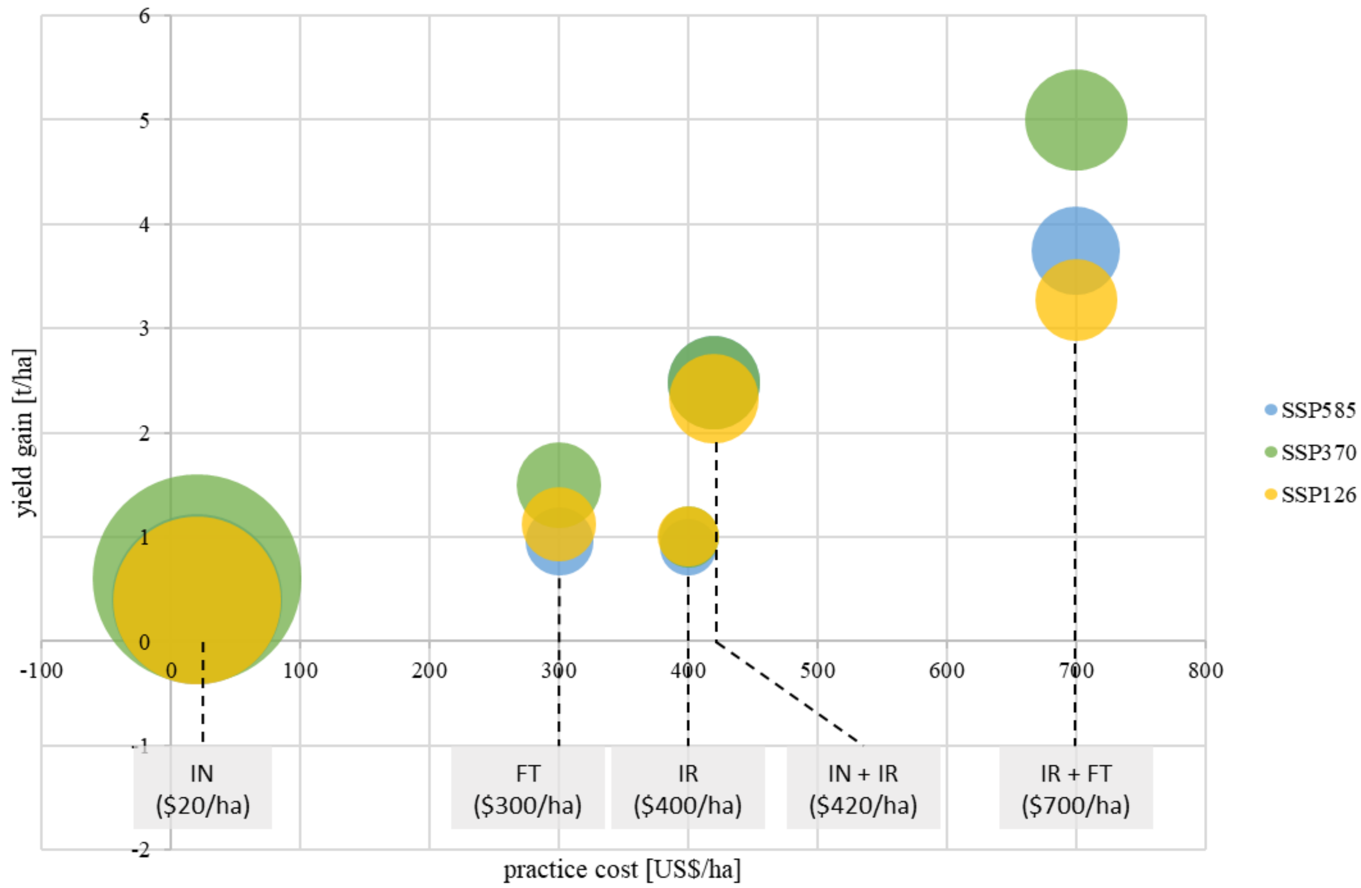

Figure 4.3 Cost-effectiveness of each management practices under different SSPs. The area of bubble depicts cost-effectiveness of each scenario [kg/$]. X-axis represent yield gain in relative to subsistence farming scenario (SS).

Under SSP126, inoculation alone provided a yield gain of 0.39 t/ha relative to the subsistence baseline, corresponding to approximately 19.5 kg of additional yield per US$1 invested. Fertilization alone delivered a gain of 1.12 t/ha, equivalent to 3.7 kg/$, while combined irrigation and fertilization achieved the highest absolute yield gain of 3.27 t/ha but lower cost-effectiveness (4.7 kg/$). These results indicate that moderate interventions such as inoculation or fertilization can generate yield improvements at relatively low cost, particularly under low-emission futures.

Under SSP370, inoculation again demonstrated the highest cost-effectiveness, with 0.60 t/ha gained per US$20 investment (≈30 kg/$), whereas IR+FT produced the largest absolute yield gain of 5.01 t/ha, corresponding to 7.2 kg/$. The contrast between absolute yield gains and cost-effectiveness illustrates a trade-off: while intensive interventions maximize production, their economic efficiency is lower, which may constrain adoption among resource-limited smallholders.

In the high-emission scenario SSP585, inoculation provided 0.40 t/ha of additional yield relative to subsistence, translating to 20 kg/$, whereas IR+FT generated 3.75 t/ha (≈5.4 kg/$). These findings highlight that, although absolute yields decline under harsher climates, cost-effective interventions such as inoculation and moderate fertilization remain robust strategies to sustain cowpea production.

Overall, the analysis demonstrates three key patterns. First, inoculation (IN) consistently provides the highest yield per unit cost, making it particularly suitable for smallholder adoption (Jefwa et al., 2022; Rasche et al., 2023). Second, fertilization (FT) is highly cost-effective under moderate climate change but offers diminishing returns under extreme heat and drought stress (FAO, 2023). Third, combined practices (IR+FT, IN+IR) produce the greatest absolute yields, enhancing resilience under future climate scenarios, but their higher costs reduce economic efficiency, suggesting they may be most appropriate for government-supported or commercial operations (Jeong et al., 2025).

These results imply that school feeding programs seeking to source cowpea locally should prioritize low-cost, high-efficiency interventions such as inoculation and moderate fertilization to enhance production while maintaining affordability. At the same time, investments in irrigation and integrated soil fertility management can provide a strategic hedge against more severe climate futures, particularly under SSP370 and SSP585.

4.4 Discussion

This study demonstrates that incorporating cowpea into the Namibian School Feeding Programme (NSFP) offers a sustainable strategy to improve child nutrition while strengthening local food systems. Cowpea-maize blends provide higher protein quality and micronutrient density than conventional maize porridge, and their supply potential is reinforced by local cultivation. Biophysical simulation results indicate that future cowpea yields strongly depend on both climate pathways and management practices. Subsistence practices alone remain insufficient to meet demand, while inoculation provides moderate improvements. Irrigation and fertilization, particularly in combination, deliver the highest yields—up to 5.4 t/ha under the moderate climate change scenario SSP370—though these benefits are reduced under high-emission futures SSP585.

Notably, the results indicate that moderate interventions such as rhizobial inoculation and phosphorus fertilization can generate substantial yield improvements at a relatively low cost, particularly under low-emission futures (SSP126). This finding aligns with numerous agronomic studies confirming the effectiveness and economic viability of such measures. Rhizobial inoculation enhances biological nitrogen fixation by increasing nodulation, nitrogen accumulation, and consequently grain yield, with reported yield increases ranging from 16% to over 30% depending on site conditions and rhizobia strains (Kyei-Boahen et al., 2017; Rasche et al., 2023; Martins et al., 2003). In some regions of Africa and Latin America, grain yield improvements of up to 56% have been observed when inoculation is combined with phosphorus fertilization, underscoring the synergistic effect of alleviating nutrient limitations on the efficiency of biological nitrogen fixation and plant growth (Onduru et al., 2008; Galindo et al., 2020).

Economically, inoculation represents a cost-effective intervention, requiring relatively low input investment but offering high yield gains per dollar spent. This efficiency makes it particularly suitable for resource-constrained smallholder farmers, a critical consideration for Namibia's predominantly subsistence agricultural sector. Fertilization alone is also effective under moderate climate scenarios, though its yield benefits can diminish under harsher climates due to environmental stresses that limit nutrient availability and uptake (FAO, 2023). In contrast, combined approaches of inoculation with moderate fertilization maintain robustness and resilience by mitigating soil fertility constraints, which is essential for sustaining production under variable and changing climatic conditions.

These insights corroborate findings from other studies on legume productivity and soil fertility management in sub-Saharan Africa and beyond (Soares et al., 2006; Zilli et al., 2009; Jeong et al., 2025). The clear trade-off between absolute yield maximization—achieved through labor-intensive, costly interventions like irrigation and fertilization—and economically efficient, moderate interventions such as inoculation alone, highlights the need for tailored policy and programmatic support. For example, small-scale irrigation infrastructure and subsidized supplies of inoculants and phosphorus fertilizers could enable scalable adoption of these climate-smart agroeconomic practices. Establishing local production and distribution networks for inoculants would further reduce dependency on imports and encourage wider uptake by smallholders (Jefwa et al., 2022; Rasche et al., 2023).

By linking procurement of cowpea directly to farmer cooperatives and school feeding programs, guaranteed demand can incentivize production, improve market access, and reduce post-harvest losses. This aligns with recommendations from the World Food Programme (2023) and the Global Child Nutrition Foundation (2024) and supports Sustainable Development Goals including Zero Hunger (SDG 2) and Climate Action (SDG 13). Thus, cowpea fortification in school meals represents a nutritionally impactful and socioeconomically synergistic intervention that leverages moderate, cost-effective agronomic practices to bolster resilience and food security in Namibia and similar semi-arid contexts.

4.5 Conclusion

This research establishes that fortifying maize porridge with locally sourced cowpea is a promising, sustainable intervention for Namibia's school feeding program. Through detailed scenario modelling and comparison to regional case studies, it is shown that improved management practices—especially inoculation and moderate fertilization—are both feasible and cost-effective for raising cowpea yields and ensuring supply sufficiency for national school nutrition schemes. Integrating cowpea into established maize-based menus boosts protein and micronutrient quality, supports cultural preferences, and strengthens local agricultural value chains.

Ultimately, advancing these interventions can enhance educational and food security outcomes, promote self-reliant food systems, and align with broader national strategies for resilience, economic growth, and social protection without relying on significant imports. The study's findings reinforce the multi-sectoral returns of school feeding programs when linked with context-tailored, climate-smart agricultural innovations.

5. Conclusion and Outlook

5.1 Summary of results

This dissertation presents an integrated analysis of Namibia's agricultural adaptation potential with a particular focus on cowpea's role in enhancing food security and nutrition through school feeding programs. The three core studies address intertwined components of biophysical productivity, resource constraints, nutritional improvements, and socioeconomic impacts, ultimately offering a cohesive narrative on opportunities and challenges for sustainable development under projected climate and socioeconomic changes.

The first study explores the potentials and limitations of cowpea production in Namibia's semi-arid environment by simulating the effects of improved management, including rhizobial inoculation, irrigation, and fertilization. Results show that inoculated cowpea yields nearly double those of uninoculated crops in northern regions, achieving an average of approximately 1.0 t/ha under rainfed conditions, with further yield enhancements—up to 5.7 t/ha—when irrigation is applied. The combined interventions not only elevate productivity but also improve resource use efficiency, reducing the land and water required per unit of output. This suggests that adopting climate-smart agronomic practices can mitigate environmental constraints and expand productive capacity under water scarcity pressures. The trade-offs highlighted between scarce water and land resources emphasize the complexity of optimizing agricultural systems, particularly given the spatial heterogeneity of Namibia's agroecology.

Building upon these biophysical potentials, the second study assesses Namibia's capacity to meet the caloric and nutritional demands of schoolchildren through the HGSFP. Simulation and optimization analyses indicate a sharp north-south disparity: northern regions such as Ohangwena and Oshana possess the resource endowment and climatic suitability to produce sufficient—if not surplus—food to satisfy schoolchildren's needs, whereas southern regions remain heavily constrained by arid conditions and low agricultural potential. Protein availability is generally adequate across scenarios, particularly with fertilization, which amplifies productivity and helps offset the negative impacts of future climate change. However, fat remains the most limiting macronutrient, reflecting the challenges of nutrition adequacy in plant-dominant diets and underscoring the critical role of livestock or alternative fat sources. These findings stress that the HGSFP's effectiveness depends fundamentally on implementing intensified and adaptive management strategies alongside infrastructure and policy measures that address regional inequalities.

The third study connects agronomic production to nutritional and economic outcomes by evaluating cowpea's potential to complement conventional maize-based porridge in school meals. Fortification with up to 30% inoculated cowpea flour significantly improves protein quality and micronutrient density—addressing critical deficiencies endemic in the current maize-heavy diet—while maintaining high levels of sensory and cultural acceptability among consumers. Economically, increased yields from inoculation reduce reliance on costly imported protein sources, offering a cost-efficient route to boost school feeding program sustainability. By linking smallholder farmers to institutional procurement through the HGSFP, the study highlights opportunities for rural income generation, market strengthening, and livelihood diversification, thereby presenting a viable model for integrating nutrition-sensitive agricultural development within policy frameworks.

Together, these studies underscore that cowpea production, enhanced through inoculation and integrated water-nutrient management, is a key climate-smart solution to tackle intertwined challenges of food insecurity, malnutrition, and rural poverty in Namibia. The cascading benefits—from optimized resource use to improved nutrition and socioeconomic uplift—demonstrate how agricultural innovation can enhance the operation and impact of school feeding initiatives like the HGSFP. While acknowledging the substantial climatic and socioeconomic barriers, the research identifies feasible pathways to leverage Namibia's regional potentials and institutional mechanisms to build more resilient, inclusive, and sustainable food systems.

The thesis concludes with the recognition that success depends not only on biophysical and economic feasibility but also on addressing social, institutional, and infrastructural enablers and constraints. Advancing interdisciplinary engagement and ground-level participatory approaches will be critical to translating these technical findings into sustained improvements in food security, nutrition, and livelihoods for Namibia's vulnerable populations.

5.2 Limitation

This thesis provides an extensive technical analysis of the potentials and constraints of cowpea production, resource management, and school feeding program sustainability in Namibia. While the studies collectively offer important insights into biophysical productivity, resource use efficiency, nutritional enhancement, and economic feasibility, several limitations remain that frame the interpretation and applicability of the findings.

First, the thesis heavily emphasizes technical and quantitative modeling approaches, including crop growth simulations, spatial optimization, and cost-effectiveness analysis. These methods enable robust estimations of production potential across varying climatic and management scenarios but inherently simplify complex social dynamics. As such, this research does not explicitly incorporate the diverse behavioral responses, decision-making processes, and adaptive capacities of key stakeholders—smallholder farmers, school administrators, policymakers, and beneficiaries of school feeding programs. The omission of these societal and institutional agents limits understanding of how factors such as farmer risk perceptions, market access barriers, policy enforcement, cultural preferences, and socio-economic inequalities may influence adoption and sustainability of proposed agricultural adaptations.

Second, the technical models rely on various assumptions and available data that integrate climatic projections, soil properties, crop parameters, and nutrient requirements. While these datasets are carefully selected and validated against observed data, uncertainties remain. Climate models carry inherent variability, especially at regional scales, and soil nutrient representations simplify heterogeneous field conditions. The crop models, although well-calibrated, do not capture certain stresses like pest outbreaks, disease dynamics, or extreme weather events in detail. Consequently, yield predictions may overestimate or underestimate real-world outcomes, particularly under future climate extremes expected in Namibia's arid environments.

Third, while the thesis examines resource trade-offs involving land and water allocation, the analyses assume idealized or uniform access to inputs such as irrigation infrastructure, fertilizers, and effective inoculants. In reality, smallholder farmers face significant barriers—including high input costs, limited credit availability, inadequate extension services, and weak supply chains—that constrain their ability to implement such practices effectively. These socio-economic constraints are only indirectly considered through scenario assumptions and require complementary qualitative and participatory research approaches for comprehensive insights.

Fourth, the nutritional analysis on cowpea fortification focuses primarily on macronutrient and select micronutrient improvements based on compositional data and dietary guidelines. However, the broader complexities of food acceptability, sensory attributes, and cultural dietary patterns are only partially addressed through secondary literature and limited sensory trial references. Institutional and logistical challenges of integrating new food formulations into the national school feeding supply chain require further operational research beyond the current technical evaluation.

Finally, the thesis's integrated assessment framework prioritizes national- and regional-scale evaluation, which inherently masks finer local variability. Namibia's diverse agroecologies, socio-cultural landscapes, and infrastructure disparities mean that localized constraints and opportunities may differ considerably from modeled averages. Therefore, while the results provide valuable direction for policy and strategic planning, targeted on-the-ground pilot studies and stakeholder engagement remain critical to contextualize and validate findings for scalable interventions.

In summary, this thesis serves as a foundational technical analysis that delineates the biophysical and economic feasibility of enhancing cowpea production and school feeding nutrition under climate and socioeconomic change in Namibia. It highlights key adaptation potentials while acknowledging that successful implementation fundamentally depends on addressing institutional, social, and behavioral dimensions, which future interdisciplinary research should prioritize. Incorporating these human factors will be crucial to translating modeling insights into effective, sustainable food security and nutrition outcomes for vulnerable Namibian communities.

5.3 Outlook

This dissertation has investigated the potential of cowpea as a cornerstone of sustainable food security in Namibia, linking agricultural adaptation with nutrition-sensitive social protection. The findings contribute to broader debates on food systems resilience in semi-arid regions, where climate change, resource scarcity, and socio-economic vulnerabilities intersect. While the results demonstrate promising technical options, they also emphasize the importance of embedding these within supportive institutional and socio-cultural contexts.

The research reveals that technological improvements such as rhizobial inoculation and targeted fertilization offer considerable scope for boosting yields and resource-use efficiency. Yet, without enabling conditions, such as input distribution, extension services, and access to markets, such innovations risk remaining confined to experimental settings. Equally, SFPs demonstrate potential as integrative platforms for linking agricultural production, child nutrition, and rural livelihoods. These insights lead to five overarching messages:

1. **Cowpea as an attractive crop**: Inoculation nearly doubles yields under rainfed conditions and achieves efficiencies comparable to irrigation without exacerbating water scarcity. This positions cowpea even more as a viable adaptation strategy in dry conditions.
2. **Persistent regional disparities**: While northern Namibia can generate surplus production, southern regions remain structurally constrained. Addressing this divide requires improved infrastructure and interregional trade mechanisms.
3. **Nutrition-sensitive agriculture is feasible**: Fortifying maize porridge with cowpea flour significantly improves dietary quality while maintaining cultural acceptance, offering a practical route to address child malnutrition.
4. **Low-input strategies are cost-effective**: Compared to irrigation, inoculation represents a resource-efficient, affordable, and scalable innovation for smallholder farmers, reducing dependence on imports and synthetic fertilizers.
5. **School feeding as a policy lever**: By connecting local production with institutional demand, the Namibia HGSFP has potential to be scaled up nationwide, while simultaneously strengthening education, health, and rural development.

These messages suggest the necessity of technical innovation and institutional support. For instance, while inoculation demonstrates strong biophysical potential, its uptake depends on availability of inoculants, farmer trust, and supportive extension networks. Similarly, while the integration of cowpea into school feeding has proven nutritional benefits, its long-term success hinges on stable procurement systems, supply chain investments, and governance mechanisms that balance national coordination with local flexibility.

The findings also highlight the need to navigate resource trade-offs in agricultural adaptation. Irrigation offers high yield gains but intensifies competition for already scarce water resources, whereas inoculation generates comparable benefits at lower environmental cost. This insight contributes to broader discourses on sustainable intensification in drylands, emphasizing strategies that maximize efficiency rather than expand resource use.

Looking forward, three avenues of research and policy action appear most urgent. First, pilot programmes are required to validate modelling insights under field conditions, capturing not only agronomic outcomes but also farmer behaviour, school-level logistics, and institutional coordination. Second, value chain development—including processing, storage, and distribution—should be prioritized to unlock the market potential of cowpea and reduce post-harvest losses. Third, targeted policy interventions are necessary to address geographic disparities, particularly through investments in infrastructure and mechanisms that enable surplus-producing northern regions to supply deficit areas in the south.

These directions extend beyond Namibia. Many semi-arid countries face similar challenges of water scarcity, low agricultural productivity, and nutritional deficits among children. The Namibian case illustrates that resilience need not rely solely on capital-intensive technologies. Instead, scaling up indigenous, climate-adapted crops such as cowpea—combined with relatively low-cost innovations like inoculation—can deliver multiple co-benefits when linked with institutional platforms such as school feeding programmes.

In conclusion, this thesis demonstrates that food security under climate change is not solely about increasing production, but about producing differently: more efficiently, equitably, and sustainably. By embedding cowpea production within nutrition-sensitive policies and strengthening institutional linkages, Namibia can chart a pathway from vulnerability to resilience. This integrative approach offers a replicable model for other dryland contexts, where adaptation strategies must reconcile resource constraints with the urgent need to nourish present and future generations.

6. References

AkdemirR, S., Kusek, G., & Ozturk, H. H. (2019). Estimation of Energy Consumption and Greenhouse Gas Emissions from Fertilizer Us in Corn, Cotten and Soybean Production in Turkey. *Scientific Papers Series : Management, Economic Engineering in Agriculture and Rural Development*, *19*(3), 27–32.

Awojobi, O. N. (2019). A systematic review of the impact of Ghana's school feeding programme on educational and nutritional outcomes. *Agro-Science*, *18*(2), 42–50. https://doi.org/10.4314/AS.V18I2.8

Baffour-Ata, F., Atta-Aidoo, J., Said, R. O., Nkrumah, V., Atuyigi, S., & Analima, S. M. (2023). Building the resilience of smallholder farmers to climate variability: Using climate-smart agriculture in Bono East Region, Ghana. *Heliyon*, *9*(11), e21815. https://doi.org/10.1016/J.HELIYON.2023.E21815

Balkovič, J., Skalský, R., Folberth, C., Khabarov, N., Schmid, E., Madaras, M., Obersteiner, M., & van der Velde, M. (2018). Impacts and Uncertainties of +2°C of Climate Change and Soil Degradation on European Crop Calorie Supply. *Earth's Future*, *6*(3), 373–395. https://doi.org/10.1002/2017EF000629

Basukala, A. K., & Rasche, L. (2022). Model-Based Yield Gap Assessment in Nepal's Diverse Agricultural Landscape. *Land 2022, Vol. 11, Page 1355*, *11*(8), 1355. https://doi.org/10.3390/LAND11081355

Becker, J. N., Grozinger, J., Sarkar, A., Reinhold-Hurek, B., & Eschenbach, A. (2023). Effects of cowpea (Vigna unguiculata) inoculation on nodule development and rhizosphere carbon and nitrogen content under simulated drought. *Plant and Soil*. https://doi.org/10.1007/s11104-023-06051-1

Black, M. M., Walker, S. P., Fernald, L. C. H., Andersen, C. T., DiGirolamo, A. M., Lu, C., McCoy, D. C., Fink, G., Shawar, Y. R., Shiffman, J., Devercelli, A. E., Wodon, Q. T., Vargas-Barón, E., & Grantham-McGregor, S. (2017). Early childhood development coming of age: science through the life course. *The Lancet*, *389*(10064), 77–90. https://doi.org/10.1016/S0140-6736(16)31389-7

Boukar, O., Belko, N., Chamarthi, S., Togola, A., Batieno, J., Owusu, E., Haruna, M., Diallo, S., Umar, M. L., Olufajo, O., & Fatokun, C. (2019). Cowpea (Vigna unguiculata): Genetics, genomics and breeding. *Plant Breeding*, *138*(4), 415–424. https://doi.org/10.1111/PBR.12589

Bouraoui, F., & Grizzetti, B. (2008). An integrated modelling framework to estimate the fate of nutrients: Application to the Loire (France). *Ecological Modelling*, *212*(3–4), 450–459. https://doi.org/10.1016/J.ECOLMODEL.2007.10.037

Buchhorn, M., Smets, B., Bertels, L., De Roo, B., Lesiv, M., Tsendbazar, N. E., Linlin, L., & Tarko, A. (2020). *Copernicus Global Land Service: Land Cover 100m: Version 3 Globe 2015-2019: Product User Manual*. https://doi.org/10.5281/zenodo.3938963

Bundy, D. ed., Silva, N. de, ed., Horton, S. ed., Jamison, D. T. , ed., Patton, G. C. , ed., Bundy, D., Silva, N. de, Horton, S., Patton, G. C., Schultz, L., Jamison, D. T., Galloway, R., Bing Wu, K., Azzopardi, P., Kennedy, E., Coffey, C., Mokdad, A., Alderman, H., Behrman, J. R., … Filippi, V. (2018). Re-Imagining School Feeding : A High-Return Investment in Human Capital and Local Economies. *MINISTERIO DE EDUCACIÓN*. https://repositorio.minedu.gob.pe/handle/20.500.12799/6582

Campbell, B. M., Thornton, P., Zougmoré, R., van Asten, P., & Lipper, L. (2014). Sustainable intensification: What is its role in climate smart agriculture? *Current Opinion in Environmental Sustainability*, *8*, 39–43. https://doi.org/10.1016/J.COSUST.2014.07.002

Cavalcante Junior, E. G., De Medeiros, J. F., Sobrinho, J. E., Figueirêdo, V. B., Da Costa, J. P. N., & Santos, W. D. O. (2016). Development and water requirements of cowpea under climate change conditions in the Brazilian semi-arid region. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *20*(9), 783–788. https://doi.org/10.1590/1807-1929/AGRIAMBI.V20N9P783-788

Chabwera, M., Mchimwa, M., Mezuwa, U., Joshua Chindenga, R., Mhango, K., Matandara, M., Namaona, E., Bulirani, M., Kapolo, D., Mkama, B., Banda, W., Kasapila, W., Ademola Otekunrin, O., Lavudya, S., & Lola Gold, K. (2026). Impacts of climate change on food systems in Africa: a systematic review. *Frontiers in Sustainable Food Systems*, *9*, 1634744. https://doi.org/10.3389/FSUFS.2025.1634744

Cottrell, R. S., Nash, K. L., Halpern, B. S., Remenyi, T. A., Corney, S. P., Fleming, A., Fulton, E. A., Hornborg, S., Johne, A., Watson, R. A., & Blanchard, J. L. (2019). Food production shocks across land and sea. *Nature Sustainability 2019 2:2*, *2*(2), 130–137. https://doi.org/10.1038/s41893-018-0210-1

Dantas, I. R. M., Delzeit, R., & Klepper, G. (2021). Economic Research on the Global Allocation of Scarce Water Resources Needs Better Data. *Https://Doi.Org/10.1142/S2382624X21500132*, *7*(3), 2150013. https://doi.org/10.1142/S2382624X21500132

de Blécourt, M., Gröngröft, A., Baumann, S., & Eschenbach, A. (2019). Losses in soil organic carbon stocks and soil fertility due to deforestation for low-input agriculture in semi-arid southern Africa. *Journal of Arid Environments*, *165*, 88–96. https://doi.org/10.1016/J.JARIDENV.2019.02.006

de Pinto, A., Cenacchi, N., Kwon, H. Y., Koo, J., & Dunston, S. (2020). Climate smart agriculture and global food-crop production. *PLoS ONE*, *15*(4). https://doi.org/10.1371/JOURNAL.PONE.0231764

Desalegn, T. A., Gebremedhin, S., & Stoecker, B. J. (2022). Successes and challenges of the Home-grown School Feeding Program in Sidama Region, Southern Ethiopia: a qualitative study. *Journal of Nutritional Science*, *11*, e87. https://doi.org/10.1017/JNS.2022.77

Dessta, T. N., & Terefe, Z. K. (2024). Development of maize-based instant porridge flour formulated using sweet lupine, orange-fleshed sweet potato, and moringa leaf powder. *Food Science & Nutrition*, *12*(11), 9151–9161. https://doi.org/10.1002/FSN3.4483

Destaw, Z., Wencheko, E., Kidane, S., Endale, M., Challa, Y., Tiruneh, M., Tamrat, M., Samson, H., Shaleka, D., & Ashenafi, M. (2022). Impact of school meals on educational outcomes in Addis Ababa, Ethiopia. *Public Health Nutrition*, *25*(9), 2614–2624. https://doi.org/10.1017/S1368980022000799

Dhillon, R., Moncur, Q., Dhillon, R., & Moncur, Q. (2023). Small-Scale Farming: A Review of Challenges and Potential Opportunities Offered by Technological Advancements. *Sustainability 2023, Vol. 15, 15*(21). https://doi.org/10.3390/SU152115478

DiGirolamo, A. M., Ochaeta, L., & Flores, R. M. M. (2020). Early Childhood Nutrition and Cognitive Functioning in Childhood and Adolescence. *Food and Nutrition Bulletin*, *41*(1_suppl), S31–S40. https://doi.org/10.1177/0379572120907763

Dube, E., & Fanadzo, M. (2013). Maximising yield benefits from dual-purpose cowpea. In *Food Security* (Vol. 5, Issue 6, pp. 769–779). https://doi.org/10.1007/s12571-013-0307-3

Ejigui, J., Savoie, L., Marin, J., & Desrosiers, T. (2007). Improvement of the nutritional quality of a traditional complementary porridge made of fermented yellow maize (Zea mays): effect of maize-legume combinations and traditional processing methods. *Food and Nutrition Bulletin*, *28*(1), 23–34. https://doi.org/10.1177/156482650702800103

Erkal, G., Yalçınkaya, Ö., & Gültekin, S. (2025). Convergence Analysis of Food Security among Sub-Saharan African Countries: Evidence from a Nonlinear TAR Panel Unit Root Test. *International Journal on Food System Dynamics*, 1–18. https://doi.org/10.1163/18696945-BJA00014

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

FAO. (2024). *FAOSTAT: Fertilizers by Nutrient.* . http://www.fao.org/faostat/en/#data/RFN

FAO: AQUASTAT. (2022). *FAO's Global Information System on Water and Agriculture*.

FAO, IFAD, UNICEF, WFP, & WHO. (2022). The State of Food Security and Nutrition in the World 2022. In *The State of Food Security and Nutrition in the World 2022*. FAO. https://doi.org/10.4060/CC0639EN

FAO, & WHO. (2004). *Vitamin and mineral requirements in human nutrition: report of a joint FAO/WHO expert consultation*. World Health Organization.

FAO, WHO, & UNU. (2001). *Human Energy Requirements*.

FAOSTAT. (2022). *Food and Agriculture Organization of the United Nations. Statistical Databases*. FAOSTAT.

Fortunato, A., & Enciso, S. (2023). *Food for Growth: A Diagnostics of Namibia's Agriculture Sector*.

Galani, Y. J. H., Orfila, C., & Gong, Y. Y. (2022). A review of micronutrient deficiencies and analysis of maize contribution to nutrient requirements of women and children in Eastern and Southern Africa. *Critical Reviews in Food Science and Nutrition*, *62*(6), 1568–1591. https://doi.org/10.1080/10408398.2020.1844636

Gallegos, D., Eivers, A., Sondergeld, P., & Pattinson, C. (2021). Food insecurity and child development: A state-of-the-art review. *International Journal of Environmental*

Research and Public Health, *18*(17), 8990. https://doi.org/10.3390/IJERPH18178990/S1

Gelli, A., Masset, E., Adamba, C., Alderman, H., Arhinful, D., Aurino, E., & Folson, G. (2021). *School Meals as a Market for Smallholder Agriculture Experimental Evidence from Ghana*.

Gelli, A., Masset, E., Folson, G., Kusi, A., Arhinful, D. K., Asante, F., Ayi, I., Bosompem, K. M., Watkins, K., Abdul-Rahman, L., Agble, R., Ananse-Baden, G., Mumuni, D., Aurino, E., Fernandes, M., & Drake, L. (2016a). Evaluation of alternative school feeding models on nutrition, education, agriculture and other social outcomes in Ghana: Rationale, randomised design and baseline data. *Trials*, *17*(1). https://doi.org/10.1186/s13063-015-1116-0

Gelli, A., Masset, E., Folson, G., Kusi, A., Arhinful, D. K., Asante, F., Ayi, I., Bosompem, K. M., Watkins, K., Abdul-Rahman, L., Agble, R., Ananse-Baden, G., Mumuni, D., Aurino, E., Fernandes, M., & Drake, L. (2016b). Evaluation of alternative school feeding models on nutrition, education, agriculture and other social outcomes in Ghana: rationale, randomised design and baseline data. *Trials*, *17*(1). https://doi.org/10.1186/S13063-015-1116-0

Gerrano, A. S., van Rensburg, W. S. J., & Adebola, P. O. (2017). Nutritional composition of immature pods in selected Cowpea [Vigna unguiculata (L.) Walp.] genotypes in South Africa. *Australian Journal of Crop Science*, *11*(2), 134–141. https://doi.org/10.21475/ajcs.17.11.02.p72

Global Child Nutrition Foundation (GCNF). (2024). *School Meal Programs Around the World: Results from the 2024 Global Survey of School Meal Programs* . http://gcnf.org/global-reports/.

Govender, L., Siwela, M., & Denhere, S. (2022). The Effect of Adding Bambara Groundnut (Vigna subterranea) on the Physical Quality, Nutritional Composition and Consumer Acceptability of a Provitamin A-Biofortified Maize Complementary Instant Porridge. *Diversity 2022, Vol. 14, Page 1088*, *14*(12), 1088. https://doi.org/10.3390/D14121088

Grönemeyer, J. L., Kulkarni, A., Berkelmann, D., Hurek, T., & Reinhold-Hurek, B. (2014). Rhizobia Indigenous to the Okavango Region in Sub-Saharan Africa: Diversity, Adaptations, and Host Specificity. *Applied and Environmental Microbiology*, *80*(23), 7244–7257. https://doi.org/10.1128/AEM.02417-14

Grönemeyer, J. L., & Reinhold-Hurek, B. (2018). Diversity of bradyrhizobia in subsahara Africa: A rich resource. *Frontiers in Microbiology*, *9*(SEP), 392369. https://doi.org/10.3389/FMICB.2018.02194/BIBTEX

Habel, J. C., Rasche, L., Schneider, U. A., Engler, J. O., Schmid, E., Rödder, D., Meyer, S. T., Trapp, N., Sos del Diego, R., Eggermont, H., Lens, L., & Stork, N. E. (2019). Final countdown for biodiversity hotspots. *Conservation Letters*, *12*(6), e12668. https://doi.org/10.1111/CONL.12668

Habib-ur-Rahman, M., Ahmad, A., Raza, A., Hasnain, M. U., Alharby, H. F., Alzahrani, Y. M., Bamagoos, A. A., Hakeem, K. R., Ahmad, S., Nasim, W., Ali, S., Mansour, F., & EL Sabagh, A. (2022). Impact of climate change on agricultural production; Issues, challenges, and opportunities in Asia. *Frontiers in Plant Science*, *13*, 925548. https://doi.org/10.3389/FPLS.2022.925548/XML

Harrison, M. T., Cullen, B. R., & Rawnsley, R. P. (2016). Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. *Agricultural Systems*, *148*, 135–148. https://doi.org/10.1016/J.AGSY.2016.07.006

He, X., Estes, L., Konar, M., Tian, D., Anghileri, D., Baylis, K., Evans, T. P., & Sheffield, J. (2019). Integrated approaches to understanding and reducing drought impact on food security across scales. *Current Opinion in Environmental Sustainability*, *40*, 43–54. https://doi.org/10.1016/J.COSUST.2019.09.006

Headey, D. D., & Jayne, T. S. (2014). Adaptation to land constraints: Is Africa different? *Food Policy*, *48*, 18–33. https://doi.org/10.1016/J.FOODPOL.2014.05.005

Holden, S. T. (2018). Fertilizer and sustainable intensification in Sub-Saharan Africa. *Global Food Security*, *18*, 20–26. https://doi.org/10.1016/J.GFS.2018.07.001

Horn, L., Shimelis, H., & Laing, M. (2015). Participatory appraisal of production constraints, preferred traits and farming system of cowpea in the northern Namibia: Implications for breeding. *Legume Research*, *38*(5), 691–700. https://doi.org/10.18805/lr.v38i5.5952

Hultgren, A., Carleton, T., Delgado, M., Gergel, D. R., Greenstone, M., Houser, T., Hsiang, S., Jina, A., Kopp, R. E., Malevich, S. B., McCusker, K. E., Mayer, T., Nath, I., Rising, J., Rode, A., & Yuan, J. (2022). Estimating Global Impacts to Agriculture from Climate Change Accounting for Adaptation. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.4222020

Hultgren, A., Carleton, T., Delgado, M., Gergel, D. R., Greenstone, M., Houser, T., Hsiang, S., Jina, A., Kopp, R. E., Malevich, S. B., McCusker, K. E., Mayer, T., Nath, I., Rising, J., Rode, A., & Yuan, J. (2025). Impacts of climate change on global agriculture accounting for adaptation. *Nature 2025 642:8068*, *642*(8068), 644–652. https://doi.org/10.1038/s41586-025-09085-w

Ingrao, C., Strippoli, R., Lagioia, G., & Huisingh, D. (2023). Water scarcity in agriculture: An overview of causes, impacts and approaches for reducing the risks. *Heliyon*, *9*(8), e18507. https://doi.org/10.1016/J.HELIYON.2023.E18507

Integrated Food Security Phase Classification. (2024). *Namibia: Acute Food Insecurity Situation*. https://www.ipcinfo.org/ipc-country-analysis/details-map/en/c/1157149/?iso3=NAM

IPCC. (2023). Future Global Climate: Scenario-based Projections and Near-term Information. In *Climate Change 2021 – The Physical Science Basis* (pp. 553–672). Cambridge University Press. https://doi.org/10.1017/9781009157896.006

IPCC. (2022). Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In *Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Cambridge University Press. https://doi.org/10.1017/9781009157988

Jefwa, J. M., Pypers, P., Jemo, M., Thuita, M., Mutegi, E., Laditi, M. A., Faye, A., Kavoo, A., Munyahali, W., Herrmann, L., Atieno, M., Okalebo, J. R., Yusuf, A., Ibrahim, A., Ndung'u-Magiroi, K. W., Asrat, A., Muletta, D., Ncho, C., Kamaa, M., … Kamaa, • M. (2022). Do Commercial Biological and Chemical Products Increase Crop Yields and Economic Returns Under Smallholder Farmer Conditions? *Challenges and Opportunities for Agricultural Intensification of the Humid Highland Systems of Sub-Saharan Africa*, 81–96. https://doi.org/10.1007/978-3-319-07662-1_7

Jeong, J., Jantke, K., Rasche, L., Eschenbach, A., Uchezuba, D., Reinhold-Hurek, B., & Schneider, U. A. (2025). Managing scarce water and land resources: The potentials of cowpea production in Namibia. *Environmental Development*, *54*, 101139. https://doi.org/10.1016/J.ENVDEV.2025.101139

Jomaa, L. H., McDonnell, E., & Probart, C. (2011). School feeding programs in developing countries: impacts on children's health and educational outcomes. *Nutrition Reviews*, *69*(2), 83–98. https://doi.org/10.1111/J.1753-4887.2010.00369.X

Jyoti, D. F., Frongillo, E. A., & Jones, S. J. (2005). Food insecurity affects school children's academic performance, weight gain, and social skills. *Journal of Nutrition*, *135*(12), 2831–2839. https://doi.org/10.1093/JN/135.12.2831

KAMANDA, J. K. (2025). AGRICULTURAL TRANSFORMATION FOR CLIMATE RESILIENCE: A REVIEW OF STRATEGIES, CHALLENGES, AND FUTURE DIRECTIONS IN SUB-SAHARAN AFRICA. *Https://Doi.Org/10.1142/S2630534825300015*, *07*(01). https://doi.org/10.1142/S2630534825300015

Kamara, A., Conteh, A., Rhodes, E. R., & Cooke, R. A. (2019). The relevance of smallholder farming to african agricultural growth and development. *African Journal of Food, Agriculture, Nutrition and Development*, *19*(1), 14043–14065. https://doi.org/10.18697/AJFAND.84.BLFB1010

Kanonge-Mafaune, G., Chiduwa, M. S., Chikwari, E., & Pisa, C. (2018). Evaluating the effect of increased rates of rhizobial inoculation on grain legume productivity. *Symbiosis*, *75*(3), 217–227. https://doi.org/10.1007/s13199-018-0550-7

Kebede, E. (2021). Competency of Rhizobial Inoculation in Sustainable Agricultural Production and Biocontrol of Plant Diseases. In *Frontiers in Sustainable Food Systems* (Vol. 5). Frontiers Media S.A. https://doi.org/10.3389/fsufs.2021.728014

Khan, R., Alabsi, A. A. N., & Muda, I. (2023). Comparing the effects of agricultural intensification on CO2 emissions and energy consumption in developing and developed countries. *Frontiers in Environmental Science*, *10*, 1065634. https://doi.org/10.3389/FENVS.2022.1065634/XML

Kirse, A., & Karklina, D. (2015). Integrated evaluation of cowpea (Vigna unguiculata (L.) Walp.) and maple pea (Pisum sativum var. arvense L.) spreads. In *Agronomy Research* (Vol. 13, Issue 4).

Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, *7*(3). https://doi.org/10.1088/1748-9326/7/3/034032

Kwakwa, P. A., Alhassan, H., & Adzawla, W. (2022). Environmental degradation effect on agricultural development: an aggregate and a sectoral evidence of carbon dioxide emissions from Ghana. *Journal of Business and Socio-Economic Development*, *2*(1), 82–96. https://doi.org/10.1108/JBSED-10-2021-0136/FULL/PDF

Kyei-Boahen, S., Savala, C. E. N., Chikoye, D., & Abaidoo, R. (2017). Growth and yield responses of cowpea to inoculation and phosphorus fertilization in different environments. *Frontiers in Plant Science*, *8*. https://doi.org/10.3389/fpls.2017.00646

Lange, S. (2019). Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). *Geoscientific Model Development*, *12*(7), 3055–3070. https://doi.org/10.5194/GMD-12-3055-2019

Liguori, J., Osei-Kwasi, H. A., Savy, M., Nanema, S., Laar, A., & Holdsworth, M. (2024). How do publicly procured school meals programmes in sub-Saharan Africa improve nutritional outcomes for children and adolescents: a mixed-methods systematic review. *Public Health Nutrition*, *27*(1). https://doi.org/10.1017/S1368980024001939

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A. J. B., & Yang, H. (2010). A high-resolution assessment on global nitrogen flows in cropland. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(17), 8035–8040. https://doi.org/10.1073/PNAS.0913658107

Liu, L., Hao, L., Zhang, Y., Zhou, H., Ma, B., Cheng, Y., Tian, Y., Chang, Z., & Zheng, Y. (2022). The CO2 fertilization effect on leaf photosynthesis of maize (Zea mays L.) depends on growth temperatures with changes in leaf anatomy and soluble sugars. *Frontiers in Plant Science*, *13*, 890928. https://doi.org/10.3389/FPLS.2022.890928/BIBTEX

Liu, W., Yang, H., Liu, J., Azevedo, L. B., Wang, X., Xu, Z., Abbaspour, K. C., & Schulin, R. (2016). Global assessment of nitrogen losses and trade-offs with yields from major crop cultivations. *The Science of the Total Environment*, *572*, 526–537. https://doi.org/10.1016/J.SCITOTENV.2016.08.093

Liu, X., Zhou, J., Liu, X. ;, & Zhou, J. (2021). Assessment of the Continuous Extreme Drought Events in Namibia during the Last Decade. *Water 2021, Vol. 13, Page 2942*, *13*(20), 2942. https://doi.org/10.3390/W13202942

Lu, C., & Fan, L. (2013). Winter wheat yield potentials and yield gaps in the North China Plain. *Field Crops Research*, *143*, 98–105. https://doi.org/10.1016/J.FCR.2012.09.015

Luchen, C. C., Uzabikiriho, J.-D., Chimwamurombe, P. M., & Reinhold-Hurek, B. (2018). Evaluating the Yield Response to Bio-Inoculants of Vigna unguiculata in the Kavango

Region in Namibia. *Journal of Plant Pathology & Microbiology*, *9*(10). https://doi.org/10.4172/2157-7471.1000456

Mabhaudhi, T., Mpandeli, S., Nhamo, L., Chimonyo, V. G. P., Nhemachena, C., Senzanje, A., Naidoo, D., Modi, A. T., Mabhaudhi, T., Mpandeli, S., Nhamo, L., Chimonyo, V. G. P., Nhemachena, C., Senzanje, A., Naidoo, D., & Modi, A. T. (2018). Prospects for Improving Irrigated Agriculture in Southern Africa: Linking Water, Energy and Food. *Water 2018, Vol. 10, 10*(12). https://doi.org/10.3390/W10121881

Maijo, S. N. (2018). Impact of School Feeding Programme on Learners' Academic Performance in Mlunduzi Ward, Tanzania. *International Journal of Educational Studies*, *5*(3), 125–130. https://doi.org/10.33687/EDUC.005.03.2667

Mekonnen, T. W., Gerrano, A. S., Mbuma, N. W., Labuschagne, M. T., Mekonnen, T. W., Gerrano, A. S., Mbuma, N. W., & Labuschagne, M. T. (2022). Breeding of Vegetable Cowpea for Nutrition and Climate Resilience in Sub-Saharan Africa: Progress, Opportunities, and Challenges. *Plants 2022, Vol. 11, 11*(12). https://doi.org/10.3390/PLANTS11121583

Metwally, A. M., El-Sonbaty, M. M., El Etreby, L. A., Salah El-Din, E. M., Abdel Hamid, N., Hussien, H. A., Hassanin, A. M., & Monir, Z. M. (2020). Impact of National Egyptian school feeding program on growth, development, and school achievement of school children. *World Journal of Pediatrics*, *16*(4), 393–400. https://doi.org/10.1007/s12519-020-00342-8

Mideksa, S., Getachew, T., Bogale, F., Woldie, E., Ararso, D., Samuel, A., Girma, M., Tessema, M., & Hadis, M. (2024). School feeding in Ethiopia: a scoping review. *BMC Public Health*, *24*(1), 1–13. https://doi.org/10.1186/S12889-023-17613-4/TABLES/4

Molotoks, A., Smith, P., & Dawson, T. P. (2021). Impacts of land use, population, and climate change on global food security. *Food and Energy Security*, *10*(1). https://doi.org/10.1002/FES3.261

Mostert, C. M. (2021). The impact of the school feeding programme on the education and health outcomes of South African children. *Children and Youth Services Review*, *126*, 106029. https://doi.org/10.1016/J.CHILDYOUTH.2021.106029

NAB, & FAO. (2021). *Rapid Assessment of Cowpea Production and Marketing in Namibia*. www.tridge.com

Namibia Agronomic Board. (2021). *A Crop Budget Guide: for Smallholder vegetable/crop Producers*.

Namibia Ministry of Education, W. (2013). *Namibian School Feeding Programme: Reference Manual*.

Namibia National Planning Commission. (2017). *Namibia's Fifth National Development Plan (NDP5)*.

Namibia National Planning Commission. (2018). *Is Agricultural Productivity an engine for growth?*

Namibia National Planning Commission. (2025). *Namibia's Sixth National Development Plan (NDP6)*.

Namibia Statistics Agency. (2023). *Namibia Census Mapping Basic Report 2019-2021*.

Nguyen, T.-H., Sahin, O., Howes, M., Nguyen, T.-H., Sahin, O., & Howes, M. (2021). Climate Change Adaptation Influences and Barriers Impacting the Asian Agricultural Industry. *Sustainability 2021, Vol. 13, 13*(13). https://doi.org/10.3390/SU13137346

Niang, I., Ruppel, O. C., Abdrabo, M. A., Dube, P., Leary, N., Schulte-Uebbing, L., Field, C., Dokken, D., Mach, K., Bilir, T., Chatterjee, M., Ebi, K., Estrada, Y., Genova, R., Girma, B., Kissel, E., & Levy, A. (2014). Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In *Aissa Toure Sarr*. Pieter Pauw.

Nickanor, N. M., & Kazembe, L. N. (2016). *Climate Change and Food Security in Namibia*.

Nnam, N. M., & Baiyeri, G. T. (2008). Evaluation of the Nutrient and Sensory Properties of Multimixes and Porridges Made from Maize, Soybean, and Plantain for Use as Complementary Food. *Ecology of Food and Nutrition*, *47*(1), 64–76. https://doi.org/10.1080/03670240701615374

Nwankwo, C. M., Mbanisi, B. O., Anakwenze, V. N., & Ezemba, C. C. (2015). Improvement on the Nutritional Value (Protein Quality) of Maize Based Pap with Soybean. *European Journal of Pharmaceutical and Medical Research*. https://papers.ssrn.com/abstract=3846255

Odero, E. E. (2017). ANALYSING THE CAUSAL RELATIONSHIP BETWEEN AGRICULTURAL VALUE ADDITION AND ECONOMIC GROWTH IN NAMIBIA. *European Journal of Basic and Applied Sciences*, *4*(2). www.idpublications.org

Oladeji, A. E., Bussie, M.-D., Ibironke, P., Therese, G., & David, C. (2016). Nutritional evaluation and consumer preference of legume fortified maize-meal porridge. *Journal of Food and Nutrition Research*, *4*(10), 664–670. https://doi.org/10.12691/jfnr-4-10-6

Oluwole, O., Ibidapo, O., Arowosola, T., Raji, F., Zandonadi, R. P., Alasqah, I., Lho, L. H., Han, H., & Raposo, A. (2023). Sustainable transformation agenda for enhanced global food and nutrition security: a narrative review. *Frontiers in Nutrition*, *10*, 1226538. https://doi.org/10.3389/FNUT.2023.1226538/BIBTEX

Orimoloye, I. R. (2022). Agricultural Drought and Its Potential Impacts: Enabling Decision-Support for Food Security in Vulnerable Regions. *Frontiers in Sustainable Food Systems*, *6*, 838824. https://doi.org/10.3389/FSUFS.2022.838824/BIBTEX

Pangapanga-Phiri, I., & Mungatana, E. D. (2021). Adoption of climate-smart agricultural practices and their influence on the technical efficiency of maize production under extreme weather events. *International Journal of Disaster Risk Reduction*, *61*. https://doi.org/10.1016/J.IJDRR.2021.102322

Pretty, J. (2008). Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1491), 447–465. https://doi.org/10.1098/RSTB.2007.2163

Rahal, I., & Elloumi, A. (2023). Climate change's effects on food Security in Sub-Saharan Africa (SSA). *MPRA Paper*. https://ideas.repec.org/p/pra/mprapa/118569.html

Rasche, L., Becker, J. N., Chimwamurombe, P., Eschenbach, A., Gröngröft, A., Jeong, J., Luther-Mosebach, J., Reinhold-Hurek, B., Sarkar, A., & Schneider, U. A. (2023). Exploring the benefits of inoculated cowpeas under different climatic conditions in Namibia. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-38949-2

Rasche, L., Katjana, J., Jantke, K., Uchezuba, D., & Schneider, U. A. (2025). Exploring the Plausibility of Inoculated Cowpeas as a Climate Adaptation Strategy for Namibian Smallholder Farmers. *Sustainability 2025, Vol. 17, Page 4041*, *17*(9), 4041. https://doi.org/10.3390/SU17094041

Results from the 2024 Global Survey of School Meal Programs © School Meal Programs Around the World. (2024). http://gcnf.org/global-reports/.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rodrigues Cruz, F. J., Júnior de Almeida, H., & Mathias dos Santos, D. M. (2014). Growth, nutritional status and nitrogen metabolism in Vigna unguiculata (L.) Walp is affected by aluminum. *Australian Journal of Crop Science*, *8*(7), 1132–1139.

Rombo, G. O., Taylor, J. R. N., & Minnaar, A. (2001). Effect of irradiation, with and without cooking of maize and kidney bean flours, on porridge viscosity and in vitro starch digestibility. *Journal of the Science of Food and Agriculture*, *81*(5), 497–502. https://doi.org/10.1002/JSFA.838

S. M. Karanja, S. M., Kibe, A. M., Karogo, P. N., & Mwangi, M. (2017). Effects of Intercrop Population Density and Row Orientation on Growth and Yields of Sorghum - Cowpea Cropping Systems in Semi Arid Rongai, Kenya. *Journal of Agricultural Science*, *6*(5). https://doi.org/10.5539/JAS.V6N5P34

Schröder, L. S., Rasche, L., Jantke, K., Mishra, G., Lange, S., Eschenbach, A., & Schneider, U. A. (2024). Combined effects of climate change and agricultural intensification on soil erosion in uphill shifting cultivation in Northeast India. *Land Degradation and Development*, *35*(2), 670–686. https://doi.org/10.1002/LDR.4944

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., & Reinhardt, J. (2017). Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, *17*(6), 1585–1600. https://doi.org/10.1007/S10113-015-0910-2/METRICS

Shilomboleni, H., Epstein, G., & Mansingh, A. (2024). Building resilience in Africa's smallholder farming systems: contributions from agricultural development interventions—a scoping review. *Ecology and Society, Published Online: 2024-09-31 | Doi:10.5751/ES-15373-290322*, *29*(3). https://doi.org/10.5751/ES-15373-290322

Shitaye, Z., Tadesse, B., & Enkuahone, K. (2024). Sources and intensity of access to agricultural information technologies by smallholder farmers: evidence from Northwest Ethiopia. *Frontiers in Sustainable Food Systems*, *8*, 1455037. https://doi.org/10.3389/FSUFS.2024.1455037/BIBTEX

Shrivastava, P., & Kumar, R. (2015). Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi Journal of Biological Sciences*, *22*(2), 123–131. https://doi.org/10.1016/J.SJBS.2014.12.001

Sithole, A., Olorunfemi, O. D., Sithole, A., & Olorunfemi, O. D. (2024). Sustainable Agricultural Practices in Sub-Saharan Africa: A Review of Adoption Trends, Impacts, and Challenges Among Smallholder Farmers. *Sustainability 2024, Vol. 16, 16*(22). https://doi.org/10.3390/SU16229766

Skalsky, R., Tarasovicová, Z., Balkovic, J., Schmid, E., Fuchs, M., Moltchanova, E., Kindermann, G., Scholtz, P., & McCallum, I. (2012). Global Homogeneous Response Units. In *PANGAEA*. https://doi.org/https://doi.org/10.1594/PANGAEA.775369

Slayi, M., Zhou, L., Dzvene, A. R., Mpanyaro, Z., Slayi, M., Zhou, L., Dzvene, A. R., & Mpanyaro, Z. (2024). Drivers and Consequences of Land Degradation on Livestock Productivity in Sub-Saharan Africa: A Systematic Literature Review. *Land 2024, Vol. 13, 13*(9). https://doi.org/10.3390/LAND13091402

Sugiyama, A., & Yazaki, K. (2012). *Root Exudates of Legume Plants and Their Involvement in Interactions with Soil Microbes*. 27–48. https://doi.org/10.1007/978-3-642-23047-9_2

Sulser, T., Wiebe, K. D., Dunston, S., Cenacchi, N., Nin-Pratt, A., Mason-D'Croz, D., Robertson, R. D., Willenbockel, D., & Rosegrant, M. W. (2021). *Climate Change and hunger: Estimating costs of adaptation in the agrifood system*. https://doi.org/10.2499/9780896294165

Sumberg, J., & Sabates-Wheeler, R. (2011). Linking agricultural development to school feeding in sub-Saharan Africa: Theoretical perspectives. *Food Policy*, *36*(3), 341–349. https://doi.org/10.1016/J.FOODPOL.2011.03.001

The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point (SOLAW 2021). (2021). *The State of the World's Land and Water Resources for Food and Agriculture – Systems at Breaking Point (SOLAW 2021)*. https://doi.org/10.4060/CB7654EN

Trisos, C. H., Adelekan, I. O., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., Ngaruiya, G., Olago, D., Simpson, N. P., & Zakieldeen, S. (2022). Africa. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In D. C. R. M. T. E. S. P. K. M. A. A. M. C. S. L. S. L. V. M. A. O. B. R. (eds.)]

[H.-O. Pörtner (Ed.), *Climate Change 2022: Impacts, Adaptation and Vulnerability.* . Cambridge University Press. https://doi.org/10.1017/9781009325844.011

UNESCO, United Nations Children's Fund, & WFP. (2023). Ready to learn and thrive: school health and nutrition around the world. In *Ready to learn and thrive: school health and nutrition around the world*. UNESCO. https://doi.org/10.54675/DSHQ1076

United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*.

USDA. (2019). *USDA National Nutrient Database for Standard Reference, Legacy Release*. Nutrient Data Laboratory, Beltsville Human Nutrition Research Centre, ARS, USDA. https://doi.org/https://doi.org/10.15482/USDA.ADC/1529216

Verguet, S., Limasalle, P., Chakrabarti, A., Husain, A., Burbano, C., Drake, L., & Bundy, D. A. P. (2020). The Broader Economic Value of School Feeding Programs in Low- and Middle-Income Countries: Estimating the Multi-Sectoral Returns to Public Health, Human Capital, Social Protection, and the Local Economy. *Frontiers in Public Health*, *8*, 587046. https://doi.org/10.3389/FPUBH.2020.587046/BIBTEX

Vogel, E., Donat, M. G., Alexander, L. V., Meinshausen, M., Ray, D. K., Karoly, D., Meinshausen, N., & Frieler, K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, *14*(5), 054010. https://doi.org/10.1088/1748-9326/AB154B

Wall, C., Tolar-Peterson, T., Reeder, N., Roberts, M., Reynolds, A., & Mendez, G. R. (2022). The Impact of School Meal Programs on Educational Outcomes in African Schoolchildren: A Systematic Review. *International Journal of Environmental Research and Public Health*, *19*(6), 3666. https://doi.org/10.3390/IJERPH19063666/S1

Welthungerhilfe, Concern Worldwide, & Institue for International Law of Peace and Armed Conflict. (2025). *2025 Global Hunger Index: 20 years of tracking progress: Time to recommit to zero hunger*. https://www.globalhungerindex.org/

WFP. (2024). *State of School Feeding Worldwide 2024*.

Why has Africa become a net food importer? (n.d.). Retrieved September 9, 2025, from https://www.fao.org/fsnforum/resources/reports-and-briefs/why-has-africa-become-net-food-importer

Williams, J. R., Gerik, T., Francis, L., Greiner, J., Magre, M., & Meinardus, A. (2013). *Environmental Policy Integrated Climate Model - User's Manual Version 0810*.

Williams, J. R., Jones, C. A., Kiniry, J. R., & Spanel, D. A. (1989). *The EPIC Crop Growth Model*.

World Bank. (2025). *The Global Water Security and Sanitation Partnership (GWSP) 2025 Annual Report*. https://www.worldbank.org/en/topic/water/publication/the-global-water-security-and-sanitation-partnership-gwsp-2025-annual-report

World Food Programme. (2023). *The State of School Feeding Worldwide 2022*. https://www.wfp.org/publications/state-school-feeding-worldwide-2022

World Health Organization., Food and Agriculture Organization of the United Nations., & United Nations University. (2007). *Protein and amino acid requirements in human nutrition*. World Health Organization.

Wudil, A. H., Usman, M., Rosak-Szyrocka, J., Pilař, L., & Boye, M. (2022). Reversing Years for Global Food Security: A Review of the Food Security Situation in Sub-Saharan Africa (SSA). *International Journal of Environmental Research and Public Health*, *19*(22), 14836. https://doi.org/10.3390/IJERPH192214836

Xiong, W., Skalský, R., Porter, C. H., Balkovič, J., Jones, J. W., & Yang, D. (2016). Calibration-induced uncertainty of the EPIC model to estimate climate change impact on global maize yield. *Journal of Advances in Modeling Earth Systems*, *8*(3), 1358–1375. https://doi.org/10.1002/2016MS000625

Yadav, A. N., Kour, D., Kaur, T., Devi, R., Yadav, A., Dikilitas, M., Abdel-Azeem, A. M., Ahluwalia, A. S., & Saxena, A. K. (2021). Biodiversity, and biotechnological contribution of beneficial soil microbiomes for nutrient cycling, plant growth improvement and nutrient uptake. *Biocatalysis and Agricultural Biotechnology*, *33*, 102009. https://doi.org/10.1016/J.BCAB.2021.102009

Zenebe, M., Gebremedhin, S., Henry, C. J., & Regassa, N. (2018). School feeding program has resulted in improved dietary diversity, nutritional status and class attendance of school children. *Italian Journal of Pediatrics*, *44*(1), 1–7. https://doi.org/10.1186/S13052-018-0449-1/TABLES/4

Zhao, J., Chen, J., Beillouin, D., Lambers, H., Yang, Y., Smith, P., Zeng, Z., Olesen, J. E., & Zang, H. (2022). Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. *Nature Communications*, *13*(1). https://doi.org/10.1038/s41467-022-32464-0

Zhu, X., & Troy, T. J. (2018). Agriculturally Relevant Climate Extremes and Their Trends in the World's Major Growing Regions. *Earth's Future*, *6*(4), 656–672. https://doi.org/10.1002/2017EF000687

7. Appendix

Appendix: Creation of Homogeneous Response Units for Namibia

Homogeneous response units (HRUs) for Namibia combine terrestrial areas with similar climate and landscape characteristics. These units reflect the country's diverse landscape and ecological conditions and support the spatially explicit modeling of agricultural and agro-ecological systems.

Spatial Resolution and Data Processing

- A 30-minute spatial resolution grid and country-level administrative boundaries provide the parent grid.
- Within each parental grid cell, soil texture, slope, and altitude data with a spatial resolution of 5 minutes are compiled.
- Soil texture, slope, and altitude data are three landscape characteristics relatively stable over time (even under climate change) and hardly adjustable by farmers.
- For each landscape characteristic, several classes were defined (see below).
- All 5-minute areas within a 30-minute parent cell are combined to create a homogeneous response unit if altitudes, slope, and soil texture values fall within the same class. For Namibia, this procedure led to 737 HRUs.

Classification of Landscape Characteristics

Altitude Classification

- Classes:
- Class 1: 0 - 500 m
- Class 2: 501 - 1000 m
- Class 3: 1001 - 1500 m
- Class 4: 1501 - 2000 m
- Class 5: >2000 m

Data Sources:

- SRTM (Shuttle Radar Topography Mission): Provides elevation data with a resolution of 3 arc seconds (approximately 90 m).
- GTOPO30: A global digital elevation model with a resolution of 30 arc seconds (approximately 1 km).

Slope Classification

- Classes:
- Class 1: 0 - 5%

- Class 2: 6 - 15%
- Class 3: 16 - 30%
- Class 4: >30%

Data Sources:

- Derived from the SRTM and GTOPO30 datasets.

Soil Texture Classification

Classes:

- Class 1: Sandy
- Class 2: Loamy
- Class 3: Clay
- Class 4: Silty
- Class 5: Peaty
- Class 6: Saline
- Class 7: Rocky

Data Sources:

- Digital Soil Map of the World (DSMW): Provides soil data at approximately 5 arc minutes resolution.
- World Inventory of Soil Emission Potentials (WISE): Offers additional soil characteristics.

Soil Type Classifications

1. Sand

- Definition: Sand consists of coarse particles ranging in size from 0.05 mm to 2 mm in diameter. It is characterized by its gritty texture and high drainage capacity.
- Properties:
  - Water Retention: Low; sandy soils drain quickly and do not retain moisture well.
  - Nutrient Content: Generally low in nutrients, requiring amendments for effective agricultural use.
  - Aeration: Excellent; allows for good air movement and root penetration.

2. Loam

- Definition: Loam is a balanced mixture of sand, silt, and clay particles. Typically, it contains about 40% sand, 40% silt, and 20% clay.
- Properties:
  - Water Retention: Moderate; retains moisture better than sand while still allowing for good drainage.
  - Nutrient Content: High; loamy soils are often rich in organic matter and nutrients, making them ideal for farming.

- Aeration: Good; provides sufficient air space for roots while maintaining moisture.

3. Clay

- Definition: Clay consists of very fine particles smaller than 0.002 mm in diameter. It has a smooth texture and is sticky when wet.
- Properties:
    - Water Retention: High; clay soils hold water well but can become waterlogged.
    - Nutrient Content: Generally high in nutrients due to the ability to hold cations (positively charged ions).
    - Aeration: Poor; compacted clay can restrict root growth and water movement.

4. Silt

- Definition: Silt particles range from 0.002 mm to 0.05 mm in size. Silt has a smooth texture and retains moisture better than sand but drains less effectively than loam.
- Properties:
    - Water Retention: Moderate; retains more moisture than sand but less than clay.
    - Nutrient Content: Moderate to high; silt can be fertile but may require organic matter to improve structure.
    - Aeration: Fair; better than clay but can become compacted.

5. Other Soil Types

- Peaty Soil: Rich in organic matter, typically found in wetland areas, with high moisture retention capabilities.
- Saline Soil: Contains high levels of soluble salts, which can affect plant growth negatively.
- Rocky Soil: Composed of larger fragments of rock, often found in mountainous regions.