Towards sustainable agricultural land use in Nepal under climate change: The role of efficient irrigation and fertilizer application.

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This dissertation is dedicated to my small family;

to my wife Sulochana, my two sweet daughters Aavni and Siya, my father Sitaram and My mother Punmaya, ……………………………

Declaration of authorship

Amit Kumar Basukala, born in Bhaktapur, Nepal, on 11th September of 1982.

All the scientific papers published, submitted and under consideration, planned to be submitted and their detailed summaries constitute an important portion of my cumulative dissertation, reflecting my scientific research. These papers were chosen due to my significant personal input, as demonstrated by my role as the lead author for each article. This involvement encompassed various tasks such as conceptualization, developing methodologies, data procurement, literature review, results analysis, writing manuscripts and original draft preparation, preparation of tables and figures, drafting, submitting, and follow up of the review process for each publication. It is also crucial to recognize the valuable contributions of the co-authors to these papers, which are indisputable and are listed below. Furthermore, none of the scientific articles included in this dissertation have been or are presently incorporated into any other cumulative dissertation.

Chapter	Title	Contribution of co-authors
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List of Acronyms and Initialisms

AEZ	Agro-Ecological Zones
ARMIS	Agriculture Result Monitoring Information System
AWD	Alternate Wetting and Drying
CBS Nepal	Central Bureau of Statistics Nepal
CCE	Canal Conveyance Efficiency
CGIAR	Consultative Group for International Agricultural Research
CH4	Methane
CMIP6	phase 6 of the Coupled Model Intercomparison Project
CO2	Carbon Dioxide
DI	Deficit Irrigation
DAP	Diammonium phosphate
DAT	Days after transplanting
DAYCENT	Daily Century Model
DHM	Department of Hydrology and Meteorology
DNDC	Denitrification-Decomposition Model
DOA	Department of Agriculture
DOLS	Department of Livestock Services
DoWRI	Department of Water Resources and Irrigation
E	Evaporation
EPIC	Environmental Policy Integrated Climate model
ESM	Earth System Model
ET	Evapotranspiration
ETc	Crop Evapotranspiration
ETo	Reference Crop Evapotranspiration
FAO	Food and Agriculture Organization
GADM	Global Administrative areas database
GFDL	Geophysical Fluid Dynamics Laboratory
GCM	Global Climate Model
GEOBENE	Global Earth Observation-Benefit Assessment
GHG	Green House Gas
GoN	Government of Nepal
GSET	Growing season evapotranspiration in mm
H	Harvesting
ha	Hectares
HI	Harvest Index
HRU	Homogenous response Units
ICIMOD	International Centre for Integrated Mountain Development
IMP	Irrigation Master Plan
IMT	Irrigation management transfer
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre-Simon Laplace
IR	Irrigation
IRRI	International Rice Research Institute
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ISF	Irrigation Service Fee
K	Potassium

kg	Kilogram
LAI	Leaf Area Index
mm	Millimeter
MoAD	Ministry of Agriculture Development Nepal
MPI	Max Planck Institute
N	Mineral Nitrogen
N2O	Nitrous Oxide
NARC	Nepal Agriculture Research Center
NPR	Nepalese Rupee
NSE	Nash-Sutcliffe efficiency
O	Over-bund flow
OC	Organic Carbon
OFWM	On-farm water management
P	Phosphorous
PBIAS	Percent Bias
PMAMP	Prime Minister Agriculture Modernization Project
RE	Relative Error
r	correlation coefficient
R	Rainfall
RQ	Research Question
R&D	Research and Development
SimU	Simulation Units
S	Seepage
SDGs	Sustainable Development Goals
SSPs	Shared Socioeconomic Pathway
SRI	System of Rice Intensification
STU	Soil typological units
SRTM	Shuttle Radar Topography Mission
t	tonnes
T	Transpiration
TP	Transplanting
USD	United States Dollar
WFP	World Food Programme
Y/Yd	Yield

Abstract

The increase in global food demand is expected to rise by 35% to 56% from 2010 to 2050, which poses a significant challenge for humanity, particularly in the face of a growing population and climate change. Achieving a balance between meeting, this increased demand for food and feed while ensuring sustainable agricultural systems without encroaching on natural ecosystems and safeguarding scarce natural resources such as water is imperative, particularly in light of projected climate change impacts. A considerable part of the world's agricultural land is currently not realizing its maximum productivity potential. Nepal is among these regions, where inadequate mineral nutrient use, insufficient management options, and inadequate irrigation water supply significantly contribute to the existing yield gaps.

Enhancing food production to achieve food self-sufficiency is the foremost objective in Nepal. Nepal's Ministry of Agriculture Development had proposed an Agriculture Development Strategy to transform the agricultural sector, which focuses on raising agricultural productivity through efficient fertilizer use, expanding irrigated areas, improving irrigation efficiency, and promoting efficient and sustainable farming practices.

In this dissertation, I endeavored to model some of the objectives outlined in the Agriculture development strategy and investigate current and future agriculture potential on a national scale in Nepal. Specifically, the primary goal of this thesis is to analyze the current yield gap of major cereal crops in Nepal, proposing ways to narrow it down, and then evaluate different scenarios of the sustainable utilization of water and mineral nutrients in the future, considering the impacts of climate change on agricultural croplands. To achieve this objective, the study is structured into three main chapters: (1) Model-based yield gap assessment in Nepal's diverse agricultural landscape, (2) Effect of irrigation canal conveyance efficiency enhancement on crop productivity under climate change in Nepal and, (3) Assessment of the effect of Alternate Wetting and Drying (AWD) and Continuous flooding (CF) in rice production in Terai Nepal.

First, I quantified the gap between current and potentially attainable yields in Nepal and determined the additional amount of fertilizer and irrigation required to bridge this gap. I then assessed the country's potential to achieve self-sufficiency in cereal food production. The findings suggest that Nepal could attain food self-sufficiency if there is consistent and effective management of mineral nutrients and water supply. Results showed considerable average yield gaps in Nepal which are 3.0 t/ha (wheat), 2.7 t/ha (rice), 2.9 t/ha (maize), 0.4 t/ha (barley), and 0.5 t/ha (millet). The pathways to narrow down this yield gap are by efficiently using additional irrigation water and fertilizer application. Cereal yields can be improved by 0.4 to 1.3 t/ha (rice), 0.1 to 2.3 t/ha (wheat), 1.6 to 1.9 t/ha (maize), 0.1 to 0.4 t/ha (millet), and 0.1 to 0.3 t/ha (barley) with irrigation water and fertilizer application, respectively.

I then assessed the potential impact of expanding irrigated areas in the near future (2023-2050) and far future (2075-2100) periods with three canal conveyance efficiency (30%, 50% and 70%) on the productivity of rice, maize, and wheat under three climate change scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5), utilizing three bias-adjusted Coupled Model Intercomparison Project based general circulation models (GFDL-ESM4, MPI-ESM1-2-HR, and IPSL-CM6A-LR). Results indicated that increasing canal conveyance efficiency to 30%, coupled with expanded irrigated areas and adjusted fertilization rates, could boost yields up to 3t/ha per hectare across all three crops at the national level in the future. The results also indicated that in future, improving canal conveyance efficiency from 30% to 50% increases yields up to 0.6 t/ha for maize and up to 1.2 t/ha for rice, while further improvement to 70% results in increases of up to 1.2 t/ha for maize and 2.1 t/ha for rice in the Terai region. The benefits of improved canal conveyance efficiency vary by location, with the subtropical Terai region experiencing the most and the mountain regions showing the least. I found that achieving canal conveyance efficiencies of 70% in the Terai region, 50% in the hill region, and 30% in the mountains is sufficient to enhance crop yields.

Finally, I found that adopting the climate-friendly water-conserving measure of Alternate Wetting and Drying over the conventional Continuous Flooding method for rice in the Terai region in the near future (2023 – 2050) has resulted in significant improvements across multiple aspects. First, rice yields increased by 0.2 to 1.4 t/ha after implementing alternate wetting and drying practices. Additionally, irrigation amounts were reduced by 350 to 450mm under the Alternate Wetting and Drying method, which suggests improved water use. In addition, there was a considerable decrease in methane emissions by 23 to 27 Gg CH4 yr-1 in the Terai region with the Alternate Wetting and Drying practice, demonstrating this approach's environmental benefits.

In summary, this doctoral thesis aims to contribute to the ongoing discourse of feeding a growing national population through domestic production, taking into account food self-sufficiency and food security in Nepal, a low-input use developing country with rugged terrain and multiple agro-climatic zones. The pathways to achieve this food self-sufficiency and food security in a sustainable manner were analyzed. These pathways encompass, first, the closing yield gaps of major cereal crops of Nepal through the efficient utilization of fertilizers and water; second, expansion of irrigated areas and enhancement of canal conveyance efficiency; and third, adoption of climate-smart adaptation measure alternate wetting and drying methods in rice cultivation.

Zusammenfassung

Es wird erwartet, dass der weltweite Nahrungsmittelbedarf von 2010 bis 2050 um 35 % bis 56 % ansteigen wird, was die Menschheit vor eine große Herausforderung stellt, insbesondere angesichts der wachsenden Bevölkerung und des Klimawandels. Ein Gleichgewicht zwischen der Deckung dieser steigenden Nachfrage nach Lebens- und Futtermitteln und der Gewährleistung nachhaltiger landwirtschaftlicher Systeme ohne Beeinträchtigung natürlicher Ökosysteme und dem Schutz knapper natürlicher Ressourcen wie Wasser ist unbedingt erforderlich, insbesondere angesichts der prognostizierten Auswirkungen des Klimawandels. Ein beträchtlicher Teil der weltweiten landwirtschaftlichen Nutzfläche schöpft derzeit nicht sein maximales Produktivitätspotenzial aus. Nepal gehört zu diesen Regionen, in denen ein unzureichender Einsatz von mineralischem Dünger, unzureichende Bewirtschaftungsmöglichkeiten und eine unzureichende Versorgung mit Bewässerungswasser erheblich zu den bestehenden Ertragslücken beitragen.

Die Steigerung der Nahrungsmittelproduktion zur Erreichung der Selbstversorgung mit Nahrungsmitteln ist das oberste Ziel in Nepal. Das nepalesische Ministerium für landwirtschaftliche Entwicklung hat eine Entwicklungsstrategie für die Landwirtschaft vorgeschlagen, um den Agrarsektor umzugestalten. Diese Strategie konzentriert sich auf die Steigerung der landwirtschaftlichen Produktivität durch effizienten Düngemitteleinsatz, die Ausweitung der bewässerten Flächen, die Verbesserung der Bewässerungseffizienz und die Förderung effizienter und nachhaltiger landwirtschaftlicher Praktiken.

In dieser Dissertation versuche ich, einige der in der Entwicklungsstrategie für die Landwirtschaft dargelegten Ziele zu modellieren und das derzeitige und künftige landwirtschaftliche Potenzial auf nationaler Ebene in Nepal zu untersuchen. Konkret besteht das Hauptziel dieser Arbeit darin, die derzeitige Ertragslücke bei den wichtigsten Getreidearten in Nepal zu analysieren und Möglichkeiten zu ihrer Verringerung vorzuschlagen. Anschließend werden verschiedene Szenarien für die nachhaltige Nutzung von Wasser und mineralischem Dünger in der Zukunft unter Berücksichtigung der Auswirkungen des Klimawandels auf landwirtschaftliche

Anbauflächen bewertet. Um dieses Ziel zu erreichen, ist die Studie in drei Hauptkapitel gegliedert: (1) Modellgestützte Bewertung der Ertragslücke in Nepals vielfältiger Agrarlandschaft, (2) Auswirkung der Verbesserung der Förderleistung von Bewässerungskanälen auf die Pflanzenproduktivität unter dem Klimawandel in Nepal, und (3) Bewertung der Auswirkungen von Alternate Wetting and Drying (AWD) und Continuous flooding (CF) auf die Reisproduktion im Terai Nepals.

Zuerst bezifferte ich die Lücke zwischen den derzeitigen und den potenziell erzielbaren Erträgen in Nepal und ermittelte die zusätzliche Menge an Düngemitteln und Bewässerung, die erforderlich wäre, um diese Lücke zu schließen. Anschließend bewertete ich das Potenzial des Landes, die Selbstversorgung mit Nahrungsmitteln aus Getreide zu erreichen. Die Ergebnisse deuten darauf hin, dass Nepal die Selbstversorgung mit Nahrungsmitteln erreichen könnte, wenn es eine konsequente und wirksame Bewirtschaftung der Mineralstoffe und der Wasserversorgung betreibt. Die Ergebnisse zeigen erhebliche durchschnittliche Ertragslücken in Nepal, die bei 3,0 t/ha (Weizen), 2,7 t/ha (Reis), 2,9 t/ha (Mais), 0,4 t/ha (Gerste) und 0,5 t/ha (Hirse) liegen. Der Weg zur Verringerung dieser Ertragslücke führt über die effiziente Nutzung von zusätzlichem Bewässerungswasser und den Einsatz von Düngemitteln. Die Getreideerträge können durch Bewässerung und Düngung um 0,4 bis 1,3 t/ha (Reis), 0,1 bis 2,3 t/ha (Weizen), 1,6 bis 1,9 t/ha (Mais), 0,1 bis 0,4 t/ha (Hirse) und 0,1 bis 0,3 t/ha (Gerste) verbessert werden.

Anschließend bewertete ich die potenziellen Auswirkungen einer Ausweitung der bewässerten Flächen in der nahen Zukunft (2023-2050) und in der fernen Zukunft (2075-2100) mit drei Kanaleffizienzen (30 %, 50 % und 70 %) auf die Produktivität von Reis, Mais und Weizen unter drei Klimawandelszenarien (SSP1-2. 6, SSP3-7.0, SSP5-8.5) unter Verwendung von drei verzerrungsbereinigten, auf dem Coupled Model Intercomparison Project basierenden allgemeinen Zirkulationsmodellen (GFDL-ESM4, MPI-ESM1-2-HR, und IPSL-CM6A-LR). Die Ergebnisse deuten darauf hin, dass eine Erhöhung der Kanalförderleistung auf 30 % in Verbindung mit einer Ausweitung der bewässerten Flächen und einer angepassten Düngung die Erträge bei allen drei Kulturen auf nationaler Ebene in Zukunft um bis zu 3 t/ha pro Hektar steigern könnte. Die

Ergebnisse deuten auch darauf hin, dass eine Verbesserung der Kanaleffizienz von 30 % auf 50 % die Erträge bei Mais um bis zu 0,6 t/ha und bei Reis um bis zu 1,2 t/ha erhöht, während eine weitere Verbesserung auf 70 % in der Terai-Region zu Steigerungen von bis zu 1,2 t/ha bei Mais und 2,1 t/ha bei Reis führt. Die Vorteile einer verbesserten Kanaleffizienz variieren je nach Standort, wobei die subtropische Terai-Region am meisten und die Bergregionen am wenigsten davon profitieren. Ich habe herausgefunden, dass eine Effizienz der Kanalisation von 70 % in der Terai-Region, 50 % in der Hügelregion und 30 % in den Bergen ausreicht, um die Ernteerträge zu steigern.

Schließlich habe ich herausgefunden, dass die Einführung der klimafreundlichen wassersparenden Maßnahme der abwechselnden Befeuchtung und Trocknung gegenüber der herkömmlichen kontinuierlichen Überflutungsmethode für Reis in der Terai-Region in naher Zukunft (2023 - 2050) zu erheblichen Verbesserungen in mehreren Aspekten geführt hat. Erstens stiegen die Reiserträge nach Einführung der alternierenden Befeuchtung und Trocknung um 0,2 bis 1,4 t/ha. Darüber hinaus wurden die Bewässerungsmengen bei der alternativen Befeuchtungs- und Trocknungsmethode um 350 bis 450 mm reduziert, was auf eine verbesserte Wassernutzung schließen lässt. Darüber hinaus wurden die Methanemissionen in der Terai-Region mit der alternativen Befeuchtungs- und Trocknungsmethode um 23 bis 27 Gg CH4 pro Jahr erheblich gesenkt, was den ökologischen Nutzen dieses Ansatzes belegt.

Zusammenfassend lässt sich sagen, dass diese Doktorarbeit einen Beitrag zum aktuellen Diskurs über die Ernährung einer wachsenden Bevölkerung durch einheimische Produktion leisten soll, unter Berücksichtigung der Selbstversorgung mit Nahrungsmitteln und der Ernährungssicherheit in Nepal, einem Entwicklungsland mit geringem Input und zerklüftetem Terrain und mehreren agroklimatischen Zonen. Die Wege zur Erreichung dieser Selbstversorgung mit Nahrungsmitteln und der Ernährungssicherheit auf nachhaltige Weise wurden analysiert. Diese Wege umfassen erstens die Schließung von Ertragslücken bei den wichtigsten nepalesischen Getreidearten durch eine effiziente Nutzung von Düngemitteln und Wasser, zweitens die Ausweitung der bewässerten Flächen und die Verbesserung der Effizienz der

Kanalisation und drittens die Anwendung von klimafreundlichen Anpassungsmaßnahmen wie alternativen Befeuchtungs- und Trocknungsmethoden im Reisanbau.

Chapter 1

1 Introduction and Overview

Addressing the issue of eradicating global hunger and ensuring food security for the rising world population remains a significant future global challenge for humankind (Doukas and Nikas, 2022; Mirzabaev et al., 2023; Pawlak and Kolodziejczak, 2020; van Dijk et al., 2021). A sustainable increase in food production without substantial environmental degradation and without exerting undue pressure on natural resources is the only viable solution to alleviate this challenge (Pawlak and Kolodziejczak, 2020; Springmann et al., 2018). However, this solution is compounded by the prospect of confronting a changing climate, potentially reduced availability of fresh water for irrigation, diminishing arable land, and escalating soil degradation (Mirzabaev et al., 2023; Senapati et al., 2022). Developing countries with a high climate risk index, insufficient utilization of agricultural inputs, and reduced provision of efficient irrigation water are expected to be severely impacted by climate change (Gerber et al., 2024). These nations also face the challenge of restricted access to infrastructure and inadequate climate-friendly technological advancements, further exacerbating their vulnerability to climate-related disruptions (IPCC, 2023).

Closing the existing yield gap using sustainable extensive agriculture in subsistence agriculture-prone areas to enhance crop productivity is one of the few sustainable solutions to this problem (Gerber et al., 2024; Mueller et al., 2012). This improved productivity helps to achieve the United Nations Sustainable Development Goals (SDGs), which are no poverty, ensuring zero hunger, promoting decent work and economic growth, climate action, and supporting life on land (UN, 2016). A significant portion of agricultural land worldwide fails to achieve its maximum productivity potential (Foley et al., 2011). Ensuring food security requires a fundamental transition in these low-productivity areas and countries (Pawlak and Kolodziejczak, 2020). If possible, these countries need to move away from dependence on imports of foods towards achieving self-sufficiency, and ideally, even exporting food surplus (Ge et al., 2021). Countries prioritizing domestic food production over imports can unlock their agricultural potential and harness their natural resources more effectively. This approach strengthens local economies, reduces dependency on international markets, enhances food sovereignty, and ensures access to nutritious food for all citizens (Leventon and Laudan, 2017). Furthermore, shifting towards local food production promotes environmental sustainability by minimizing carbon emissions associated with long-distance transportation and indirect land-use management emission related to imported food production (Pradhan et al., 2015; Shabir et al., 2023). However, this shift may also lead to an increase in agricultural emissions associated with production, utilization, and transportation of fertilizer (Pradhan et al., 2015; Staniszewski et al., 2023; Yu et al., 2024).

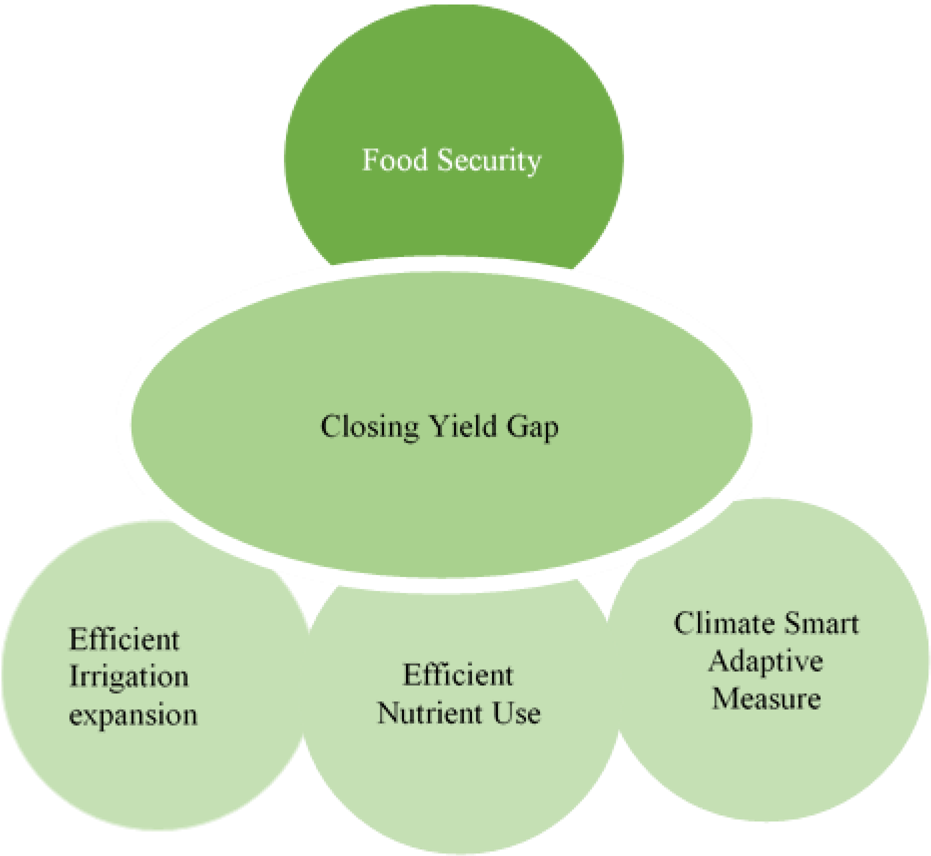

Figure 1-1. Pillars of Food Security in developing countries

Significant challenges to achieving food self-sufficiency arise from climate change-induced factors such as rising temperatures, changing rainfall patterns, and a rise in the incidence of extreme weather events, which impact crop yields primarily due to water availability (Mirzabaev et al., 2023). Addressing these challenges effectively requires the implementation of adaptive measures that enhance crop resilience to the impacts of climate change-induced water scarcity (Eldho et al., 2023; Iglesias and Garrote, 2015; Phung et al., 2022). The adaptive measures include improving water availability, reducing losses, efficient water management techniques, breeding drought-resilient crop varieties, optimizing agronomic practices against droughts, and adopting climate-smart agricultural approaches (Eldho et al., 2023). Expanding irrigation infrastructure with a focus on improving canal conveyance efficiency can serve as an essential adaptive measure in the context of climate change (Bekchanov, 2024; Haymale et al., 2020). This measure enhances water availability for agriculture and helps mitigate the impacts of drought, erratic precipitation patterns, and water scarcity on crop production.

Expanding and intensifying irrigated agriculture to increase crop yields to meet future food demand may, however, exacerbate environmental consequences (Beltran-Peña et al., 2020; Pawlak and Kolodziejczak, 2020; Staniszewski et al., 2023; Tittonell, 2014; Yu et al., 2024). Besides energy use in industry, building, and transportation, the agricultural sector is a significant source of greenhouse gas emissions, which plays a substantial role in environmental transformation (Ritchie, 2020). The agriculture sector is estimated to contribute directly and indirectly to approximately one-third of global anthropogenic greenhouse gas (Ivanovich et al., 2023). Therefore, it is imperative to identify methods for sustainable agricultural intensification, which involve closing yield gaps through efficient input usage while minimizing associated environmental impacts. Studying the effects of adaptive crop management practices like alternate wetting and drying (AWD) on water conservation, crop yield enhancement, and methane emissions in rice would be beneficial in addressing these challenges.

In summary, as shown in Figure 1-1, researching (i) the estimation of the current status of yield gaps and strategies to close the gaps, (ii) the impact of irrigation expansion coupled with improvements in canal conveyance efficiency and appropriate fertilizer application, and (iii) the impact of adaptive measures to mitigate greenhouse gas emissions while enhancing yield and water productivity can provide valuable insights for evidence-based decision-making. Such a study can contribute to developing climate-resilient agricultural systems that ensure food security and sustainable livelihoods for future generations.

Hence, this thesis aims to contribute to the ongoing discourse on feeding a growing population through local production, utilizing available water resources efficiently, and mitigating human-induced environmental changes at a regional scale. The analysis covers a national perspective of Nepal, representing the developing world with a high climate risk index (Eckstein et al., 2021), characterized by insufficient provision and utilization of agricultural inputs, insufficient irrigated areas, restricted infrastructure access, and inadequate climate-friendly technological advancement. This study provides a valuable local perspective through which Nepal's food security can be enhanced sustainably.

1.1 Nepal economy and agriculture sector

Nepal is an ancient Asian country located on the Southern slopes of the central Himalayas between latitudes 26° 22’ N and 30° 27’ N and longitudes 80° 00’ E and 88° 00’ E (Figure 1-2). Divided into seven provinces and 77 districts, the nation’s terrain is categorized into five physiographic regions: Terai, Siwaliks, Middle Mountains, High Mountains, and High Himalayas, which are further classified into three zones: the Terai, the Hill, and the Himalayas (Kansakar et al., 2004; Shrestha and Aryal, 2011). The country’s altitude ranges from 60 meters above sea level to 8,850 meters, posing a complex topography (Shrestha and Aryal, 2011). Nepal boasts a highly varied climate, classified into subtropical, tropical, temperate, subalpine, alpine, and arctic (Paudel et al., 2021). Nepal experiences four distinct seasons, each with unique weather patterns: the pre-monsoon season from March to May, the summer monsoon from June to September, the post-monsoon season from October to November, and the winter period from December to February. The average annual precipitation is approximately 1,800 mm (Shrestha and Aryal, 2011). Seasonal temperature variations occurs, with summer temperatures ranging from 20 °C to 35 °C and winter temperatures ranging from 2 °C to 12 °C (Department of Hydrology and Meteorology (DHM), 2015). Nepal’s primary crops include rice, maize, wheat, millet, and barley, while major cash crops are tea, coffee, and sugarcane. Common livestock includes cattle, buffaloes, goats, sheep, and poultry (MoALD, 2023). The typical diet consists mainly of staples like cereals (rice, flour of wheat, maize, millet and barley), lentils (dal), and seasonal vegetables, accompanied by pickles, and proteins derived from pulses, chicken, fish, and occasionally red meat (Liu et al., 2023).

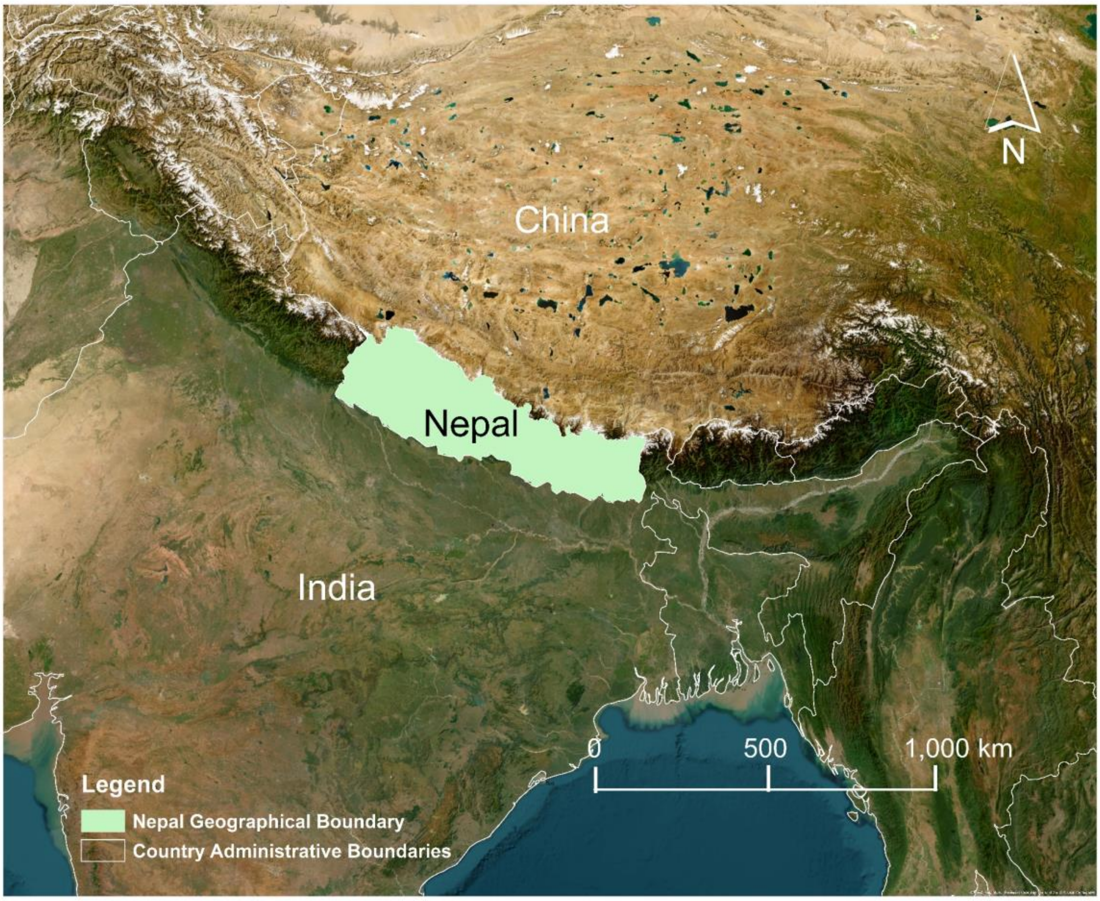

Figure 1-2. Location of Case Study Region Nepal in South Asia. Source of background imagery: Esri, and the GIS User Community.

Nepal is classified as a low, middle-income nation with a GDP per capita of US$ 1336.5 in 2022 (WorldBank, 2022). Nepal's economic growth trajectory has been underwhelming despite having a youthful population, strategic geographic positioning between two major and rapidly expanding economies (India and China), international support, and boasting natural beauty (Pokhrel, 2019). Over the period from 1965 to 2022, the country's real per capita GDP saw only a meager average annual growth rate of 3.8% (WorldBank, 2022). The agriculture sector is still the biggest sector of Nepal's economy after the service sector, contributing 21.06% to GDP and generating employment for 60% of Nepal's population, as shown in Figure 1-3 (MoALD, 2023). It is expected that the estimated expenditure elasticities, based on consumer budget data, will undergo a 25% reduction by the year 2035 (Pokhrel, 2019).

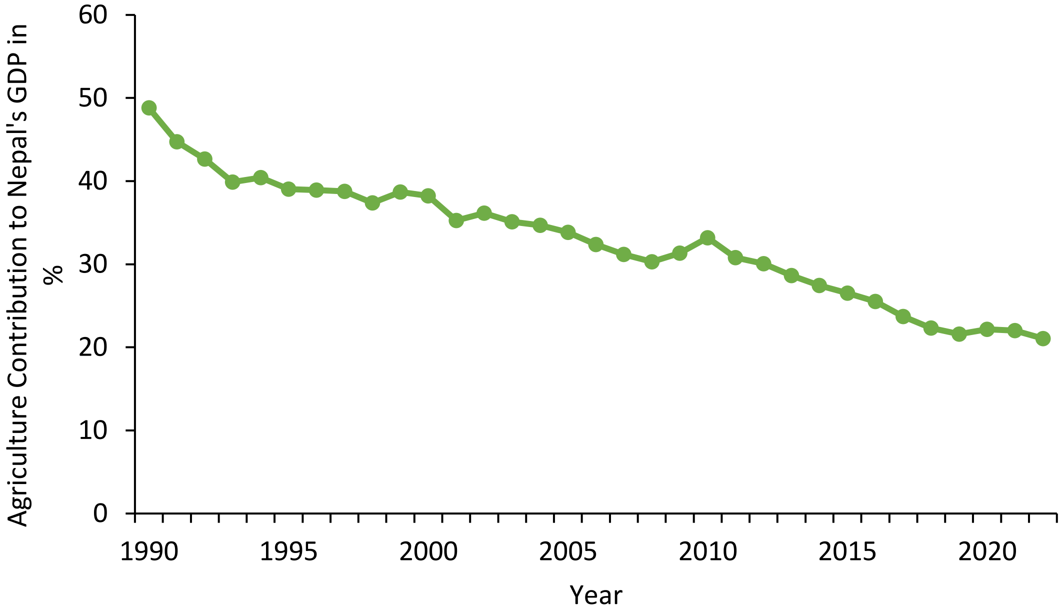

Figure 1-3: Contribution of Agriculture Sector in Nepal's GDP from 1990 to 2022

Agricultural exports still play a vital role in generating significant revenue for the country. However, the agriculture sector faces numerous challenges hindering its growth and competitiveness (Basukala and Rasche, 2022; DoWRI, 2019; MoAD, 2014). Some of the major challenges are listed below:

Low Productivity: While agriculture contributes significantly to GDP and employment, its productivity growth has been slow compared to neighboring countries. Low yields and a lack of technical advancements are significant concerns. Nepal's Agricultural Development Strategy (ADS), spanning from 2015 to 2035, reveals that the nation stands at the 46th position among the 52 countries falling below the Global Hunger Index, which integrates undernourishment and indicators of child malnutrition like wasting, stunting, and mortality (MoAD, 2014).

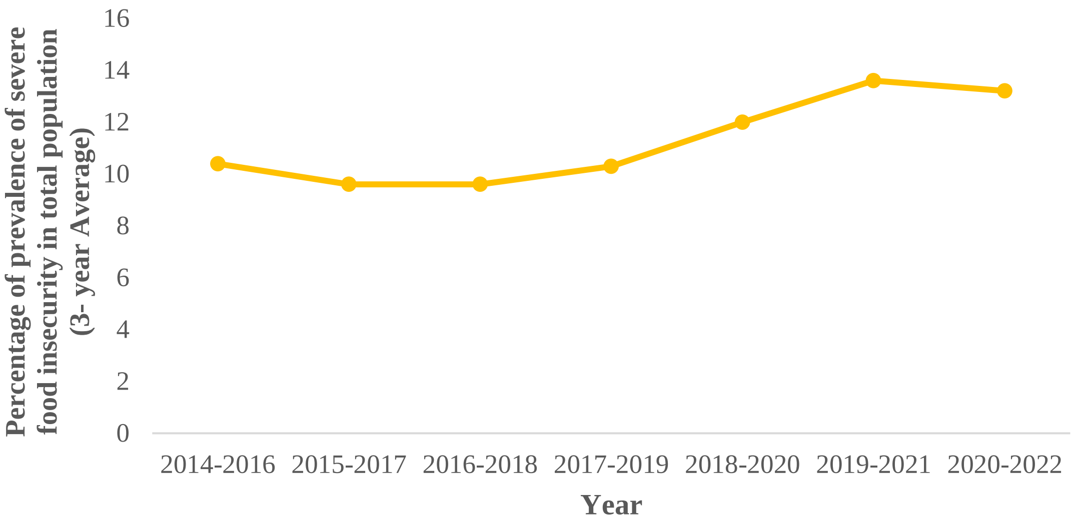

Figure 1-4: Percentage of the prevalence of severe food insecurity in the population (%) in Nepal (3-year average), based on the Food Insecurity Experience Scale (WorldBank, 2022).

Shift to Net Food Importer: Nepal has transitioned from being a net food exporter in the 1980s to a net importer after the 2000s, exacerbating its food security challenges (Bigyan et al., 2021). Import rates for staples and high-value foods have surged, indicating a decline in domestic agricultural competitiveness (Sharma, 2017). Nepal imports 0.54 million tons of rice, 0.14 million tons of wheat, and 0.35 million tons of maize grains. These imports were valued at USD 232 million, USD 38.4 million, and USD 90.8 million, respectively (FAOSTAT, 2020). Despite this import, the percentage of prevalence of severe food insecurity in the population in Nepal is still rising as shown in Figure 1-4. The percentage of prevalence of severe food insecurity in the population is the indicator assessed using the Food Insecurity Experience Scale (FIES), which shows the percentage of people who live in households categorized as severely food insecure. A household is deemed severely food insecure if at least one adult has experienced extreme situations during the year, such as reducing food quantity, skipping meals, or going hungry for an entire day due to a lack of money or resources. Nepal’s seventy-seven districts struggle to provide an adequate supply of meals to meet the primary needs of the population (WorldBank, 2022).

Low fertilizer application rate: Fertilizer is crucial for agriculture in Nepal. Despite its importance, the country uses fertilizer 74.1 kg nutrients/ha which is far below international norms (Joshi and Joshi, 2019). Increasing its application has been seen as essential for advancing Nepal’s agricultural sector (Basukala and Rasche, 2022; Takeshima, 2019). Fertilizers are available for purchase at local markets, agricultural cooperatives, government distribution centers, and nongovernmental organizations, although they face challenges related to supply chain issues, affordability, timely availability, and black market (Uprety, 2016). Nepali farmers face challenges in obtaining sufficient fertilizer, as only 60% of the demand is met (Gautam et al., 2022).

Insufficient Irrigation: Irrigation in Nepal is insufficient, and its expansion is important for the following reasons. First, rainfall in Nepal is highly seasonal and concentrated during the monsoon season, which lasts from June to September (FAO, 2012). Poor amount and delay monsoon were observed in recent decades (Joshi and Joshi, 2019), leading to water scarcity issues during the dry months when crops still need consistent water supply for optimal growth (Baniya et al., 2024; Pandey et al., 2023). Second, Nepal's geographical and topographical diversity means the uneven rainfall distribution. While some regions may receive ample rainfall and have plentiful river water, rest may face water shortages, especially in rain-shadow areas or higher altitudes (Karki et al., 2017a). Effective irrigation systems can help redistribute water to these water-scarce regions, ensuring that all farms have sufficient water resources. Third, reliance solely on rainfall makes agriculture highly unpredictable and vulnerable to climate variability and change (DoWRI, 2019; Mishra et al., 2018). Droughts, erratic rainfall patterns, or delayed monsoons can devastate crops if irrigation systems are not in place. Low precipitation in 1992, 1994, 2005, 2006, 2008, 2009, and 2015 caused significant droughts throughout the country (Adhikari, 2018) adversely affecting agricultural production (Hamal et al., 2020). Thus, irrigation provides a more reliable and controlled water supply, reducing the risk to farmers from an unpredictable climate. In irrigated regions, the supply of irrigation water is not efficient due to limited infrastructure and poor water conveying setups and canals (DoWRI, 2019).

Small Landholding size: Farm holdings in Nepal are predominantly small and marginal, with 53% under 0.5 ha of land and 80% under 1 ha of land (CBS, 2011). The average landholding size has decreased over time, from 0.68 ha in 2011 to 0.5 ha in 2021. Farmers with land holding above 0.5 ha are food self-sufficient (Joshi and Joshi, 2019). Farm assets generally consist of small to medium-sized, often fragmented land plots, basic farming tools, and occasionally mechanized equipment like small tractors, with financial resources typically limited and farmers relying on informal credit networks or cooperatives (CBS, 2011; MoALD, 2023).

Climate Change Challenges: Climate change poses additional threats to Nepal's agriculture, with erratic rainfall patterns (Talchabhadel et al., 2022), longer droughts (Bagale et al., 2021), and more severe floods (Duwal et al., 2023) impacting farming activities. These changes pose a high risk to smallholder farmers. Over the past two decades, Nepal has ranked among the top 10 vulnerable countries significantly affected by extreme climatic hazards such as landslides, storms, floods, droughts, and heatwaves (Eckstein et al., 2021; MoAD, 2014). Nepal's National Adaptation Program of Action (NAPA) to climate change reports multiple challenges, including glacial melt, flash floods, landslides, and erratic and extreme rainfall, temperature, and hailstorm patterns (MoEnv, 2010).

According to this adaptation plan, nearly two million individuals in Nepal face high vulnerability to climate change, with an estimated additional 10 million people expected to confront climate-related hardships in the future.

Poor Extension services: Agricultural research and extension systems in Nepal is managed by institutions like the Nepal Agricultural Research Council (NARC), the Department of Agriculture (DOA), and the Department of Livestock Services (DOLS), which face challenges due to insufficient capacity and resources. However, the effectiveness of extension services in Nepal has been limited due to low service coverage, inadequate infrastructure, a weak supply system, weak monitoring and evaluation, poor databases, and poor coordination between extension services, research, education, farmers, and the private sector. Additionally, there are issues with weak implementation and insufficient human resource capacity (Ghimire et al., 2021).

Impact of Conflict and Political Instability: The 10-year armed conflict, which spanned from 1996 to 2006, and subsequent political instability have disrupted agricultural activities, leading to labor shortages, land abandonment, and reduced investments (Sangroula, 2020). Ineffective policy implementation and inadequate institutional capacity have compounded these challenges (Poudel and Gopinath, 2024).

Migration trend, remittance flow and labor shortage: Labor migration and remittances significantly impact agriculture by altering labor availability and investment patterns. Additionally, large-scale migration of rural youth abroad further exacerbates agricultural labor shortages (Poudel et al., 2023). Rising from $111 million in 2000 to nearly $7 billion in 2015, remittances have become crucial for household incomes and the national economy (Paudel and Waglé, 2019). The 2010/11 Nepal Living Standards Survey found that 55.8% of households received remittances, with significant regional differences.

Limited Investments: Most Nepalese farmers are marginal or small-scale with low income to save money; they cannot invest using their own funds due to poverty and face significant barriers in obtaining institutional credit. On the enterprise level, both public and private agricultural investments have been inadequate (Pokhrel, 2019). While there has been a slight increase in the agriculture sector budget in recent years, private sector investment remains constrained due to political instability and collateral requirements (Korzenevica, 2016).

Urbanization and Land Use Changes: Swift urbanization and the conversion of peri-urban agricultural land to residential use pose significant challenges to food production.

In conclusion, Nepal's agriculture sector faces numerous challenges, so addressing these issues and capitalizing on emerging opportunities are essential for sustaining agricultural growth, ensuring food security, and improving rural livelihoods. Effective policy implementation, increased investments, and adaptation to climate change are crucial steps towards achieving these goals.

1.2 Priorities of Nepal's Government

To tackle the problems mentioned above, since the mid-90s, the government of Nepal has also prioritized the agriculture sector with different plans and strategies. The Agriculture Perspective Plan (APP), a long-term agricultural strategic initiative launched in 1995-96, was announced with a focus on overall agricultural sector advancements in productivity, infrastructure, food security, and poverty reduction. In the 12th Plan (2010/11–2012/13), the Government of Nepal (GoN) prioritized cereal production for food security, primarily through agricultural input subsidies and investments in irrigation infrastructure. Subsequently, during the 13th Plan (2013–2017), subsidies were extended to machinery and equipment to address labor shortages, alongside the introduction of crop insurance schemes (Choudhary et al., 2022). Further, Nepal's government has created national agricultural sector action plans with objectives, including attaining a food grain trade surplus of at least 5% by 2035, sustaining agricultural GDP at 20%, reducing poverty to 10%, and achieving food self-sufficiency to eliminate hunger via Agriculture development strategy (ADS) (MoAD, 2014). The

ADS action plan and roadmap aim to realize the vision of stakeholders, which envisions "A self-reliant, sustainable, competitive, and inclusive agricultural sector that drives economic growth and contributes to improved livelihoods and food and nutrition security leading to food sovereignty." The ADS additionally also emphasizes the need for expanding agribusiness and non-farm rural activities to reduce poverty and foster a balanced rural economy. The ADS encompasses various sectors beyond agriculture production, including processing, trade, and support services. It also acknowledges Nepal's transition from an agriculture-centric to a more diversified economy, aiming to address challenges such as climate change impacts and youth outmigration while accelerating agricultural transformation. In 2016, the Prime Minister Agriculture Modernization Project (PMAMP), Nepal's largest initiative under the Ministry of Agriculture and Livestock Development, was established, with an estimated cost of NPR 130 billion over ten years. It comprises four components: pocket, block, zone, and super zone development programs. PMAMP implements the web-based Agriculture Result Monitoring Information System (ARMIS) to manage real-time data and provide up-to-date information to stakeholders. ARMIS aims to enhance farm productivity, income, and decision-making by delivering relevant monitoring reports and services to stakeholders nationwide (PMAMP, 2022).

Nepal’s government also highly prioritized irrigation sector development by proposing an irrigation master plan in 2019 (IMP) to direct irrigation planning and investment over the next 25 years until 2044 (DoWRI, 2019). The Irrigation Master Plan (IMP) builds upon the foundation laid by the Irrigation Master Plan 1990, which has guided the development and management of the irrigation subsector over the past three decades. The 1990 Master Plan aimed to provide a long-term irrigation development strategy aligned with available resources and national development policies, devising shorter-term investment programs based on identified priorities and implementation capacities and establishing a robust database and planning methodology. Other than the irrigation master plan, some of the significant legislations and regulations related to water resources and irrigation that have been implemented in Nepal over the past years are Irrigation Regulations (2003), Irrigation Act (draft) (2015), National Water Plan (2005), National Water Resources Strategy (2002), and

Irrigation Policy (2013). The irrigation master plan and proposed irrigation policies main objectives include the strategy to increase year-round irrigation coverage from 18% (in 2010) to 30% (in 2015) and 60% (in 2025), and 80% (in 2035) (DoWRI, 2019).

The Ministry of Agriculture and Livestock Development-based Department of Agriculture (DoA) and the Department of Livestock Services (DoLS) are delivering extension services to improve agricultural production and livelihoods in Nepal. Extension staff and technicians operate through district and sub district offices nationwide (Ghimire et al., 2021; Uprety, 2016). Information and education through extension services, government programs, local cooperatives, NGOs, media sources (radio, television), internet, and mobile phones, with on-site training programs, agricultural fairs, and workshops are on the rise compared to before, but more efforts are still needed. (Ghimire et al., 2021).

Even though Nepal’s government has prioritized the agriculture sector, the prevalence of severe food insecurity is increasing, as shown in Figure 1-4, while the contribution of agriculture to Nepal’s GDP is decreasing, as shown in Figure 1-3, and food imports are on the rise. Climate change, input resource constraints, and low technological advancements will further challenge this trend. In this context, using process-based crop modeling to predict yields, assess the impact of climate change, model nutrient, and water use, and model different water-conserving techniques can provide valuable insights to inform government, agriculture and irrigation departments, development agencies to formulate policies on improving agriculture sector and food security in Nepal.

1.3 Objectives and Research Questions

With motivation based on the preceding discussion regarding closing yield gaps, assessing sustainable use of water, fertilizer input, and land resources in irrigated cropland and their environmental implications, this thesis endeavors to address the following overarching research question:

How can both current and future food security in Nepal be effectively ensured while concurrently mitigating the environmental impacts of agriculture through the efficient use of water and mineral fertilizers?

This PhD thesis provides a case study overview of current and future sustainable use of water resources and nutrient input to achieve food self-sufficiency in Nepal, considering various factors, including climate change, irrigation canal conveyance efficiency, and water-conserving agronomic practice. In these regards, I have defined the following chapter-wise major research questions (RQ):

Chapter 2: Model-Based Yield Gap Assessment in Nepal's Diverse Agricultural Landscape:

RQ1. How large is the current yield gap for the five key arable crops grown in the country (rice, wheat, maize, millet, and barley)?

RQ2. How much fertilizer is needed to close the yield gap, and where should it be applied?

RQ3. How much irrigation water is needed to close the yield gap, and which are the priority regions where irrigated areas should be increased?

Chapter 3: Effect of irrigation canal conveyance efficiency enhancement on crop productivity under climate change in Nepal:

RQ4. How will a change from the current management scenario to potential irrigation expansion with 30% CCE affect future crop yields?

RQ5. How will an increase in canal conveyance efficiency from 30% to 50% influence crop yields under current to near future climate conditions?

RQ6. How will an increase in CCE from 30% to 50% influence crop yields under current to end of the century climate conditions?

RQ7. What are the projected benefits in terms of crop yields when increasing CCE to 70%?

Chapter 4: Effect of Alternate Wetting and Drying (AWD) and Continous flooding in Rice production in Terai Nepal:

RQ8. What will be the effect of alternate wetting and drying of rice fields on crop yields and water use under climate change?

RQ9. What will be the effect of continuous flooding on rice yields and water use under climate change?

RQ10. How will these methods affect methane emissions?

1.4 Research Approach and thesis Overview:-

The dissertation's overall structure, outlining the chapters' flow, is presented in Figure 1-5. I utilized the EPIC biophysical crop model to simulate crop yield and management processes to address the research questions outlined earlier in section 1.3. Initially designed for soil erosion and productivity, the EPIC model, which consists of ten distinct components covering weather, hydrology, erosion-sedimentation, nutrients, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control, has evolved into a comprehensive tool for understanding environmental processes related to crop growth (Williams et al., 1989). The EPIC model has proven to be a valuable tool in various research areas, including investigating crop yield gaps (Lu and Fan, 2013; Schierhorn et al., 2014), studying the implications of climate change on crop productivity (Xiong et al., 2016), assessing environmental impacts (Liu et al., 2010; Liu et al., 2016), examining soil degradation (Balkovic et al., 2018), analyzing soil erosion and nutrient loss (Bouraoui and Grizzetti, 2008), and to managing crop cultivation (Thomson et al., 2006). This model has been validated from local field-level studies (Balkovic et al., 2018; Folberth et al., 2012) to global analysis (Muller et al., 2017a). The robustness and versatility of the EPIC model led to its selection for my study.

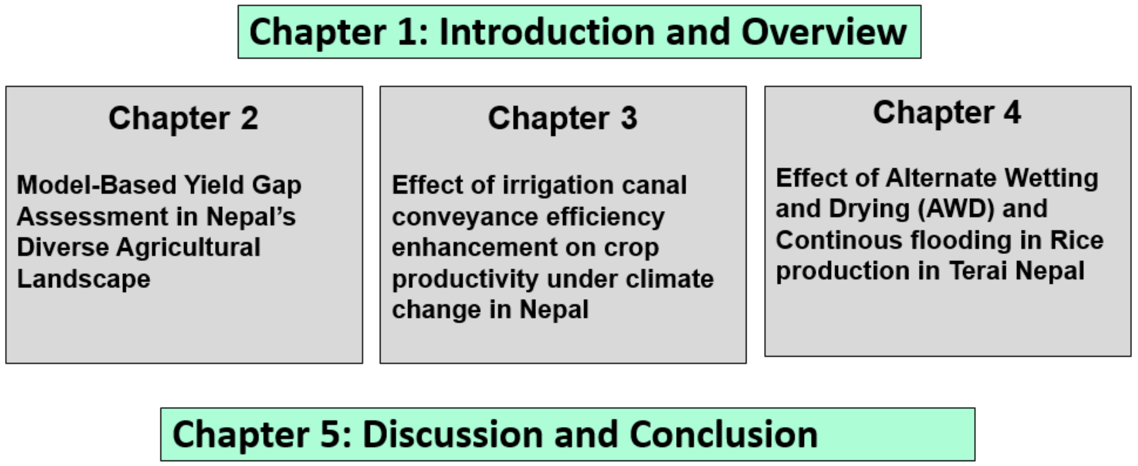

Figure 1-5: Schematic diagram presenting the step-wise process as a chapter in this thesis for answering the research questions (RQs) posed in Section 1.3.

First, I identified the current yield gap in Nepal for rice, wheat, maize, barley, and millet. Then, I paved the way to close this gap by efficiently using supplemental irrigation water and fertilizer, addressing research questions 1, 2, and 3 in Chapter 2. I analyzed four scenarios across 3430 simulation units covering Nepal's entire agricultural landscape: (i) current management practices (current yield); (ii) current management practices with additional fertilizer; (iii) current management practices with additional irrigation; and (iv) current management practices with additional fertilizer and irrigation. I compared results from scenario (i) business as usual with scenario with (iv) simulating crop growth without nutrient or water stress to estimate attainable yields for each spatial unit, thus identifying the current yield gap between attainable and actual yields. My analysis aimed to determine if Nepal could achieve food self-sufficiency by enhancing productivity on existing cropland through increased nutrient and water inputs. In addition, I quantified the nutrient and water management adjustments needed to bridge this gap by comparing scenario (i) with scenario (iii) and again scenario (i) with scenario (iii), demonstrating the effects of supplemental irrigation and fertilizer on closing the gap. The compared outcomes will highlight the need to prioritize between expanding the share of irrigated areas and the application of additional fertilizers to improve crop yields and close yield gaps in Nepal.

Second, in Chapter 3, I addressed research questions 4, 5, 6, and 7. I assessed the impact of expanded irrigation and varying canal conveyance efficiencies (CCE) of 30%, 50% and 70% on the production of essential crops, rice, wheat, and maize, across Nepal's diverse landscapes while considering shifting climatic conditions with three future forcing pathways (SSP126, SSP370), and SSP585) and three CMIP6 global climate models (GFDL-ESM4, MPI-ESM1-2-HR, and IPSL-CM6A-LR) using the EPIC crop model. To understand the effects of irrigation efficiency and its influence on crop yields, I simulate potential yields at ecoregion levels for two periods: near future (2023 to 2050) and end-century (2075 to 2100) with management scenarios (i) business as usual, (ii) CCE at 30%, (iii) CCE at 50%, and (iv) CCE at 70%. For scenarios (i), (ii), (iii) I had applied supplemental fertilizers of maximum 300 kg/ha mineral nitrogen and required phosphorous. I presented how the benefits of enhanced irrigation efficiency vary by location, resulting in differing effects on crop yields across regions.

Third, in Chapter 4, I investigated the effects of two water management practices, climate-smart alternate wetting and drying (AWD) and conventional continuous flooding in rice cultivation, to address Research Questions 7, 8, and 9. In this chapter, I aimed to establish a pathway for sustainable rice production with reduced water consumption and reduced methane gas emissions in Nepal's bread basket Terai region for the near-future period (2023 – 2050) using three future forcing pathways (SSP126, SSP370), and SSP585) and three CMIP6 global climate models (GFDL-ESM4, MPI-ESM1-2-HR, and IPSL-CM6A-LR). The findings aim to highlight the potential of AWD adoption in the area as a promising pathway toward sustainable agriculture, yielding positive outcomes for both agricultural productivity and environmental conservation

In Chapter 5, I thoroughly examined the outcomes derived from addressing the individual research questions (RQs 1–10) elucidated in Chapters 2 through 4. This chapter illustrates the connections among all chapters of this thesis, as depicted in Figure 1-1 and 1-4. Additionally, Chapter 5 digs into a detailed discussion of the primary findings of this thesis, presenting its conclusions and addressing the overarching, guiding research question.

Chapter 2

2 Model-Based Yield Gap Assessment in Nepal’s Diverse Agricultural Landscape

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Abstract

Rice, wheat, maize, millet, and barley are the five major staple cereal crops in Nepal. However, their yields are low, and imports are needed to meet domestic demand. In this study, we quantify the gap between current and potentially attainable yields in Nepal, estimate how much additional fertilizer and irrigation are required to close the gap, and assess if self-sufficiency can thus be achieved. For this, we first test the ability of the crop model EPIC to reproduce reported yields in 1999–2014 accurately. On average, simulated and reported yields at the national level were in the same range, but at the district level, the error was large, as the resolutions of the available climate and soil input data were not high enough to depict the heterogenic conditions in Nepal adequately. In the main study, we show that average yield gaps in Nepal amount to 3.0 t/ha (wheat), 2.7 t/ha (rice), 2.9 t/ha (maize), 0.4 t/ha (barley), and 0.5 t/ha (millet). With additional irrigation and fertilization, yields can be increased by 0.1/2.3 t/ha (wheat), 0.4/1.3 t/ha (rice), 1.6/1.9 t/ha (maize), 0.1/0.3 t/ha (barley), and 0.1/0.4 t/ha (millet), respectively. The results show that providing reliable and affordable access to fertilizer should be a priority for closing yield gaps in Nepal.

Keywords: yield gap; crop modeling; irrigation; fertilizer application; nitrogen management; phosphorous management

2.1 Introduction

The global food demand is predicted to increase by 35% to 56% between 2010 and 2050 (van Dijk et al., 2021). Meeting increased demands for food and feed without over-exploiting agricultural systems and encroaching on natural ecosystems will be a challenge for humans in the coming decades, especially considering the projected effects of climate change (Cassman and Grassini, 2020). Intensification of current agricultural systems is one way toward increasing crop yields and strengthening food security (Struik and Kuyper, 2017). Currently, yields on a considerable proportion of global agricultural land do not attain their full potential (Foley et al., 2011). Significant yield variations exist even among regions with similar agro-climatic conditions, signifying the presence of yield gaps (Licker et al., 2010). These yield gaps are defined as the differences between the potential yields of a specific crop under optimal management and the actual yields attained by farmers (van Ittersum et al., 2013). The main causes for the yield gaps are insufficient nutrient and water supply and inadequate pest and disease management (Foley et al., 2011). By addressing these impediments, crop yields in low-yielding regions could be increased without changing crop varieties, resulting in enhanced food supply, improved food self-sufficiency, and higher food security at regional, national and global scales (Pradhan et al., 2015).

Increasing food production is a priority in low-yielding regions worldwide, and Nepal is one such example. Nepal's agricultural sector provides livelihoods to over 80% of Nepal's population, employs almost 68% of the labor force, and contributes 35% to Nepal's gross domestic product (GDP) (International Centerfor Tropical Agriculture; World Bank; CGIAR Research Program on Climate Change Agriculture and Food Security; Local Initiatives for Biodiversity Research and Development, 2017). Although agriculture is the main contributor to GDP, the average yields of cereal crops are much lower in Nepal than in neighboring countries, mainly because of poor infrastructure and a high proportion of subsistence farming with its dependency on rainfall and low fertilizer application rates (Hussain et al., 2018). The average fertilizer use in Nepal in 2014 was 67.4 kg per ha, while in the same year, 464.8 kg/ha were used in China, 163.5 kg/ha in India, 279.2 kg/ha in Bangladesh, and 134.9 kg/ha in Pakistan (WorldBank, 2014). Furthermore, only 36% of the agricultural area in Nepal is irrigated, and the lack of irrigation and the low application of fertilizer is a significant impediment to increasing agricultural productivity (Department of Water Resources and Irrigation, 2019).

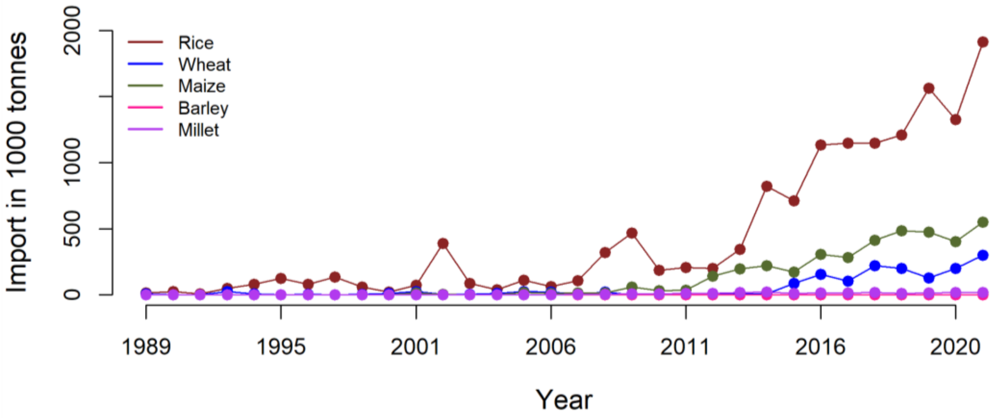

Figure 2-1: Import rates of the five main cereals consumed in Nepal (rice, wheat, maize, barley, and millet) from 1989 to 2020(FAOSTAT, 2020).

Due to the low productivity of the agricultural sector in Nepal, national production cannot meet the national food demand, and food imports are necessary to close the gap. Cereals are the most vital food for providing caloric and nutritional requirements and are the main low-cost source of energy and protein in Nepal. Figure 2-1 shows the import rates of the five main cereal crops in Nepal. The country went from being a net food exporter in the 80s to becoming an importer, with increasing import rates of on average 39% per annum for rice, 26% for maize, and 126% for wheat (Bigyan et al., 2021; Sharma, 2017).

In order to address these issues, Nepal's Ministry of Agriculture Development (MOAD) proposed an Agriculture Development Strategy (ADS) with the goal of transforming the agricultural sector over the next 20 years (MoAD, 2014). The ADS comprises measures to raise agricultural productivity, including efficient use of fertilizers, an expansion of the irrigated area, and an improvement of irrigation efficiency. It also includes measures to strengthen the agricultural sector and improve its sustainability and resilience in the longer term, such as an expansion of its agricultural research and extension services, and the development and promotion of efficient and sustainable farming practices and sustainable use of natural resources to increase the resilience to climate change.

The first step toward increasing agricultural productivity is a robust, spatially explicit estimation of the potentially attainable crop yields, followed by an analysis of how the gap between the attainable and the actual yields can be closed most efficiently (Cortner et al., 2019). Previous studies on the yield gap in Nepal focused only on specific households, places, basins, regions, or crops (Campolo et al., 2021; Gyawali et al., 2018; Jha et al., 2019; Matthews and Pilbeam, 2005). In this paper, we present a spatially explicit, country-level assessment of intensification scenarios for the five major cereal crops grown in Nepal. We want to answer the following questions:

(i) How large is the current yield gap for the five key arable crops grown in the country (rice, wheat, maize, millet, and barley)?

(ii) How much fertilizer is needed to close the yield gap, and where should it be applied?

(iii) How much irrigation water is needed to close the yield gap, and which are the priority regions where irrigated areas should be increased?

To answer these questions, we use the bio-geophysical crop model EPIC to simulate crop production on 3430 simulation units covering all of Nepal's agricultural area and aggregate results to district levels. In the first step, we calibrate the model to reproduce the observed historical crop yield from 1999 to 2014, and then simulate current agricultural practices with this calibrated model to identify spatial variations of crop yields. In the second step, we simulate crop growth without nutrient or water stress to estimate attainable yields for every spatial unit and thus identify the current yield gap between attainable and actual yields. In the third step, we quantify the nutrient and water management changes that are necessary to close this gap. We also discuss the difficulties of obtaining the spatially explicit, high-quality input data necessary for running the model in a country such as Nepal.

2.2 Materials and Methods

2.2.1 Study Area

Nepal is a Himalayan landlocked country in South Asia with an area of 147,181 km2 (Figure 2-2a) and a population of 29.13 million in 2020 (WorldBank, 2020). The country is poor—the annual per capita income was USD 1155 in 2020—with 68% of the population depending mostly on agriculture. The total cultivated area is 41,210 km2 (28% of the total land area), most of which is located in the south of the country (Figure 2-2b), where the land is flat ("Terai", Figure 2-2c). The middle hill region consists of numerous hilly peaks, fertile valleys, and river basins, of which one-tenth of the land is cultivable. The northern mountain region consists of only two percent of cultivable land. In 2015, 52% of the agricultural land was irrigated, but year-round irrigation is only available on 36% of the cultivated land (Pokhrel, 2019). Altitudes in the country vary from 60 m above the mean sea level in the South to 8848 m at the peak of Mount Everest in the North. Areas below 1000 m are part of the tropical zone, followed by the subtropical zone (1000–2000 m), the temperate zone (2000–3000 m), the subalpine zone (3000–4000 m), the alpine zone (4000–5000 m), and the nival zone (above 5000 m) (Figure 2-2d,e) (Paudel et al., 2021). The large altitudinal range and the topography containing several river basins, ridges, and valleys give rise to multiple microclimate sub-pockets within the hills and mountains (Pokhrel, 2019). The mean annual rainfall in Nepal varies from place to place due to the sharp topographical variations and ranges from less than 150 mm to above 5000 mm (Figure 2-2f). Monsoonal precipitation contributes around 80% of the annual precipitation, whereas precipitation during the winter and pre- and post-monsoon seasons contributes only 3.5%, 12.5%, and 4.0%, respectively (Karki et al., 2017a). Since monsoon precipitation is the largest contributor to annual precipitation, the spatial pattern of annual precipitation follows monsoon precipitation patterns (Department of Hydrology and Meteorology (DHM), 2015). Annual temperatures are increasing in the high-elevation areas of the country (North and Central Region); in the Southern regions, the increase is less pronounced. It is projected that the yearly average temperature may increase in Nepal by 1.2 °C by 2030, 1.7 °C by 2050, and 3 °C by 2100 (Khadka and Pathak, 2016).

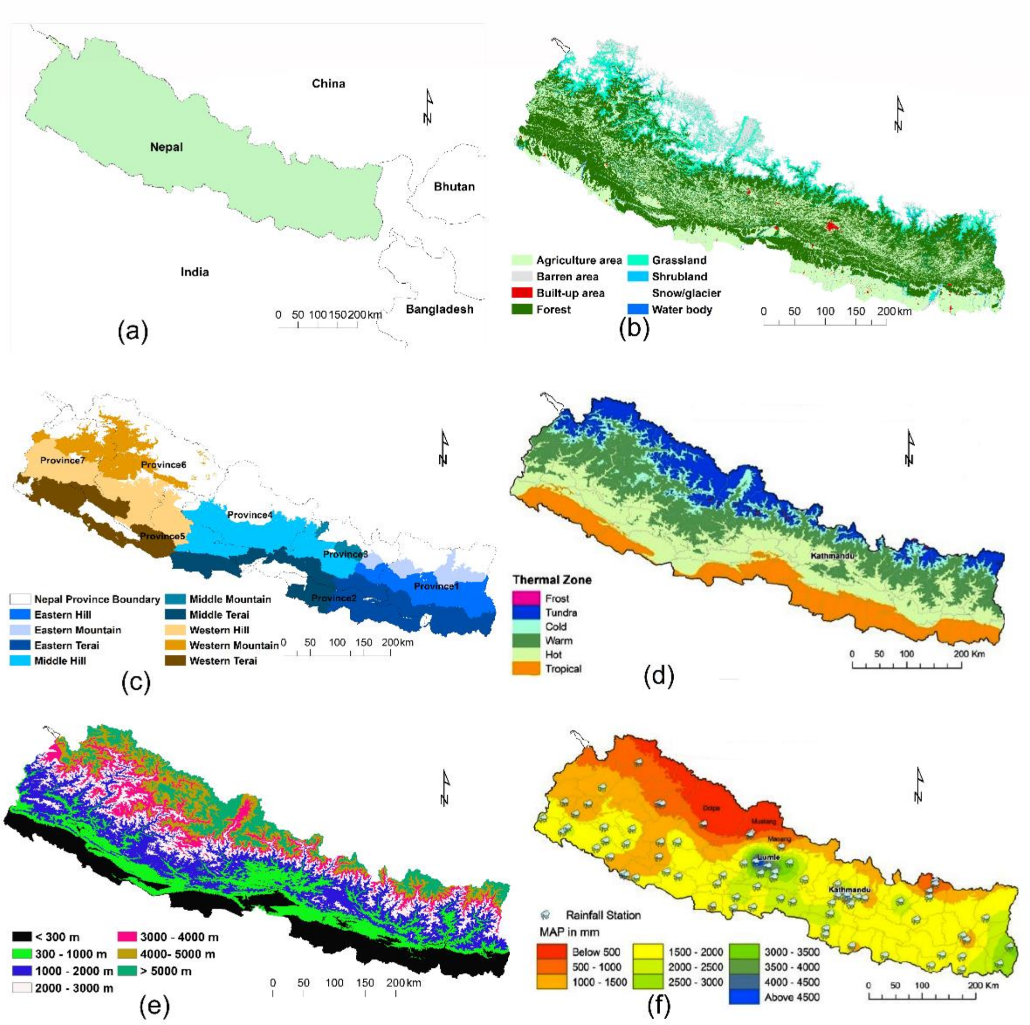

Figure 2-2: (a) Location of Nepal in South Asia; (b) land use in Nepal; (c) the nine different agro-ecological zones of Nepal; (d) thermal zone classification of Nepal (Talchabhadel et al., 2019) ; (e) elevation classes of Nepal; (f) mean annual precipitation in mm (Talchabhadel et al., 2019).

2.2.2 Derivation of Simulation Units

For the simulation of Nepal's agricultural area, we first classified the territory into Homogeneous Response Units (HRUs), following a similar methodology as used in the development of the Global Earth Observation-Benefit Assessment (GEOBENE) database (Skalský et al., 2008). We used seven elevations, seven slopes, and ten soil classes (Table 2-1).

The elevation raster was obtained from the NASA Shuttle Radar Topographic Mission (SRTM) 90 m Digital Elevation Database (v4.1), accessible through the Consortium for Spatial Information (CGIAR-CSI) of the Consultative Group for International Agricultural Research (CGIAR) (Jarvis et al., 2008), with a resolution of 90 m at the equator. Soil typological units (STU) were derived from the global dominant soil typological units contained in the GEOBENE database (Skalský et al., 2008). STU characterizes distinct soil types described by attributes specifying the nature and properties of the soils (Jones and Thornton, 2015).

Table 2-1: Classes of elevation, slope, and soil texture used for the delimitation of the homogeneous response units in this study.

Elevation Classes		**Slope Classes**		**Soil Typological Units**	
Elevation [m]	**Classification (Barnekow Lillesø, 2005)**	**Class**	**Slope [%]**	**Class**	**Dominant Soil**
<300	Lower Tropical	1	<3	1	Eutric Cambisols (Be)
300–1000	Upper Tropical	2	3–6	2	Eutric Fluvisols (Je)
1000–2000	Subtropical	3	6–10	3	Calcic Cambisols (Bk)
2000–3000	Temperate	4	10–15	4	Dystric Regosols (Rd)
3000–4000	Subalpine	5	15–30	5	Dystric Cambisols (Bd)
4000–5000	Alpine	6	30–50	6	Humic Acrisols (Ah)
>5000	Trans Himalayan	7	>50	7	Humic Acrisols (Ah)
				8	Rankers (U)
				9	No soils (RK2)
				10	Lithosols (I)

After the HRU delineation, we further divided the units based on district boundaries, land use and land cover, and the climate data raster. The district boundaries were obtained from the Global Administrative areas database (GADM, 2018). The land use mask was obtained from the Land Cover of Nepal 2010 dataset developed by the International Center for Integrated Mountain Development (ICIMOD) (Uddin et al., 2015). The climate data that were used for this study were created in phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b), which is based on the output of phase 6 of the Coupled Model Intercomparison Project (Eyring et al., 2016). The spatial resolution of this dataset is 0.44 degrees. In the last step, we identified cropland and non-cropland areas using the land use mask and only included units with cropland presence in the list of simulation units. The final count of simulation units was 3430 (Figure 2-3).

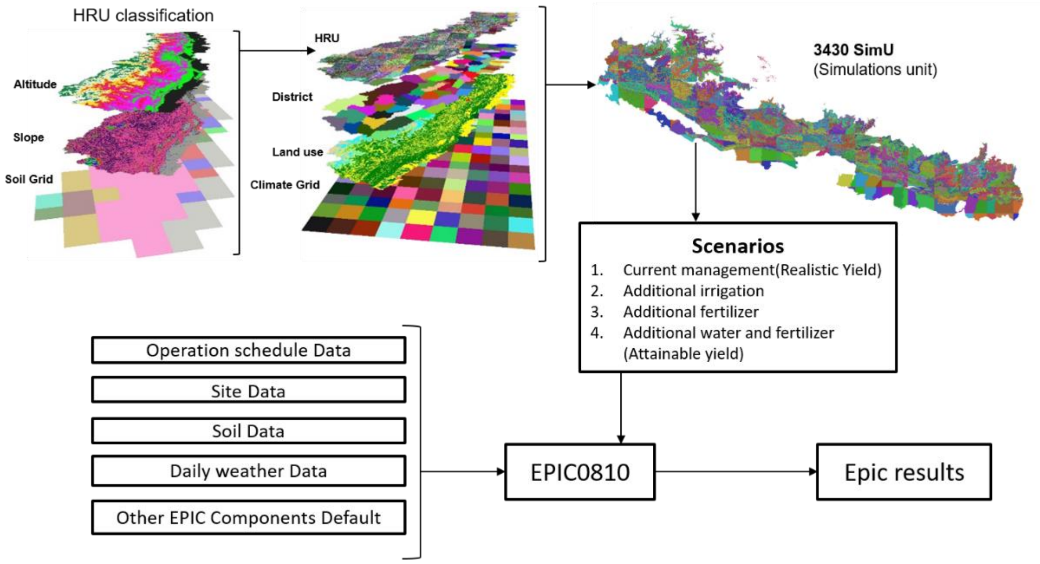

Figure 2-3: Flow chart of the methodological framework used for the yield gap analysis in Nepal, including homogeneous response unit (HRU) and simulation unit delineation, scenario portfolio, and input data to the EPIC crop model.

2.2.3 Simulation Framework and Input Data

For the simulations, we used the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1989). EPIC is a field-level biophysical process-based model which can simulate crop growth and crop yield, soil nutrient cycling, soil erosion, and the effects of agro-ecological practices for climate change mitigation and adaptation (Di Bene et al., 2022; Gaiser et al., 2010). The plant biophysical processes simulated by EPIC include interception of photosynthetically active solar radiation dependent on LAI, conversion to biomass based on radiation use efficiency and crop growth stresses (nutrient and water availability, temperature), partitioning of the daily biomass increase into the root and aboveground biomass, and adaption of the harvest index to drought conditions (Zhang et al., 2018). The soil submodel consists of several soil pools tracking the amount of organic nitrogen and carbon, mineral nitrogen, organic phosphorous, and mineral phosphorous in the soil. Only the labile pools contain nutrients available for plant uptake; nitrogen and phosphorous in the other pools are assumed to be sorbed to organic or inorganic soil particles. If mineral fertilizer is applied, the nutrients are added to the plant-available pool but may quickly be immobilized. The user can choose between five potential evapotranspiration equations (Balkovič et al., 2013) and simulate a wide range of crop rotations, tillage systems, and management practices.

The EPIC model has been effectively employed to study crop yields and yield gaps (Lu and Fan, 2013; Schierhorn et al., 2014), climate change impacts on crop yields (Xiong et al., 2016), environmental impacts (Liu et al., 2010; Liu et al., 2016), soil degradation (Balkovic et al., 2018), soil erosion and nutrient leaching (Bouraoui and Grizzetti, 2008), and crop management operations (Thomson et al., 2006). The model has been validated across scales from the field to continental (Balkovic et al., 2018; Folberth et al., 2012) and global studies (Muller et al., 2017b). We chose to use the EPIC model in this study due to this proven robust performance in a variety of settings, cognizant of the fact that the environmental conditions in Nepal make crop simulations a challenge. The model output of EPIC comprises detailed information on crop growth, water, nutrient, and carbon fluxes in daily, monthly, and yearly steps. For this study, we focus on the estimated annual yield (Yd, t/ha), the growing season evapotranspiration (GSET, mm), and the amount of water provided by irrigation annually (IR, mm). We use the Hargreaves method in the EPIC Model for estimating evapotranspiration (Hargreaves and Samani, 1985).

EPIC requires detailed input data on management, soil, topography, and weather. Data related to crop area and crop yields of rice, wheat, maize, millet, and barley for the fiscal years from 1979/80 to 2013/14 were obtained from agricultural statistics of cereal crops in Nepal (MoAD, 2014). The amount of fertilizer and irrigation water applications per hectare as well as application times were derived from CBS Nepal decadal agriculture census data published in the years 1981, 1991, 2001, and 2011 and from Takeshima (Takeshima, 2019) (Table 2-2).

Table 2-2. Annual inorganic and organic fertilizer use in Nepal based on data from CBS Nepal decadal agricultural census data and Takeshima et al.

Fertilizer Type	**Terai**	**Hill**	**Mountain**
Urea	28 kg/ha	18 kg/ha	12 kg/ha
Complex	3 kg/ha	4 kg/ha	2 kg/ha
DAP	17 kg/ha	3 kg/ha	1 kg/ha
Organic N fertilizer	22 kg/ha	16 kg/ha	13 kg/ha
Organic P fertilizer	11 kg/ha	4 kg/ha	2 kg/ha
Other inorganic	0 kg/ha	0 kg/ha	0 kg/ha

Table 2-3. Crop calendar for the main cereal crops cultivated in Nepal split by ecological zone and irrigation management. P—planting; TP—transplanting; H—harvesting.

Crop	**Ecological Zone**	**Irrigation**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Rice	Hill	Rainfed					TP	TP			H	H		
		Irrigated			TP	TP			H	H				
	Terai	Rainfed						TP	TP		H	H	H	
		Irrigated			TP	TP			H	H	H			
Maize	Mountain	Rainfed			P	P				H	H	H		
	Hill	Rainfed			P	P				H	H			
	Terai	Rainfed		P	P			H	H					
Wheat	Mountain	Rainfed					H	H					P	P
	Hill	Rainfed			H	H	H					P	P	P
	Terai	Rainfed			H	H						P	P	
Millet	Mountain	Rainfed				P	P					H	H	
	Hill	Rainfed						P	P			H	H	
Barley	Mountain	Rainfed				H	H						P	P
	Hill	Rainfed			H	H						P	P	P

District-wise crop calendar data for Nepal's major crops were taken from an FAO/WFP food security assessment mission to Nepal (Table 2-3). Soil data were taken from the GEOBENE database (Skalský et al., 2008). The latitude and longitude of the centroid of each simulation unit were extracted from the administrative boundary dataset of Nepal downloaded from GADM. Elevation and slope for every simulation unit were derived from the SRTM 90 m Digital Elevation Database (v4.1), and daily values for the weather variables solar radiation, maximum and minimum temperature, relative humidity, and wind speed were taken from the ISIMIP3b database.

2.2.4 Model Calibration

For the testing of the performance of the EPIC model in Nepal, we used district-wise yield data for the crops rice, wheat, maize, millet, and barley provided in the agricultural statistics of cereal crops in Nepal (MoAD, 2014) for the years 1999–2014. We first ran the model for the years 1999–2014 with default parameters, aggregated the crop yields to the district level (using the crop areas provided in the agricultural statistics (MoAD, 2014)) and compared reported to simulated yields. We then iteratively calibrated the crop-specific parameters potential heat units, radiation use efficiency, harvest index, and optimal and base temperature to decrease the difference. We were not able to identify one set of crop parameters that could be applied to all regions of Nepal and decided to derive a separate crop parameter set for each of the nine ecoregions (Figure 2-2c) instead. We calculated the percent bias (PBIAS, Equation (1)) to identify the average tendency of the simulated data to be larger or smaller than the observed data. Positive values indicate an underestimation, negative values an overestimation bias, and zero no bias at all. Generally, PBIAS values 0–10 are considered very good, 10–15 good, 15–25 fair, and values >25 unsatisfactory (de Salis et al., 2019).

$$PBIAS = 1 - \frac{\sum_{i=1}^{n}(Y_i - \mathrm{X_i}) * 100}{\sum_{i=1}^{n} Y_i} \qquad (1)$$

where X_i is the reported crop yield in district i, Y_i simulated crop yield in district i, and n is the total number of districts.

We also calculated the relative error RE (Equation (2)) to examine systematic errors in the simulated data. Considering the versatility of agro-ecological zones and the scale of this study, we assume an RE of ≤30% to be an acceptable result, whereas RE > 50% should be considered to be extreme error (Balkovič et al., 2013; Niu et al., 2009).

$$\mathrm{RE_i} = \frac{(\overline{\mathrm{Y}}_\mathrm{i} - \mathrm{X_i})}{\mathrm{X_i}} \cdot 100 \qquad (2)$$

where $\mathrm{X_i}$ is the reported crop yield in district i, $\overline{\overline{\mathrm{y}}}_\mathrm{i}$ is simulated average crop yield in districts.

The calibration was considered successful once the acceptable ranges for PBIAS and RE were achieved.

2.2.5 Simulation Scenarios

Irrigation and fertilizer applications explain 60–80% of the global yield variability for most major crops (Mueller et al., 2012), which is why we only consider these two factors explicitly in our scenarios and ignore other factors such as changes in tillage, mulching, pest control, or cultivar development. Our four scenarios are:

(1) Current management practices (current yield);

(2) Current management practices with additional fertilizer applications up to a maximum of 300 kg/ha per year (additional fertilizer);

(3) Current management practices with additional irrigation of up to 2000 mm per year (additional irrigation);

(4) Current management practices with additional fertilizer and irrigation applications with the same maxima as in (2) and (3) (attainable yield).

The additional irrigation and fertilizer applications were triggered automatically during the simulation if the plant experienced a moderate amount of water or nutrient stress on a specific day (stress factor higher or equal to 15%). Each scenario was run for all 3430 simulation units covering Nepal for the period from 1999 to 2014 (Figure 2-3).

2.3 Results

2.3.1 Calibration of Crop Yields

We simulated crop yields under reported management for the period from 1999 to 2014 on all simulation units. District, province, and national level crop yields were determined by aggregating the yields of all simulation units contained in the specific spatial boundaries. The simulated mean crop yields at the country level were lower than reported mean crop yields but in the same range: rice 2.3 vs. 2.59 t/ha (simulated/reported), wheat 1.07 vs. 1.94 t/ha, maize 1.87 vs. 2.15 t/ha, millet 1.06 vs. 1.08 t/ha, and barley 0.84 vs. 1.02 t/ha. At the district level, the same pattern was visible, with simulated yields slightly lower than reported yields in many cases but overall in the same range. PBIAS between reported and simulated mean annual yields was −3.1% for rice, −5.1% for maize, −20.5% for barley, −2% for millet, and 26% for wheat. According to these values, the calibration of millet, rice, and maize can be considered very good, and the calibration of barley and wheat unsatisfactory. The RE values vary between −33.02 and 36.8% (mean −14.08%) for rice, between −58.87% and 48.85% (mean −41.86%) for wheat, between −37.43 and 40.04% (mean −10.43%) for maize, between −48.37 and 48.29% (mean −1.90%) for millet, and between −58.95% and 37.12% (mean −22.62%) for barley. Except for wheat, all mean RE values fall into the range for 'good' RE values, but the range over the different districts shows that many RE values exceed this range, indicating unsatisfactory results. These outliers are also visible in the scatterplot of Figure 2-4, where we compare reported and simulated mean annual yields at the district level. The plot shows that there is a moderate agreement between simulated and reported values, with many outliers on both sides. For wheat and barley, a clear systematic underestimation of yields by the model is apparent.

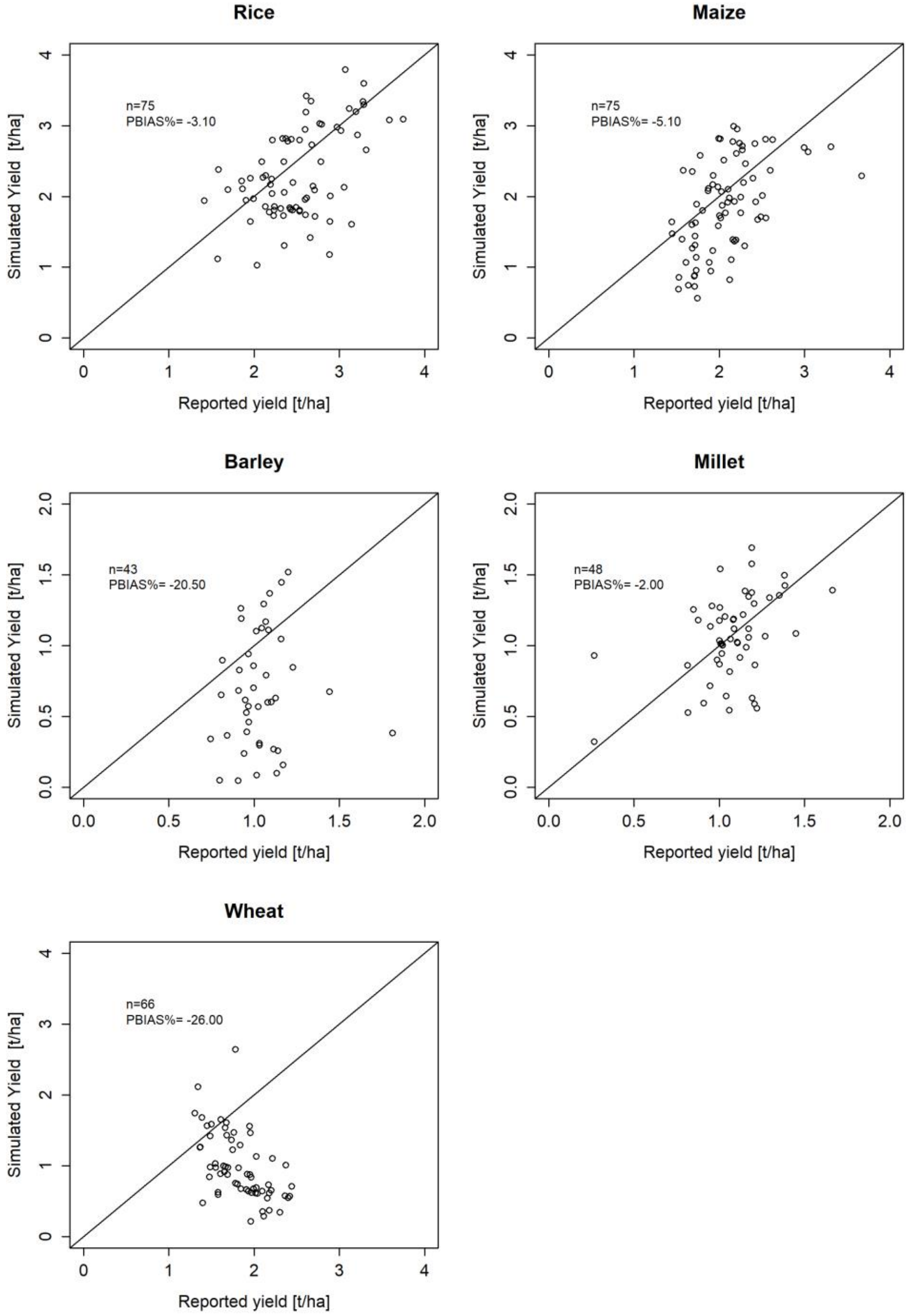

Figure 2-4. Comparison of mean simulated crop yields (t/ha) to mean reported crop yields from Ministry of agriculture development (MOAD) Nepal. Each data point represents a long-term average yield (from 1999 to 2014). The line indicates x = y (perfect agreement).

Even though the statistics show that the calibration is not satisfactory for some crops, we nevertheless decided to accept it. The main reason for this is data constraints. The resolution of 50 km of the bias-adjusted modeled climate data appears to be too coarse for a country such as Nepal, where the geographic heterogeneity is high, and there are many areas with microclimates. Another source of uncertainty is the global gridded soil data we used, whose resolution is also too coarse to depict the spatial variations of soil conditions in Nepal well. In the absence of soil and weather data with a higher resolution, we would have needed to further increase the number of crop parameter sets to compensate for the input data issues. Furthermore, there is a considerable range of reported yields in the district-wise dataset (Table 2-5 in Appendix). We assume that agronomic practices vary more across districts than we simulate in the model and that we would need district-wise fertilizer application and irrigation data to increase the quality of the calibration. In addition, there is no information on the difference in yield levels under irrigated and rainfed conditions in the dataset, and there is no spatial information on the location of irrigated fields. We had to rely on percentage shares of irrigated area per district to calculate mean crop yields, which adds another source of uncertainty and difficulty in calibrating the crop parameters. Hence, instead of continuing with the calibration and potentially overcalibrating the model, we decided to accept the results and proceed with the study. Since we only use the simulated data for the yield gap analysis, the negative effects of the unsatisfactory calibration can be considered negligible for this specific study.

2.3.2 Yield Gaps in Nepal

The yield gaps in Nepal are different for the different crops. The gap is smallest for millet and barley with 0–1 t/ha and 0–1.85 t/ha, respectively, and largest for wheat with up to 7 t/ha. Rice and maize show yield gaps between 3 and 4 t/ha. There is a clear spatial pattern in the gaps, with the largest yield gaps present in the tropical Terai and the lower part of the subtropical hill region (Figure 2-5). The highest yield gaps for rice and wheat can be observed in Province 2, which is part of the Eastern/middle Terai. Aggregated to national level, the yield gaps amount to 3.01 t/ha (wheat), 2.7 t/ha (rice), 2.9 t/ha (maize), 0.44 t/ha (barley), and 0.49 t/ha (millet).

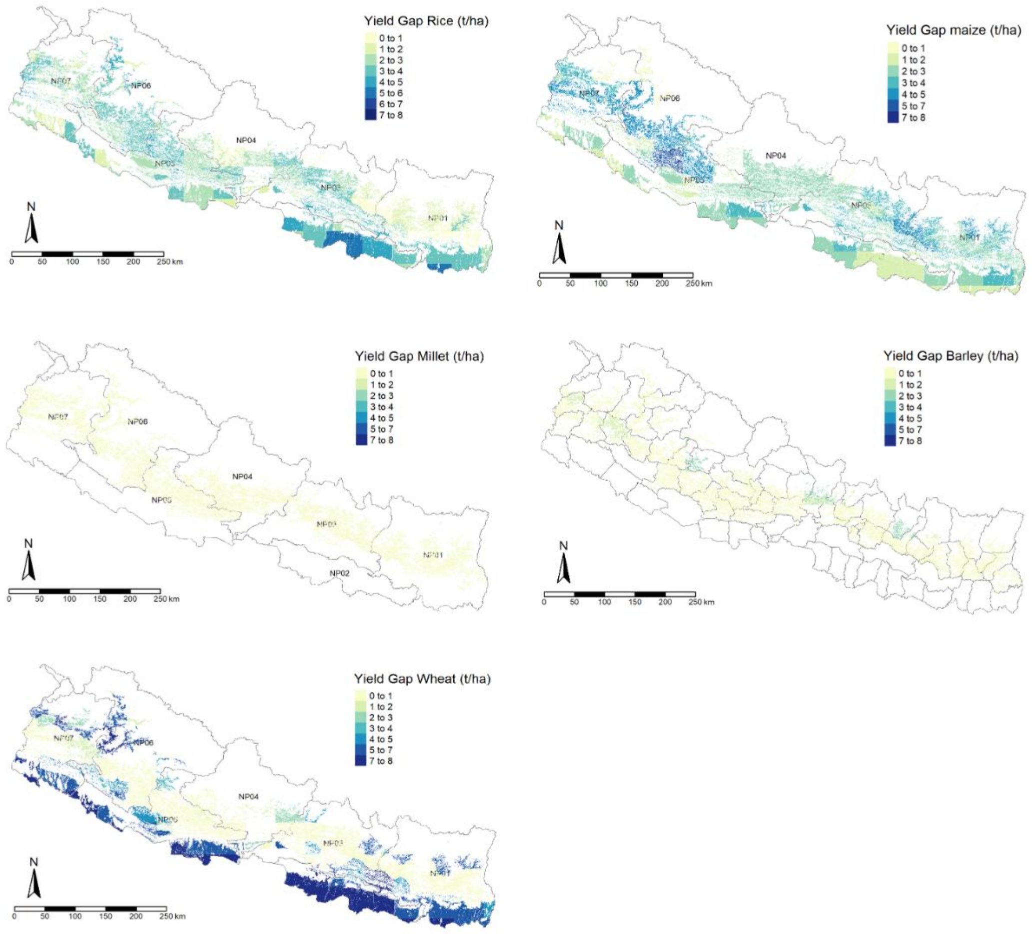

Figure 2-5. Simulated yield gaps of (a) Rice, (b) wheat, (c) maize, (d) millet, and (e) barley in tons per hectare.

The attainable yield (scenario 4) was simulated using additional irrigation and fertilizer applications. To identify priority areas for investment, we simulated two scenarios with only additional irrigation water (scenario 3) and only additional fertilizer applications (scenario 2). With the addition of irrigation water (scenario 3), yields can on average be increased by 0.1 t/ha (wheat), 0.4 t/ha (rice), 1.6 t/ha (maize), 0.1 t/ha (barley), and 0.1 t/ha (millet). Irrigation is thus especially effective for maize. Figure 2-6 shows that additional irrigation water alone can close the yield gaps to a large degree for maize. The yields of the other four crops, rice, barley, millet, and wheat, are only marginally improved by additional irrigation. For rice, there is a larger effect in provinces three and four, which are located mostly in the middle hill ecoregion. For wheat, with additional irrigation water alone, yields do not or only marginally increase beyond current levels.

With the addition of fertilizer (scenario 2), yields can be increased by 2.3 t/ha (wheat), 1.3 t/ha (rice), 1.9 t/ha (maize), 0.3 t/ha (barley), and 0.4 t/ha (millet) at national level. Additional fertilizer has a more pronounced effect on crop yields than irrigation for all crops and in all provinces. For wheat, millet, and barley, only additional fertilizer is enough in many provinces to close the yield gap almost entirely or to a large degree. For rice, even though fertilizer has a pronounced effect on crop yields, a combination of fertilizer and irrigation water is necessary to reach attainable yields. For maize, additional fertilizer applications close the yield gap by more than 50% in most provinces.

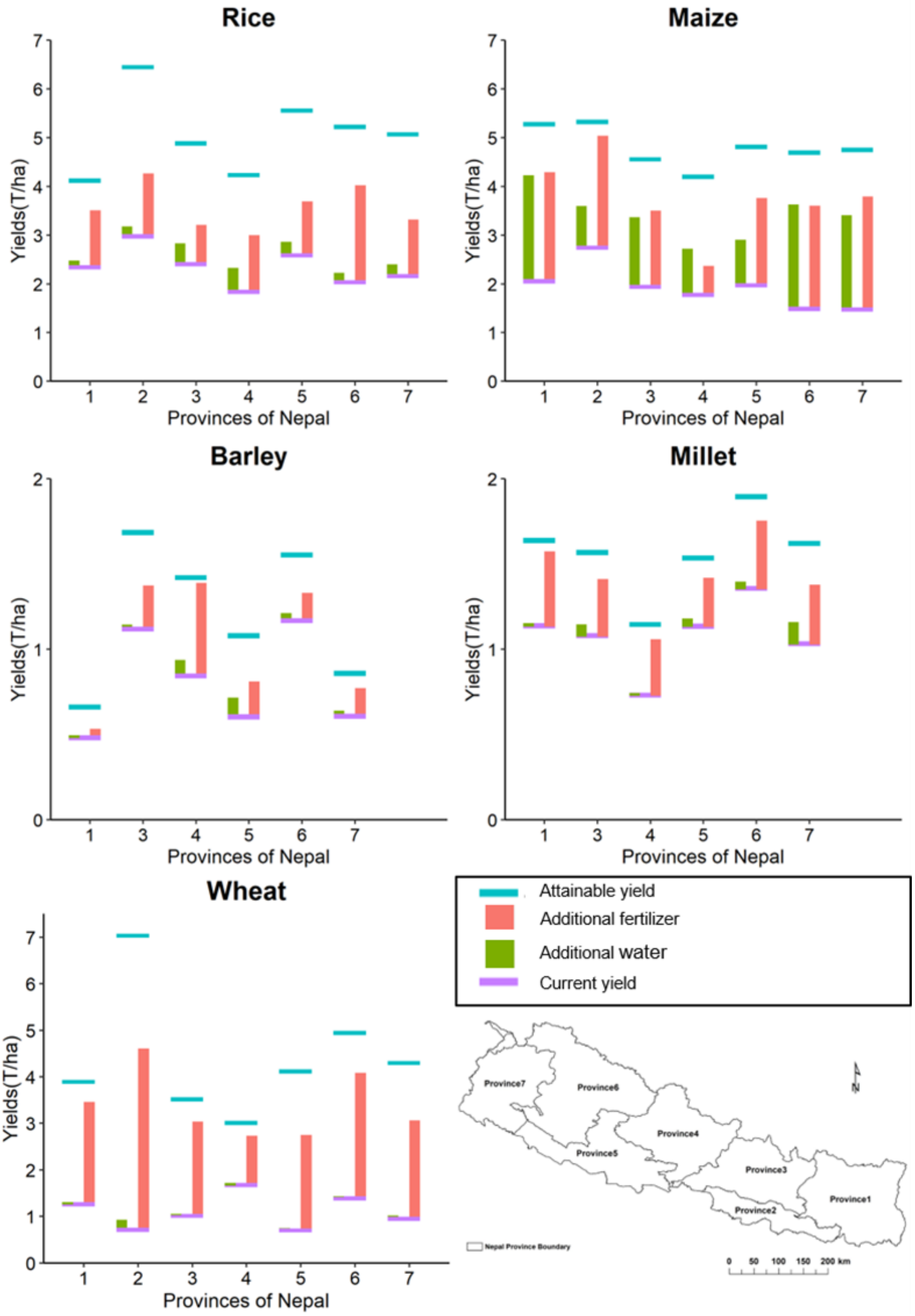

Figure 2-6. Current yields, attainable yields and yields produced under current management plus additional irrigation water and current management plus additional fertilizer at province level.

2.3.3 Additional Irrigation and Fertilizer Requirements for Closing the Yield Gaps in Nepal

Rice is the most water-consuming crop grown in Nepal. Robust estimations of the water volumes required to irrigate this crop can thus serve as a base for future irrigation infrastructure planning in Nepal. Aggregated to the district level, the irrigation requirement for rice ranges from 0 to 958 mm (see online supplementary material for a table of the data). At the level of single simulation units, the required supplemental irrigation ranges from 0 to 1100 mm annually, with the highest requirements in the tropical Terai regions and decreasing with increasing altitude (Figure 2-7a). The tropical Terai regions require on average 785 mm of irrigation, the subtropical hill regions 540 mm, and the mountain areas 384 mm. Maize is the crop with the second highest water requirements after rice, varying from 0 to 700 mm. The highest water demands are simulated in the hilly and mountainous province 4, the lowest in the Terai regions of provinces 1, 2, and 5 (Figure 2-7b). This is a reverse of the pattern observed for rice. For wheat, the irrigation requirement varies from 0 to 520 mm, for millet from 0 to 420 mm, and for barley from 0 to 365 mm.

The mineral N requirements to achieve attainable yields vary from 12.1 to 205.2 kg/ha for rice, from 30.5 kg/ha to 260.5 kg/ha for maize, from 0 to 245.4 kg/ha for wheat, from 39.3 to 239.85 kg/ha for millet, and from 0 to 218.75 kg/ha for barley. The mineral P requirement to achieve attainable yields varies from 1.75 to 31.2 kg/ha for rice, from 6.4 to 69.7 kg/ha for maize, from 0 to 24.57 kg/ha for wheat, from 10.4 kg/ha to 34.4 kg/ha for millet, and from 0 to 5 kg/ha for barley. Spatially, the patterns observed for irrigation are also visible for nutrients: for rice and wheat, more fertilizer and irrigation water is required in the warmer provinces, while the hilly and mountains regions require less to close the yield gap (Figure 2-7c). For maize, more nitrogen is required in the hill and mountainous regions than in the Terai regions (Figure 2-7d), which is also apparent for barley and millet (Figure 2-7e).

A list of district-wise irrigation requirements for each crop is provided in the online supplementary material. Maps of all crops not shown in Figure 2-7 are provided in Figure 2-8, Figure 2-9, Figure 2-10, Figure 2-11 and Figure 2-12 in the Appendix.

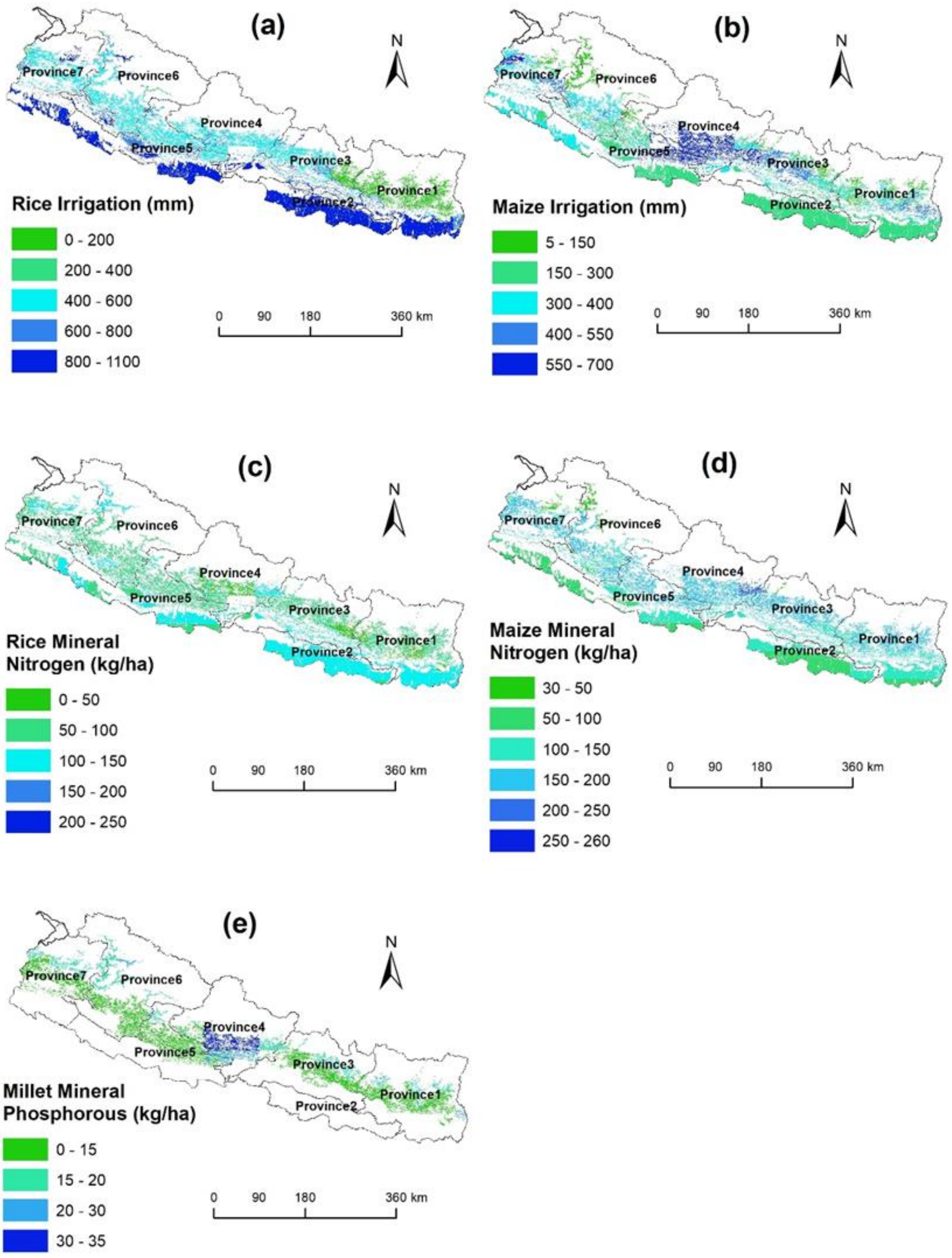

Figure 2-7. Annual irrigation and fertilizer requirements to achieve attainable yields at simulation unit level. (a) annual irrigation (mm) for rice; (b) annual irrigation (mm) for maize; (c) mineral nitrogen (kg/ha) for rice; (d) mineral nitrogen (kg/ha) for maize; (e) mineral phosphorous (kg/ha) for millet. The missing maps are provided in the appendix in Figures 2-8, Figure 2-9, Figure 2-10, Figure 2-11 and Figure 2-12.

2.3.4 Effects of Closing the Yield Gaps on Food Self-Sufficiency in Nepal

The simulations of attainable yields show that an additional 4316.85 metric kilotons of rice, 2625.30 metric kilotons of wheat, 2870.30 metric kilotons of maize, 110.96 metric kilotons of millet, and 8.19 metric kilotons of barley can be produced with increased fertilizer and irrigation applications, which is sufficient for Nepal to achieve self-sufficiency. Especially province 2, located in the middle and Eastern Terai ecoregion, may play an important role in increasing rice and wheat yields (Table 2-4). For wheat, closing the yield gap in this province alone would be enough to replace all imports. For rice, the yield gap in province 5 would have to be closed as well to achieve self-sufficiency. For maize, closing the yield gap in province 1 (covering the ecozones Eastern Terai/hill/mountain) would be sufficient to entirely meet domestic demand. The yields of millet and barley, grown primarily in the more Northern mountain provinces, can only be increased to a small degree, which is still sufficient to replace all imports with domestic production.

Table 2-4. Additional yields [1000 tons] that can be produced in Nepal if irrigation and fertilizer applications are increased, at provincial and national level. The import rates in the last line show that Nepal could achieve self-sufficiency for all five crops if the yield gaps were closed.

Province	Rice	Wheat	Maize	Millet	Barley
Province 1	859.46	157.33	890.60	30.27	0.33
Province 2	1329.26	1084.56	136.67		
Province 3	348.05	140.71	559.71	20.35	1.31
Province 4	311.38	70.50	344.26	38.30	1.52
Province 5	896.57	651.71	397.26	3.72	1.50
Province 6	124.60	225.96	362.97	9.30	2.48
Province 7	447.54	533.09	178.81	9.01	1.05
Nepal (sum)	4316.85	2863.87	2870.30	110.96	8.19
2020 Imports	1912	300	550	18	0

2.4 Discussion

Cereals are an important cheap source of calories and protein in Nepal, but domestic production is low, and import rates are rising to meet the increasing demand. In this study, we show that it would be possible to increase domestic production by closing the gap between current yields and yields attainable with additional irrigation water and fertilizer applications. Yields could even reach levels where it is possible for Nepal to achieve self-sufficiency for the five cereals considered in this study, which would reduce the economic burden on the country. The government of Nepal is aware of this potential. In the fiscal year 2021/22, it has announced a budget of NPR 45.09 billion for the development of the agricultural and livestock sector; NPR 12 billion have been allocated to manage chemical fertilizers (Government of Nepal: Ministry of Finance, 2021). The plan is to make the country fully self-reliant in agriculture within five years through modernization, commercialization, and mechanization of the agricultural sector. However, even though a budget was allocated to increase crop and livestock production, in reality, farmers are still struggling to buy fertilizers. There is a shortage almost every year during the peak season (Cosic et al., 2017). Recently, there was even an incident of looting, where farmers took fertilizers from trucks headed for the capital (Shrestha, 2022). The timely and regular availability of fertilizer thus must be guaranteed; otherwise, a steady increase in the productivity of Nepal's agricultural sector is in jeopardy, and food self-sufficiency cannot be achieved.

To support smallholder farmers and encourage more resource-intensive agriculture, the government has also attempted to subsidize chemical fertilizer use and reduce prices. However, these measures primarily benefited larger commercial farmers and not smallholders (Takeshima, 2019); more direct support is needed to reach these farmers. Increasing the use of fertilizers could also be achieved by improving the quantity and quality of organic farmyard manure fertilizers (Dhakal and Escalante, 2022). In the municipality of Bhaktapur, for example, organic compost manure is produced from the biodegradable waste collected from households (Rai, 2022). Since 77% of the typical household waste in Bhaktapur is organic, this represents an abundant source of compost manure (Ranjit et al., 2019). The composition of wastes in other cities follows similar trends, indicating a considerable source of raw materials for making compost manure.

It has been shown many times before that increasing fertilizer and irrigation will increase crop yields. However, for policy and infrastructure planning purposes, it is important to know where the resources should be allocated, in which order, and in which quantity. For example, the Nepalese government is currently investing considerable resources in the irrigation infrastructure of the country. Our results show that they should be focusing on the issue of fertilizer availability first, as providing crops with adequate nutrients contributes more towards closing the yield gap than irrigation. The only exception is maize, where the roles of irrigation and fertilizer are equal in closing the yield gap. In contrast to wheat and rice, where the irrigated area share is already higher than 25%, maize is mostly grown under rainfed conditions. Increasing the area under irrigation, especially in dry regions, can thus increase yields considerably. Spatially, the regions that would benefit most from additional agricultural inputs are the warm regions of the South, where mainly the crops rice, wheat, and maize are grown. In the mountainous areas of Nepal, the growing season is shorter, and more hardy crops such as barley and millet are cultivated. In these regions, the climatic conditions and not input shortages limit yields, which is why additional fertilizer and irrigation water applications do not increase yields markedly in most places. The development of new varieties could be an option to improve productivity in these areas.

Beyond investments in irrigation infrastructure and fertilizer availability, rural and infrastructure development policies are needed to stimulate overall growth and development in the agricultural sector. A good infrastructure is vital to linking rural farmers to markets and institutions where they can buy and sell products and inputs, and access services. Furthermore, trade-related policy measures discouraging foreign crop imports could strengthen the domestic market and production.

There are some limitations to this study. First, we had to simplify crop management practices. Farmers in Nepal choose the crops and the dates of fieldwork based on a number of factors such as weather, seed availability, input availability, market prices, available subsidies, and demand. For the simulations, we assume that cropping schedules are annually static for all scenarios. Farmers also practice intercropping, whereas in EPIC, usually only one crop is grown at a time on a simulation unit. Furthermore, there is the issue of data. As we discuss in Section 2.3.1. (Calibration of crop yields), weather and soil data would need to have a higher resolution to adequately cover all microclimatic conditions in Nepal and thus allow a more accurate simulation of actual crop yields. Furthermore, there was also limited availability of aggregated and joined data for agricultural productivity, resource use, and management in Nepal; the data had to be combined from various sources of different quality. The situation was aggravated by the fact that data acquisition in countries such as Nepal can be a challenge. Organization webpages were not up to date, so we had to contact authorities directly. The data we received were in parts in Nepalese, in parts in English, and often not in a format that was easily machine-readable and had to be retyped, such as scanned or photographed books.

Even though our calibration was not perfect, our estimated yield gaps and estimated attainable yields fall into the range of values reported in the literature. The national level yield gap of the prevailing rice varieties was estimated to range from 1.7 to 3.0 t/ha in 2000–2016, as reported in the proceedings of a stakeholder workshop organized by the Nepal Agricultural Research Council (K.C et al., 2020). In our study, the rice yield gap amounts to 2.7 t/ha at the national level, and a simulation study on the attainable yield of maize in Nepal showed that the average simulated maize yields with high fertilization rates (180:60:60 N:P:K kg/ha) ranged from 3.9 to 7.5 t/ha across districts [(Devkota et al., 2015). In our study, attainable maize yields have a similar range of 1.4–6.6 t/ha. The same study recommended N fertilizer rates between 65 and 208 kg/ha to reach attainable yields, which is also similar to our values of 30.5–260.5 kg/ha. This shows that even though the calibration was not perfect, the results of the main simulation study appear to be robust.

2.5 Conclusions

Our analysis of the current yield gaps of the five major cereal crops in Nepal showed that there are considerable differences between attainable and current yields. By increasing productivity on the existing cropland with additional nutrient and water inputs, Nepal could potentially increase the yields of these crops to the degree that domestic demand can be met entirely by domestic production. Even though increasing the share of irrigated areas enhances crop yields, additional fertilizer applications have a higher potential for closing the yield gaps in Nepal. The priority of the Nepalese government should therefore be to ensure a steady and sufficient supply of affordable fertilizer and develop efficient organic fertilization schemes before investing in additional irrigation infrastructure projects on a larger scale. The results of this analysis can be used by policymakers to prioritize further research and to identify regions with a potential for higher crop production. The methodology applied in this study can also be relevant for other regions of the world where the population is increasing, cropland area expansion is not possible, and climate change impacts are projected to be substantial.

Acknowledgments

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Supplementary Materials

The following supporting information can be downloaded at https://www.fdr.uni-hamburg.de/record/10340#.YtmldrdBxaQ: Table with the district-wise simulated current and attainable yields, yields simulated with additional water and irrigation applications, yield gaps, nitrogen, phosphorous and irrigation requirements, agricultural area, and total attainable yields per district can be downloaded.

Chapter 3

3 Effect of irrigation canal conveyance efficiency enhancement on crop productivity under climate change in Nepal

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Abstract

Nepal is expanding its irrigation facilities as an adaptive measure to climate change; however, the current canal conveyance efficiency (CCE) is low with significant water losses. In this study, we assess the potential impact of increasing CCE on the productivity of rice, maize, and wheat under different climate change scenarios (SSP1-2.6, SSP3-7.0, and SSP5-8.5), utilizing three bias-adjusted general circulation models. The study simulates potential yields at ecoregion levels for two periods: near future (2023 to 2050), and end-century (2075 to 2100). Management scenarios include: 1) business as usual, 2) CCE at 30%, 3) CCE at 50%, and 4) CCE at 70%. Results indicate that increasing CCE to 30%, coupled with expanded irrigated areas and adjusted fertilization rates, could boost yields by three tons per hectare across all three crops at the national level. Further increasing CCE to 50% could yield additional increases of up to 0.6 t/ha of maize and 1.2 t/ha of rice in the Terai region. A CCE of 70% result in further increases of up to 2.1 t/ha of rice and 1.2 t/ha of maize. The benefits of improved CCE vary by location, with the subtropical Terai region experiencing the most and the mountain regions showing the least. We conclude that CCE should be increased to 70% in the Terai region, 50% in the hill region, and 30% in the mountains. Wheat appears to benefit the least from improved CCE. This work highlights efficient irrigation as a reliable adaptive measure for future climate change in Nepal.

Keywords Crop modelling; Climate change adaptation, Irrigation water management, Irrigation efficiency, Canal conveyance efficiency

3.1 Introduction

Global food production must be doubled by 2050 to meet the needs of the growing human population (Rosa et al., 2020). Irrigated agriculture, which accounts for 40% of global food production, occupies only 22% of the total cultivated land (Beltran-Peña et al., 2020). Projections suggest that the extent of global irrigated agriculture will need to double by 2050, which will significantly increase the demand for irrigation water(Puy et al., 2020). Currently, half of the water used for irrigation is unsustainable, surpassing the local renewable water supplies and negatively impacting water flows both locally and downstream in various regions(Rosa et al., 2019). This decreased water availability contributes to water insecurity, especially in the wake of climate change. The implementation of efficient and sustainable irrigation systems is essential for ensuring the long-term viability of agriculture and the health of the environment.

Adopting sustainable irrigation practices in a world facing with water scarcity involves reducing water losses in irrigation systems, decreasing the demand for irrigation water, and improving water productivity. In irrigation systems, significant conveyance water losses are caused by seepage through canal bunds, deep percolation in the canal and field soil layers, runoff into the drain, and evaporation from the water surface (Eltarabily et al., 2020). Factors such as soil permeability, the depth of water channels, the length of the wetted perimeter, water table level, and flow velocity, contribute to these conveyance losses (Abd-Elaty et al., 2022; Nam et al., 2016). Canal lining with materials like concrete, geomembrane, bentonite, polyvinyl chloride, or plastic can significantly enhance canal conveyance efficiency by minimizing water loss before it reaches the fields (Han et al., 2020). This strategy not only increases the availability of water for irrigation but also improves water quality. Water conservation through canal lining ensures equitable and reliable water distribution to farmers, leading to higher crop yields and cropping intensity. It also helps in controlling waterlogging, preventing erosion and breaches along channel banks, and reducing operational and maintenance costs (Singh, 2017).

Gravity water flow through long canal systems has been a primary method for transporting water for irrigation in Nepal. These canals are notably inefficient in terms of canal conveyance efficiency (Fig. 3-1a and 3-1b). Most of the canals are earthen structures (Fig. 3-1a), resulting in significant water loss during conveyance from the canal head to the farmers' fields (ADB-Mid-Hill-Project, 2016). Addressing seepage and percolation losses in these canals (Fig. 3-1c) could potentially allow for the irrigation of additional agricultural land. Presently, irrigation efficiency in Nepal is below 30%, which is significantly lower than the achievable efficiency of 60% (DoWRI, 2019). Consequently, the Government of Nepal has not only prioritized expanding the area under irrigation but also aims to achieve an irrigation efficiency of 50% by 2027, as outlined in its National Water Plan-Nepal 2020. In the context of Nepal's underperforming agricultural sector (Basukala and Rasche, 2022), developing efficient irrigation infrastructure and ensuring effective operation and maintenance of existing systems are crucial for boosting agricultural production. This is especially important considering the challenges faced in constructing new irrigation systems, such as rising capital costs, adverse topography, inadequate infrastructure, and political instability.

Figure 3-1. (a) Earthen canal with low conveyance effieciency with high seepage and percolation loss , (b) Concrete lined canal but not well maintained with low effieciency, (c) High effieciency well maintained canal lined with concrete.

There are studies related to the evaluation of efficiency of surface irrigation systems (Kulkarni and Nagarajan, 2019; Lamichhane et al., 2022; Shumye and Singh, 2018), calculation canal conveyance losses (Liao et al., 2022; Luo et al., 2015; Syed et al., 2021), and minimizing these losses (Barkhordari et al., 2020; Cui et al., 2023; El-Molla and El-Molla, 2021; Elkamhawy et al., 2021; Josiah et al., 2016; Kalybekova et al., 2023; Lamichhane et al., 2022; Yuguda et al., 2020). Additional research has focused on failure mechanism and treatment measures for canals (Chen et al., 2023), and the economic aspects of irrigation efficiency in relation to fuel consumption (Baral et al., 2022). However, studies that assess the impact of varied canal conveyance efficiencies on crop yields, particularly through biophysical crop models that consider the perspective of climate change, are scarce.

Similarly, there are studies exploring the expansion of irrigation related to crop production and irrigation water demand under various climate scenarios for crops like maize (Liao et al., 2024; Shan et al., 2023; Yan and Du, 2023; Yetik and Sen, 2023), wheat (Acharjee and Mojid, 2023; Gao et al., 2024; Haymale et al., 2020; Kaini et al., 2022; Luo et al., 2022; Peng et al., 2019; Rowshon et al., 2019; Wang et al., 2022a; Yan and Du, 2023), and rice (Houma et al., 2021; Kulyakwave et al., 2023; Sun et al., 2024). However, the effects of different canal conveyance efficiencies on crop yield are not accounted for in these studies. Therefore, this study aims to investigate the effects of climate change on rice, wheat, and maize crop yields across different Shared Socioeconomic Pathway (SSPs) scenarios, taking into account water availability based on varying canal conveyance efficiencies. Our analysis covers timeframes for the near future (2022–2050) and the end of the century (2075–2100) using low (SSP1-2.6), high (SSP3-7.0), and extreme (SSP5-8.5) emissions scenarios. We utilize three general circulation models (GFDL-ESM4, IPSL-CM6A-LR, and MPI-ESM1–2-HR) sourced from the ISIMIP3b database and bias-adjusted as part of CMIP6. This data, derived from ensembles of global circulation models, represents various climatic conditions. Our research aims to address the following research questions:

i. How will expanding irrigation and increasing canal conveyance efficiency (CCE) to 30% influence future crop yields?

ii. How will improving CCE from 30% to 50% affect crop yields under current to near-future climate conditions?

iii. How will an increase in CCE from 30% to 50% impact crop yields under climate conditions projected for the end of the century?

iv. What are the projected benefits in terms of crop yields when increasing CCE to 70%?

This study aims to support decision-making related to the expansion of irrigation, focusing on the appropriate conveyance efficiency of canal systems for major crops—rice, maize, and wheat across the diverse ecoregions of Nepal.

3.2 Materials and Methods

3.2.1 Study area

Nepal is a Himalayan country located in South Asia and covers an area of 147,181 square kilometres. It has a population of approximately 30.5 million as of 2022 (WorldBank, 2022), and is characterized by a diverse range of cultures and ethnicities. The socio-economic landscape of the country presents challenges, with 44% of the population living below the poverty line and approximately 82% residing in rural areas (NSO, 2024). The economy of the nation relies heavily on agriculture, which provides livelihoods for about 68% of the population.

Nepal has a wide range of ecological regions, from subtropical lowlands at 60 m.a.s.l. to alpine heights of over 8800 m.a.s.l. (Fig. 3-2), creating a unique blend of climates and terrains, including tropical, subtropical, temperate, subalpine, alpine, and nival zones (Paudel et al., 2021). Due to the sharp topographical constrasts, Nepal also has diverse rainfall patterns: Mean annual precipitation ranges from under 150 mm to over 5,000 mm. Monsoons contribute roughly 80% of the annual precipitation, with the winter and pre- and post-monsoon seasons contributing 3.5%, 12.5%, and 4.0%, respectively (Karki et al., 2017b). The spatial distribution of annual precipitation follows the monsoon pattern (Department of Hydrology and Meteorology (DHM), 2015). Nepal is known for its abundance of water resources, however, the hydrology of the Himalayan region is rapidly changing due to climate change (Talchabhadel and Chhetri, 2023). For temperatures, in the high-elevation areas like the North and Central Regions, annual temperatures are increasing, while the Southern regions experience a more gradual increase. Projections suggest that Nepal's average yearly temperature may rise by 1.2°C by 2030, 1.7°C by 2050, and 3°C by 2100 (Khadka and Pathak, 2016). Developing nations like Nepal are particularly vulnerable to the impacts of climate change due to restricted adaptive capacity (Khadka et al., 2022).

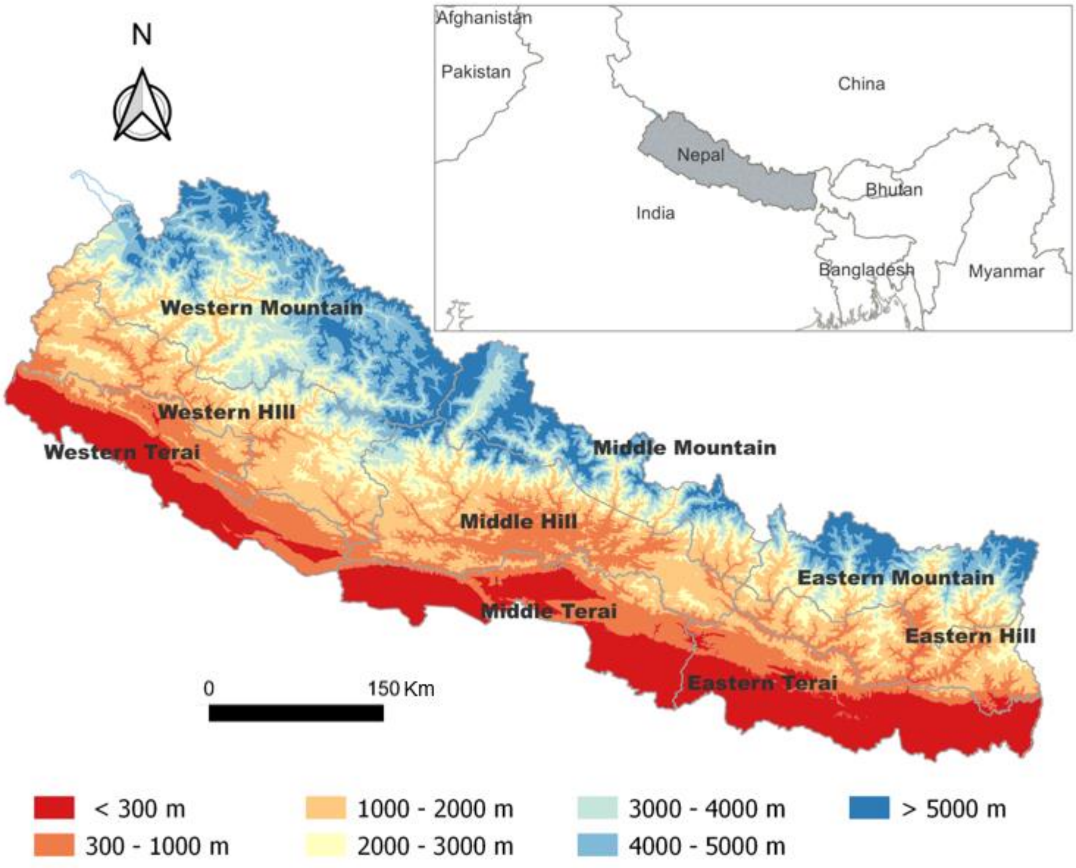


Figure 3-2. The nine different agro-ecological zones of Nepal with different elevation classes. The enclosure at the top right shows the location of Nepal in South Asia with neighboring countries.

The total cultivated land in Nepal covers 41,210 km2, primarily concentrated in the flat Southern region known as the "Terai". The middle hill region consists of fertile valleys, hilly peaks and river basins, with only a small fraction of the land suitable for cultivation. The northern mountain region has a mere two percent of cultivable land.

Rice, wheat, and maize are the three major cereal crops in Nepal, collectively contributing 31% of the agricultural GDP (Ministry of Agricultural Development (MOAD), 2022). These crops play a crucial role in ensuring food security and improving livelihoods (FAOSTAT, 2020). As of 2015, 52% of agricultural land was irrigated, with year-round irrigation available on 36% of the area (Pokhrel, 2019). Even though water is available in abundance, the agricultural sector nevertheless has been struggling since 1995, leading to the need for food imports to ensure food security (Bigyan et al., 2021). The reason for underperforming agriculture sector of Nepal is unavailability and low application rates of both organic and inorganic fertilizer, dependency on rainfall for irrigation, poor agriculture infrastructure, land abandonment, and vulnerability to external shocks such as climate change induced erratic rainfalls, floods and prolonged droughts (Basukala and Rasche, 2022; Bocchiola et al., 2019; Joshi et al., 2021). Political instability has further impeded effective policy implementation and investment in agriculture sector, worsening existing problems.

3.2.2 Data

Climate Data

We utilized daily climate data encompassing precipitation, maximum and minimum temperatures, relative humidity, solar radiation, and wind speed for three distinct periods: a baseline (2015- 2021) a near future (2022-2050), and a far future (2075-2100). The future climate projections incorporate three scenarios derived from phase 6 of the Coupled Model Intercomparison Project (CMIP6). The scenarios in our study encompass low-end (SSP126), medium-high (SSP370), and high-end (SSP585) future forcing pathways. Bias-corrected and statistically downscaled climate data from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) (Lange, 2019) were used for all scenarios. We used three CMIP6 models: GFDL-ESM4, MPI-ESM1-2-HR, and IPSL-CM6A-LR. The dataset has a spatial resolution of 0.44 degrees. The ISIMIP3b climate data were downloaded from the ISIMIP repository (https://data.isimip.org/search/).

In the Terai region, GFDL predictions for SSP5, SSP3, and SSP1 scenarios show temperature rises of 3.9°C, 2.8°C, and decline of 0.2°C, respectively. The MPI model anticipates temperature changes of 3.3°C (SSP5), 2.8°C (SSP3), and 0.8°C (SSP1) in the area (Fig. 3-3). In the Hill region, projections from the GFDL climate model for SSP5, SSP3, and SSP1 scenarios suggest temperature increases of 3.8°C, 3.3°C, and 0.5°C, respectively. Correspondingly, the MPI model predicts temperature elevations of 3.6°C (SSP5), 3.1°C (SSP3), and decline of 0.5°C (SSP1) in the same region. The IPSL model forecasts higher increments, with temperature changes of 7.7°C (SSP5), 5.1°C (SSP3), and decline of 0.9°C (SSP1) at the Hill region. For the Mountain region, GFDL model projections show a temperature rise of 4.2°C (SSP5), 3.7°C (SSP3), and a decrease of 0.3°C (SSP1). The MPI model indicates temperature changes of 4.3°C (SSP5), 3.2°C (SSP3), and 0.8°C (SSP1). The IPSL model predicts increases of 8.5°C (SSP5), 6.3°C (SSP3), and 0.4°C (SSP1) within this region.

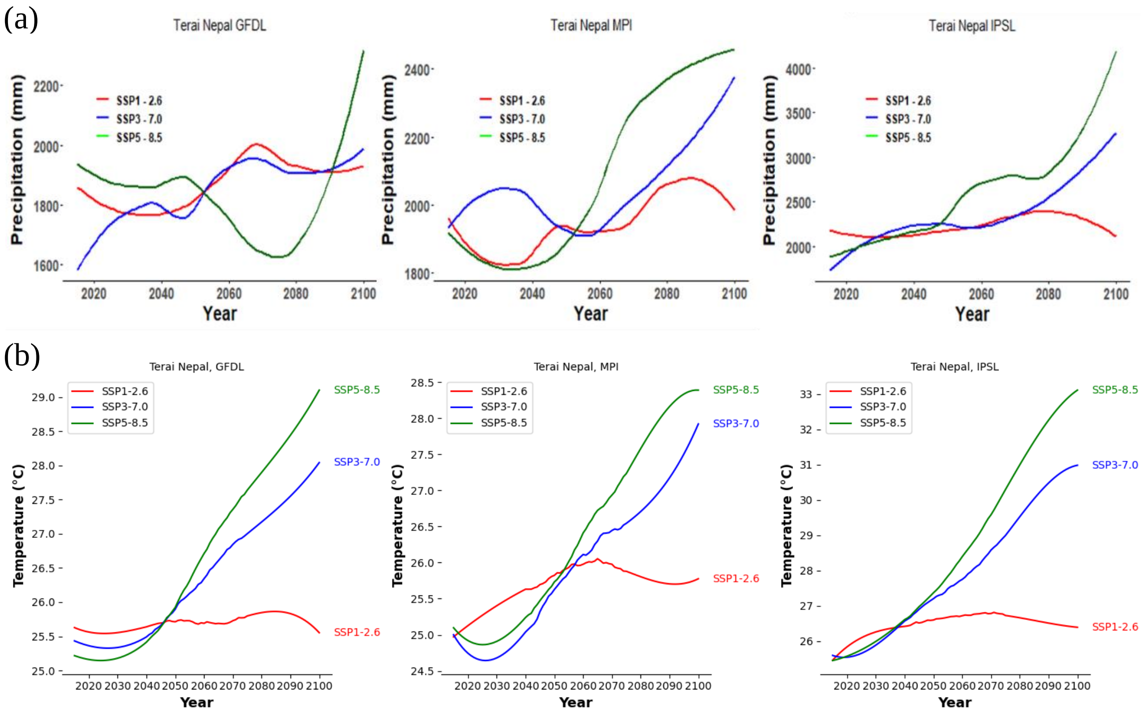


Figure 3-3. Trends of annual precipitation and annual average temperature in the Terai ecoregion under three different climate scenarios using three different general circulation models.

By the end of century based on GFDL climate model in Terai, the annual precipitation increase by 130 mm, 440 mm and 300 mm for SSP1-2.6, SSP3-7.0 and SSP5-8.5 respectively. Similarly, by the end of century, with reference to MPI climate model in Terai, the annual precipitation increase by 190 mm, 282 mm and 533 mm for SSP1-2.6, SSP3-7.0 and SSP5-8.5 respectively. Based on IPSL climate model in Terai, the annual precipitation increase by 214 mm, 1092 mm and 1950 mm for SSP1-2.6, SSP3-7.0 and SSP5-8.5 respectively at the end of century.

Soil, elevation and slope data

The soil typological units (STU) of each simulation unit were derived from the global dominant soil typological units outlined in the GEOBENE database (Skalský et al., 2008). These STUs provide data on analytical characteristics of soils required by biophysical model, e.g. bulk density, water content at field capacity and at wilting point, pH, cation exchange capacity, electric conductivity, etc. (Jones and Thornton, 2015). The topography map for the study area was procured from the NASA Shuttle Radar Topographic Mission (SRTM) 90m Digital Elevation Database (v4.1). This resource, accessible through the Consortium for Spatial Information (CGIAR-CSI) under the Consultative Group for International Agricultural Research (CGIAR), offers a resolution of 90m at the equator (Jarvis et al., 2008).

Management data

Information regarding rice, wheat, and maize crop area and yields spanning fiscal years 1990 to 2022 were sourced from Nepal's agricultural statistics for cereal crops (Ministry of Agricultural Development (MOAD), 2022). Data regarding fertilizer and irrigation applications per hectare (Table 3-1), including application timings, were obtained from Nepal's CBS decadal agriculture census records for 2011, 2021 as well as from Takeshima (2019). For Nepal's key crops, the district-specific crop calendar details were sourced from an FAO/WFP food security assessment mission to Nepal (Table 3-2).

Table 3-1. Annual inorganic and organic fertilizer use in Nepal based on data from CBS Nepal decadal agricultural census data and Takeshima et al.(Takeshima, 2019).

Fertilizer type	**Terai**	**Hill**	**Mountain**
Urea	28 kg/ha	18 kg/ha	12 kg/ha
Complex	3 kg/ha	4 kg/ha	2 kg/ha
DAP	17 kg/ha	3 kg/ha	1 kg/ha
Organic N fertilizer	22 kg/ha	16 kg/ha	13 kg/ha
Organic P fertilizer	11 kg/ha	4 kg/ha	2 kg/ha
Other inorganic	0 kg/ha	0 kg/ha	0 kg/ha

Table 3-2. Crop calendar for the main cereal crops cultivated in Nepal split by ecological zone and irrigation management. P= Planting; TP= Transplanting; H= Harvesting.

Crop	**Ecological Zone**	**Irrigation**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Rice	Hill	Rainfed					TP	TP			H	H		
		Irrigated			TP	TP			H	H				
	Terai	Rainfed						TP	TP		H	H	H	
		Irrigated			TP	TP			H	H	H			
Maize	Mountain	Rainfed			P	P				H	H	H		
	Hill	Rainfed			P	P				H	H			
	Terai	Rainfed		P	P			H	H					
Wheat	Mountain	Rainfed					H	H					P	P
	Hill	Rainfed			H	H	H					P	P	P
	Terai	Rainfed			H	H						P	P	

3.2.3 Derivation of simulation units

We simplified the representation of Nepal’s diverse agriculture landscape, spatial heterogeneity and climatic conditions by creating Homogenous response units (HRUs). We followed the method used for constructing the Global Earth Observation – Benefit Assessment (GEOBENE) database (Skalský et al., 2008). The classification involved dividing the territory based on seven elevation categories, seven slope categories, and ten soil classes (Table 3-3), ensuring a consistent and standardized representation for simulation purposes.

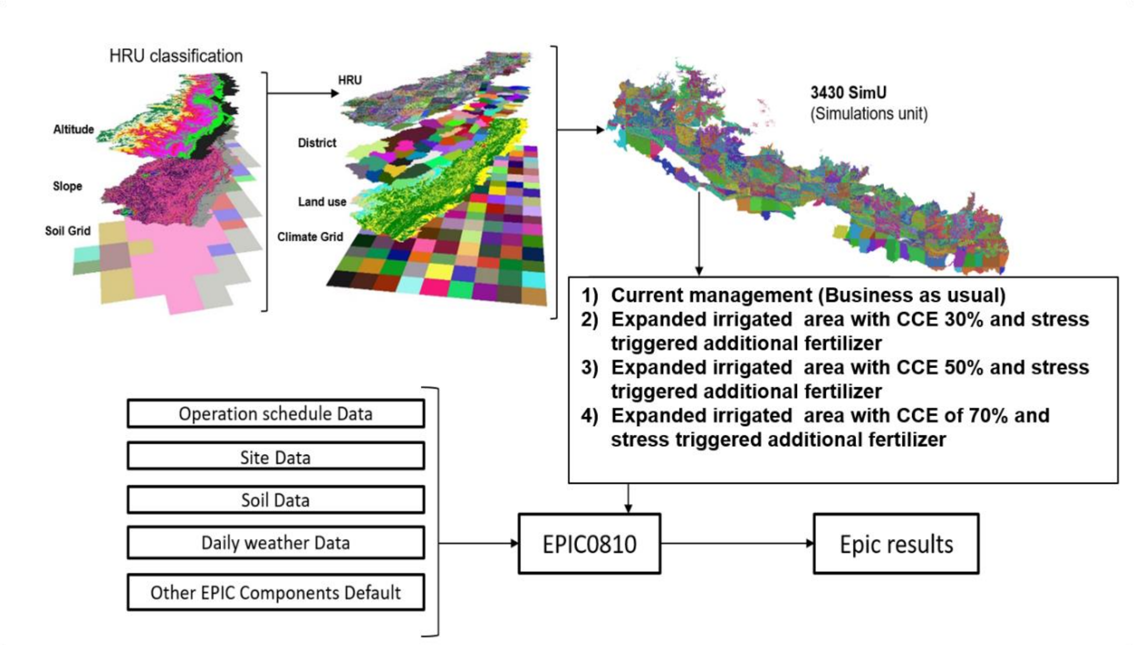
Table 3-3. Classes of elevation, slope and soil texture used for the delimitation of the homogeneous response units in this study.

Elevation classes		Slope classes		Soil typological units	
Elevation [m]	Classification (Barnekow Lillesø, 2005)	Class	Slope [%]	Class	Dominant soil
< 300	Lower Tropical	1	< 3	1	Eutric Cambisols (Be)
300 - 1000	Upper Tropical	2	3 - 6	2	Eutric Fluvisols (Je)
1000 - 2000	Subtropical	3	6 - 10	3	Calcic Cambisols (Bk)
2000 -3000	Temperate	4	10 - 15	4	Dystric Regosols (Rd)
3000- 4000	Subalpine	5	15 - 30	5	Dystric Cambisols (Bd)
4000 - 5000	Alpine	6	30 - 50	6	Humic Acrisols (Ah)
> 5000	Trans Himalayan	7	> 50	7	Humic Acrisols (Ah)
				8	Rankers (U)
				9	No soils (RK2)
				10	Lithosols (I)

After demarcating the HRUs, we proceeded to subdivide these units based on district boundaries, land use and land cover, as well as the climate data raster. To define district boundaries, we sourced data from the Global Administrative Areas database (GADM, 2018). The land use mask utilized was extracted from the Land Cover of Nepal 2010 dataset, developed by the International Center for Integrated Mountain Development (ICIMOD) (Uddin et al., 2015). Subsequently, we identified cropland and non-cropland areas through the land use mask and excluded the non-cropland areas from the simulations. The final count of simulation units was 3430 (Fig. 3-4). For the discussion of the results, we divided the country into nine sub-regions based on physiography and longitude (cf. Fig. 3-1).

3.2.4 Crop model:

In this study, we utilized the Environmental Policy Integrated Climate (EPIC) model for crop simulations (Williams et al., 1989). EPIC is a complex biophysical process based simulation tool designed to assess the complex interactions between agricultural systems, climate dynamics, and environmental conditions. EPIC is developed to address the challenges posed by climate change and sustainable agricultural practices. EPIC combines meteorological data, soil information, and crop-specific parameters to simulate various aspects of agricultural processes. Through its comprehensive modeling framework, EPIC can predict crop growth, yield, water usage, nutrient dynamics, soil erosion rates, and greenhouse gas emissions (Di Bene et al., 2022; Gaiser et al., 2010).



1) Current management (Business as usual)
2) Expanded irrigated area with CCE 30% and stress triggered additional fertilizer
3) Expanded irrigated area with CCE 50% and stress triggered additional fertilizer
4) Expanded irrigated area with CCE of 70% and stress triggered additional fertilizer

Figure 3-4. Flow chart of the methodological framework used for the yield gap analysis in Nepal, including homogeneous response unit (HRU) and simulation unit delineation, scenario portfolio, and input data to the EPIC crop model.

Plant growth in EPIC is simulated via intercepted solar radiation and the ability of each plant to convert the intercepted radiation into biomass (Zhang et al., 2018). The leaf area index (LAI) represents the total area of leaves in relation to the ground area, providing insights into a plant's ability to capture sunlight for photosynthesis. Biomass, the accumulated organic material produced by plants, is a key output of the EPIC model. The potential daily biomass increase may be reduced if the plant is water-, temperature- or nutrient-stressed. Within the soil submodel of EPIC, many distinct soil pools are used to monitor the levels of organic nitrogen and carbon, mineral nitrogen, organic phosphorus, and mineral phosphorus. Among these, the labile pools contain nutrients accessible for plant uptake, while nitrogen and phosphorus in the other pools are more immobile due to being sorbed to organic or inorganic soil particles. In cases where mineral fertilizer is applied, nutrients are directed to the plant-available pool, yet rapid immobilization may occur. Additionally, EPIC offers flexibility by providing a selection of five potential evapotranspiration equations (Balkovič et al., 2013), diverse crop rotations, tillage systems, and management practices.

We opted for the utilization of the EPIC model in this study, due to its consistently reliable performance across diverse settings, especially considering the challenging environmental conditions present in Nepal for crop simulations. The outputs generated by the EPIC model offer comprehensive details on crop growth, water dynamics, nutrient interactions, and carbon fluxes at daily, monthly, and yearly intervals. In this investigation, our emphasis is on key parameters such as the estimated annual yield (Yd, t/ha), growing season evapotranspiration (GSET, mm), and the annual irrigation water supply (IR, mm).

3.2.5 Model calibration

We first calibrated the yields of rice, wheat, and maize for the baseline period (2015-2021). The initial crop parameter values were derived from the standard crop parameter set in the EPIC crop database file. Calibration focused on crop-specific parameters such as potential heat units, radiation use efficiency, harvest index, and optimal and base temperature. We began the calibration by running the model separately for each crop. The resulting simulated crop yields were compared against the reported district-wise yield data for rice, wheat, and maize from the agricultural statistics of cereal crops in Nepal (Ministry of Agricultural Development (MOAD), 2022) for the years 2015-2021. We then iteratively calibrated the aforementioned crop-specific parameters to minimize the discrepancies. The range of crop parameter values for iterations was restricted, we did not allow it to deviate by more than 20% from the original values or the range defined as feasible in the EPIC user guide. Through this process, we fine-tuned the crop parameters to match the local crop variety characteristics. We could not identify a single set of crop parameters applicable to all regions of Nepal and therefore decided to derive a separate crop parameter set for each of the 77 districts in Nepal.

A total of four statistical measures were used to assess the adequacy of fit of the crop model during calibration with statistical indicators which are (i) Nash Suttcliffe Effieciency, (ii) correlation coeffiecient value, (iii) relative error and (iv) percent bias.

Nash-Sutcliffe efficiency (NSE) quantifies the agreement between observed and simulated data, providing a measure of model accuracy, with values ranging from -∞ to 1. Higher values indicate better model performance in replicating observed data.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i - \bar{\mathrm{Y}}_i)^2}{\sum_{i=1}^{n}(X_i - \bar{\mathrm{X}})^2} \qquad (1)$$

The percent bias (PBIAS, Eq. 1) identified the average tendency of the simulated data to be larger or smaller than the observed data. Positive values indicate an underestimation, negative values an overestimation bias, and zero no bias at all. Generally, PBIAS values 0-10 are considered very good, 10-15 good, 15-25 fair, and values >25 unsatisfactory (de Salis et al., 2019).

$$PBIAS = 1 - \frac{\sum_{i=1}^{n}(Y_i - \mathrm{X_i}) * 100}{\sum_{i=1}^{n} Y_i} \qquad (2)$$

where Xi is the reported crop yield in district i, Yi simulated crop yield in district i and n is the total number of districts.

The correlation coefficient is a statistical measure that assesses the strength and direction of the linear relationship between two variables. It ranges from -1 to 1, with a positive value indicating a positive correlation, a negative value indicating a negative correlation, and 0 indicating no linear correlation. It's commonly used to gauge the degree of association between variables in data analysis and modelling

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{\mathrm{X}})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{\mathrm{X}})^2 \ \sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \qquad (3)$$

where $\bar{\mathrm{X}}$ is the simulated crop yield mean and $\bar{Y}$ is reported crop yield mean.

We also calculated the relative error RE (Eq. 2) to examine systematic errors in the simulated data. Considering the versatility of agroecological zones and the scale of this study, we assume an RE of ≤30% to be an acceptable result, whereas RE > 50% should be considered to be extreme errors (Balkovič et al., 2013; Niu et al., 2009).

$$\mathrm{RE_i} = \frac{(\bar{\mathrm{Y}}_\mathrm{i} - \mathrm{X_i})}{\mathrm{X_i}} \cdot 100 \qquad (4)$$

where X_i is the reported crop yield in district i, Y_i simulated crop yield in district i, and $\bar{Y}_i$ is the simulated average crop yield in district i.

The calibration was stopped once the acceptable ranges for NSE, PBIAS, r and RE were achieved.

3.2.6 Calculation of future irrigation requirements

We conducted simulations of irrigation requirements over a 78-year period from 2022 to 2100 for each simulation unit and each crop, drawing inspiration from (Wriedt et al., 2009) for their methodology in estimating irrigation needs in Europe. During the simulation, additional irrigation was automatically applied on days when plants experienced a moderate level of water stress (stress factor of 15% or higher). For each district, the net irrigation requirement in mm was determined by calculating the area-weighted average of the net irrigation requirements from all simulation units for the near future and end-of-century periods. The irrigation volumes for each scenario were then determined individually, factoring in the water conveyance efficiency of the irrigation systems (referenced in Figure 3-12, 3-13,3-14). These calculated irrigation amounts were subsequently integrated into the scenarios run in the EPIC model. Water conveyance efficiency refers to the ratio between the water that reaches a field and that is diverted from the irrigation water source.

$$\mathrm{E_c} = \frac{\mathrm{V_f}}{\mathrm{V}_t} \cdot 100 \qquad (5)$$

In this equation, E_c is water conveyance efficiency, V_f is the volume of water applied to the land, and V_t is the volume of water diverted from the source.

3.2.7 Simulation scenarios

Irrigation and fertilizer applications explain 60%–80% of the global yield variability for most major crops (Muller et al., 2019), which is why we consider these two factors explicitly in our scenarios and ignore other factors such as changes in tillage, mulching, pest control, or cultivar development. The four scenarios are:

1) Current management (Business as usual)
2) Expanded irrigated area with water conveyance efficiency of 30%, additional fertilizer if required
3) Expanded irrigated area with water conveyance efficiency of 50%, additional fertilizer if required
4) Expanded irrigated area with water conveyance efficiency of 70%, additional fertilizer if required

The expansion of irrigated area implies that irrigation is allowed on all simulation units if the plant experiences water stress. Under current management, irrigation is only allowed on the simulation units where irrigation is currently practiced. The additional fertilizer applications in scenarios 2, 3 and 4 were triggered automatically during the simulation if the plant experienced a moderate amount of nutrient stress on a specific day (stress factor higher or equal to 15%). For scenarios 2, 3 and 4 stress triggered mineral phosphorous applications and a maximum annual amount of 300 kg of mineral nitrogen per hectare were allowed. Irrigation was allowed up to the district wise maximum irrigation calculated for each CCE in section 2.5. Each scenario was run for all 3430 simulations units covering Nepal for the periods 2015 to 2050 and 2075 to 2100.

3.3 Results

3.3.1 Calibration of crop yields

Crop yields were simulated under reported management practices from 2015 to 2022 across all simulation units. Crop yields at the district, provincial, ecological, and national levels were calculated by summing up the outputs from all individual simulation areas within those geographic limits. The simulated mean crop yields at the national level were within the same range as the reported mean crop yields: rice yielded 3.7 t/ha versus the reported 3.4 t/ha, wheat 2.1 t/ha versus the reported 2.5 t/ha, and maize 2.63 t/ha versus the reported 2.68 t/ha. At the district level, simulated rice yields were in some instances slightly higher than reported yields, yet overall they remained comparable. For wheat, simulated yields were lower than reported yields in certain cases but were generally within the same range. Maize yields, both simulated and reported, demonstrate a performance that is notably better compared to the other two crops, and their results align closely within each other. The Nash-Sutcliffe efficiency (NSE) values were 0.54 for wheat, 0.59 for rice, and 0.72 for maize. These values indicate that the simulation model performed more effectively in predicting crop yields compared to a simple average of the observed yields across all crops. The percent bias (PBIAS) between reported and simulated mean annual yields was -7.2% for rice, 1.1% for maize, and -12.3% for wheat. The correlation coefficient r was 0.83 for rice, 0.86 for maize, and 0.9 for wheat, which indicate a strong positive linear relationship between reported and simulated crop yields for all three crops. The degree of agreement, as measured by the index of agreement, ranged from 0.84 for wheat and 0.85 for rice to 0.86 for maize, indicating a high level of consistency between the compared data sets. The relative error (RE) values spanned from-35.02% to 31.07% for rice, -41.1% to 48.1% for wheat, and -44.21% to 29.14% for maize. These values represent the measure of accuracy of the numerical approximations as compared to both the reported and simulated values. Based on the statistical indicator values, the calibration of rice, wheat, and maize models can be considered satisfactory. The scatterplot illustrates that our calibrated EPIC model slightly overestimated the average rice yield, underestimated the average winter wheat yield, but provided a good estimate for the maize yield in Nepal (Fig. 3-5).

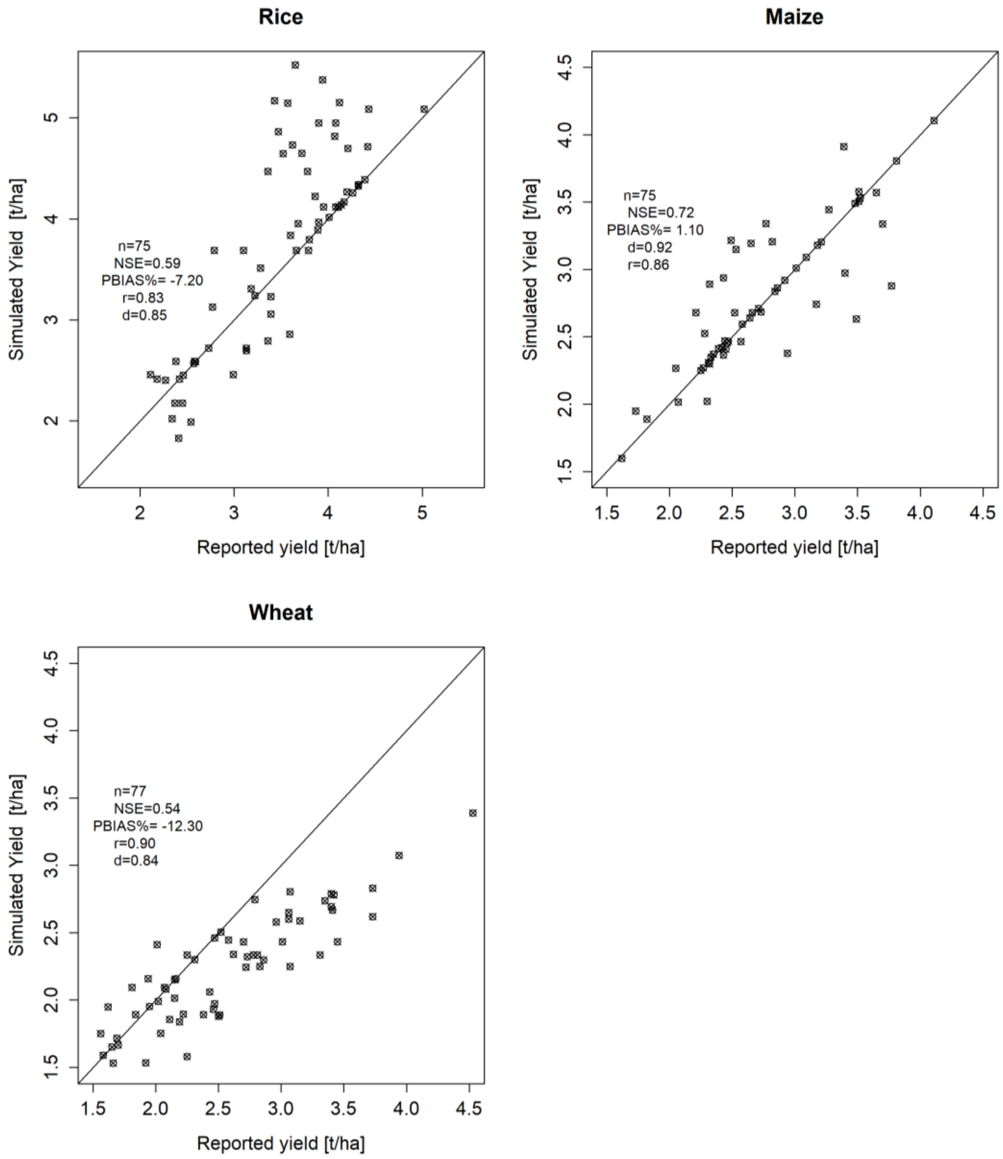


Figure 3-5. Comparison of district level mean simulated crop yields and mean reported crop yields published by the Ministry of Agriculture Development (MOAD) Nepal. Each data point represents a long-term average yield (from 2015 to 2021). The line indicates x = y (perfect agreement). NSE represents Nash-Sutcliffe efficiency; PBIAS represents percentage bias, n the number of districts, r the Pearson correlation coefficient and d the degree of agreement

3.3.2 Crop yield development under different scenarios in the different ecoregions of Nepal

To assess the absolute variations in crop yield values across different Shared Socioeconomic Pathway (SSP) scenarios and canal conveyance efficiency (CCE) scenarios, we aggregated the results to the nine ecoregions.

Rice

Across all ecoregions, transitioning from current management practices to the adoption of irrigation expansion with a 30% conveyance efficiency (CCE) leads to an increase in rice yields. In the mountain region, the rice yields increase by 1.6 t/ha, in the hills by 1.6 t/ha, and in the Terai region, the increase is substantially higher at 3.1 t/ha (Fig. 3-6a). With a further improvement of CCE, the most significant impact is observed in the Terai region. Here, yields increase by an average of 0.5 t/ha when CCE is enhanced from 30% to 50%, and by 0.93 t/ha when CCE is further increased from 30% to 70%. The Middle Terai region, in particular, exhibits the most significant benefits from increasing CCE, where the yield increases by 0.64 t/ha with a transition from 30% to 50% CCE, and by 1.19 t/ha when transitioning from 30% to 70% CCE. Conversely, there is no discernible impact on rice yield enhancement in the Eastern Hill region and across all Mountain regions from improving CCE. This stress that achieving a CCE of at least 50%, ideally 70%, is strongly recommended for the Terai region, especially in the Middle Terai, for the near future. Meanwhile, for the hill and mountain regions, a 30% CCE is sufficient.

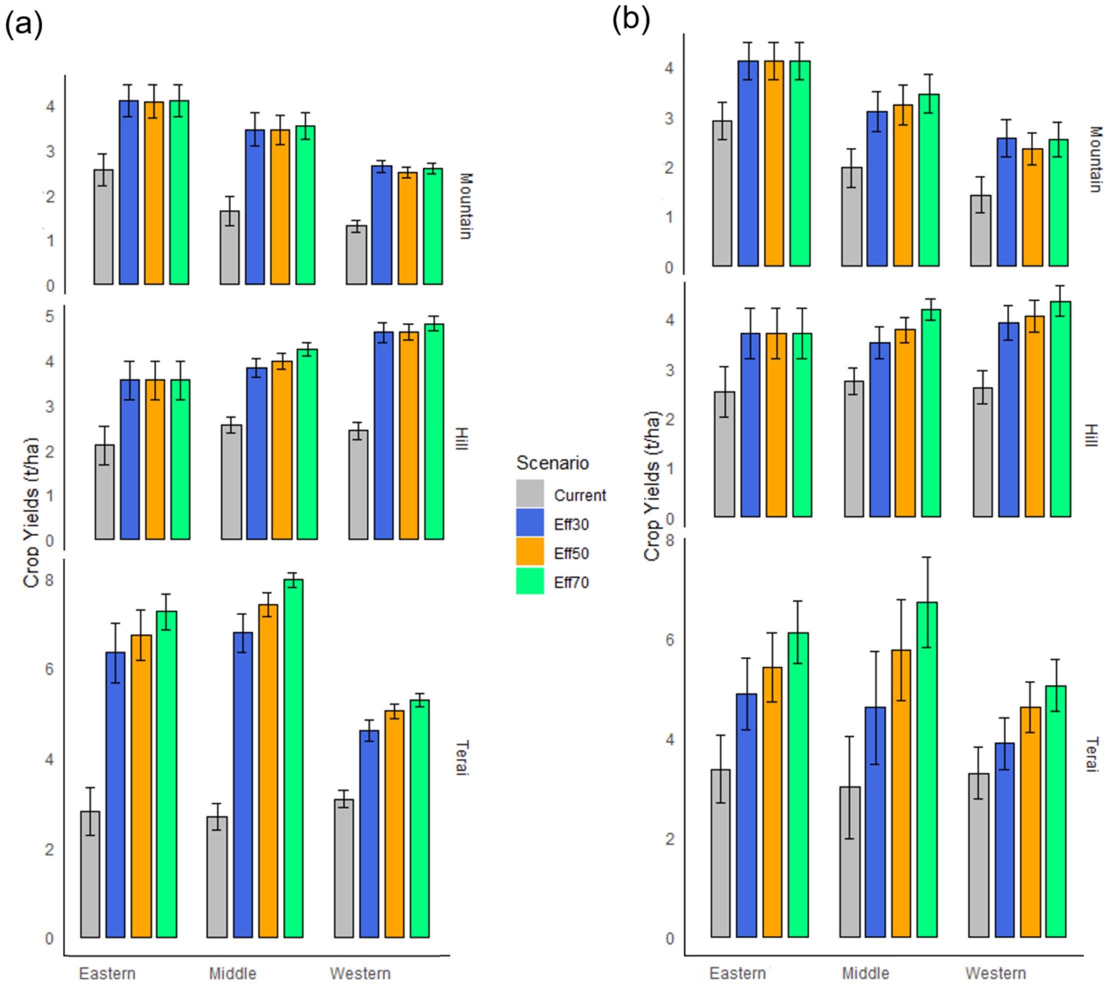


Figure 3-6. Rice yields in the a) near future and b) far future. Eff30 = canal conveyance efficiency (CCE) of 30%, Eff50 = CCE of 50%, Eff70 = CCE of 70%. The confidence intervals denote the range over the three climate change scenarios and the three GCM models

In the far future, a transition from current management to irrigation expansion with a 30% conveyance efficiency (CCE) leads to yield increases in the Mountain regions of 1.2 t/ha, in the hill regions of 1.1 t/ha, and in the Terai regions of 2.5 t/ha (Fig. 3-6b). A further enhancement of CCE yields the most pronounced impact within the Terai region. In this locale, augmenting the CCE from 30% to 50% engenders a yield augmentation of 0.8 t/ha throughout the Terai, whereas an elevation of CCE to 70% leads to a yield increment of 1.51 t/ha. The Middle Terai region, in particular, witnesses the most yield amplifications, noted by an increase of 1.15 t/ha following a CCE transition from 30% to 50%, and a further surge of 2.13 t/ha as CCE increases from 30% to 70%. In the Middle Hill region, yields increase by 0.26 t/ha after a 30% to 50% CCE transition, and by 0.67 t/ha after a 30% to 70% CCE adjustment. While yield improvements are evident across other Hill regions, their magnitude does not parallel the amplifications witnessed in the Terai region. The forecast for the three Mountain regions shows only marginal or insubstantial yield increments. Based on the results we conclude that a CCE of 30% is sufficient for hill and mountain regions, while the tropical Terai would benefit from a CCE of 50% and more.

Maize

Moving from existing management practices to irrigation expansion with a 30% conveyance efficiency (CCE) significantly boosts maize yields in all ecoregions. In the Mountain regions, yields increase by 2.7 t/ha, in Hill regions by 3.1 t/ha, and in the Terai region by 2.7 t/ha respectively (Fig. 3-7a). The most substantial effect of enhancing CCE is seen in the Terai region. Upgrading CCE from 30% to 50% across the Terai results in a yield gain of 0.6 t/ha, while a further increase to 70% CCE yields an approximate rise of 1.0 t/ha. In the Hill region, yields increase by 0.4 t/ha with the 30% to 50% CCE transition and by 0.6 t/ha with the 30% to 70% CCE transition. For all three Mountain regions, only marginal or insignificant increases in maize yields are anticipated in the near future. Thus, the data indicates that for maize, expanding irrigation with a 50% to 70% conveyance efficiency is advisable in the Terai regions in the near future. For other regions, a conveyance efficiency of 30% is sufficient.

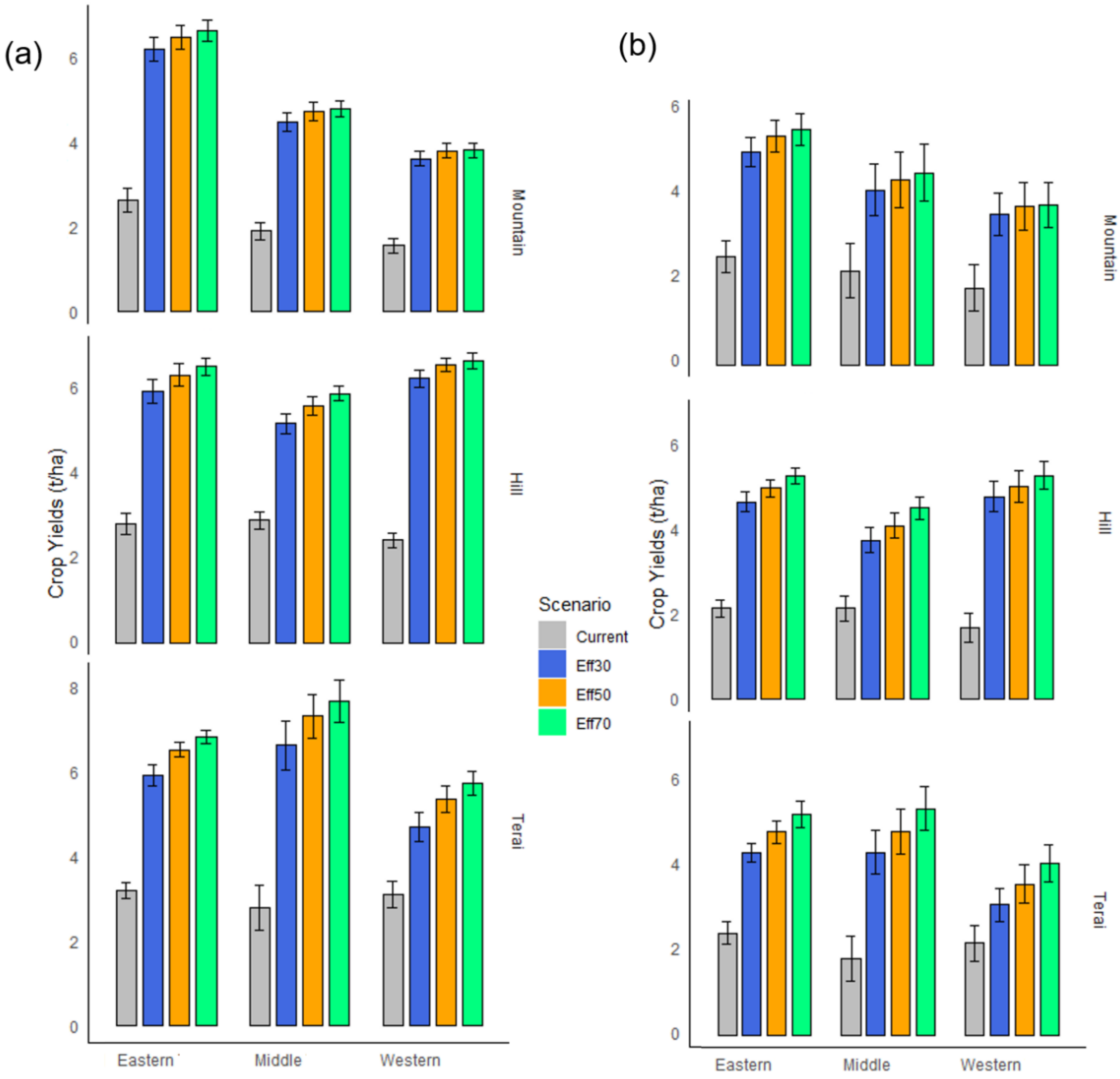


Figure 3-7. Maize yields in the a) near future and b) far future. Eff30 = canal conveyance efficiency (CCE) of 30%, Eff50 = CCE of 50%, Eff70 = CCE of 70%. The confidence intervals denote the range over the three climate change scenarios and the three GCM models.

Regarding maize yield by the end of the century, transitioning to irrigation with a 30% CCE from current management enhances maize yields across all ecoregions (Fig. 3-7b). In the Mountain regions, yields increase by 2.1 t/ha, in Hill regions by 2.9 t/ha, and in the Terai region by 2.4 t/ha. Similarly, moving from a 30% to a 50% CCE in the Terai results in a yield increase of 0.6 t/ha, while advancing to a 70% CCE leads to a growth of 1.2 t/ha. In the Hill region, the yield rises by 0.4 t/ha with the 30% to 50% CCE transition and by 0.7 t/ha with the 30% to 70% CCE transition. Across all three Mountain regions, marginal or negligible yield increases are anticipated by the century's end. Based on these findings, expanding irrigation with a conveyance efficiency ranging from 50% to 70% is highly recommended for the Terai and Hill regions. In contrast, for Mountain regions, a conveyance efficiency of 30% is sufficient.

Wheat

Switching from current practices to irrigation with a 30% conveyance efficiency (CCE) significantly increases wheat yields in all ecoregions. In the Mountain region, yields increase by 1.9 tons/ha; in the Hill region, by 3.03 tons/ha; and in the Terai region, by 3.13 tons/ha. However, in all of Nepal's regions, only marginal or negligible improvements in wheat yields are expected when CCE is further enhanced to 50% and 70% by the near future. According to this analysis, it is clear that implementing irrigation with a conveyance efficiency of 30% is more than adequate for all ecoregions along with the required amount of application of fertilizer.

In the far future, switching from current practices to irrigation with a 30% conveyance efficiency (CCE) significantly increases wheat yield in all ecoregions. Specifically, in the Western and Eastern Mountain regions, yields improve by 2.2 and 1.3 tons/ha, respectively; in Hill regions, by 1.8 tons/ha; and in the Terai region, by 1.96 tons/ha. When CCE is increased from 30% to 50% in the Terai, yields increase by 0.2 tons/ha, and a transition from 30% to 70% CCE results in a yield increase of 0.3 tons/ha. In Hill regions, there are only slight yield increases of 0.2 tons/ha when CCE improves from 30% to 70%. Across all other regions, marginal or negligible increases in wheat yields are expected by the end of the century. The findings make it clear that a conveyance efficiency of 30% is adequate for wheat production.

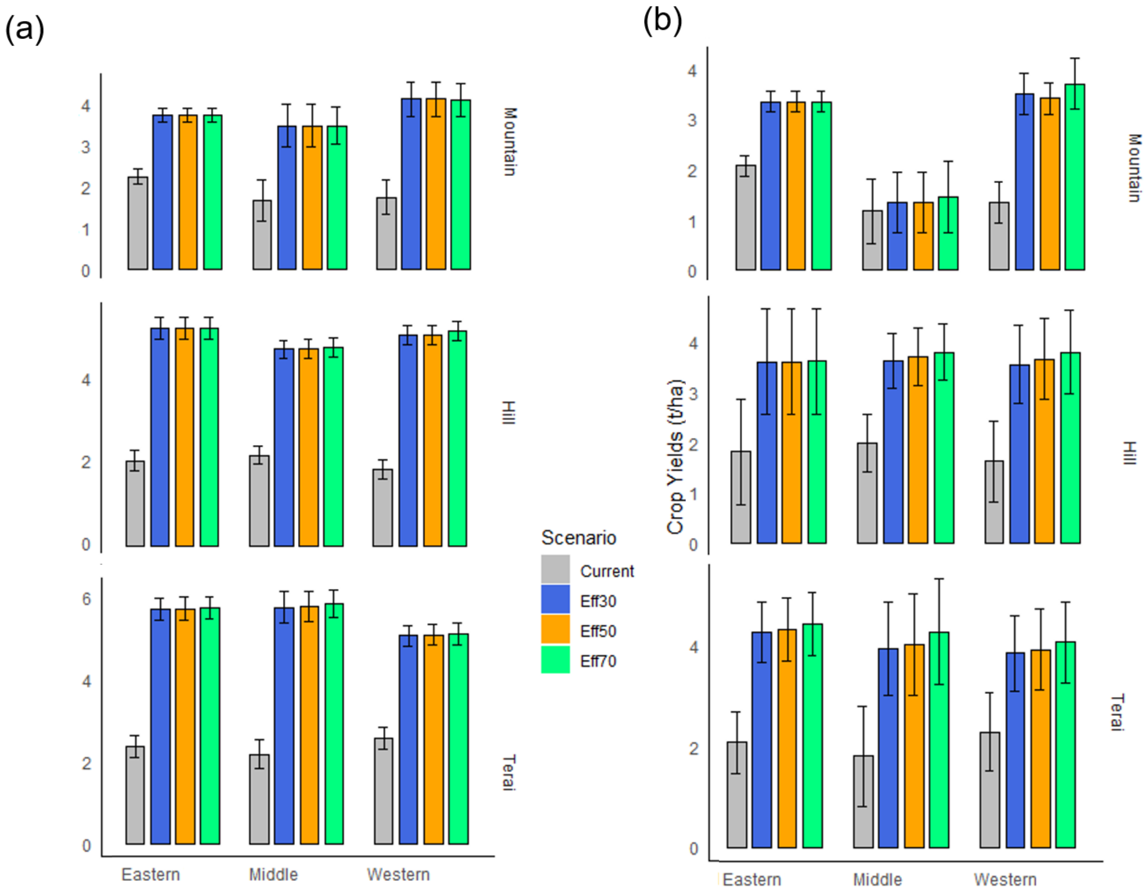


Figure 3-8. Wheat yields in the a) near future and b) far future. Eff30 = canal conveyance efficiency (CCE) of 30%, Eff50 = CCE of 50%, Eff70 = CCE of 70%. The confidence intervals denote the range over the three climate change scenarios and the three GCM models.

3.3.3 Identifying the most promising ecoregions for CCE improvements

The previous section detailed the absolute changes in yields under various scenarios. In the following section, we present relative changes to identify the most promising ecoregions for CCE improvements.

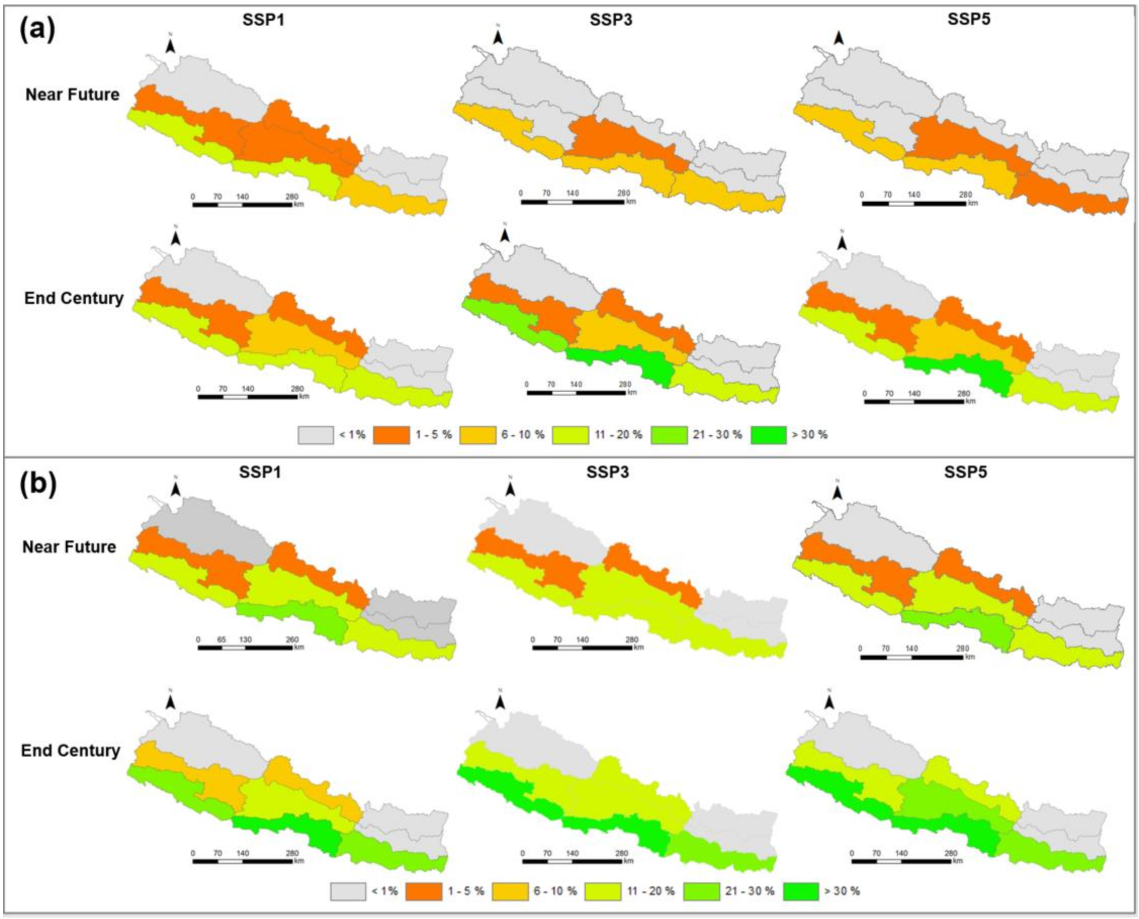


Figure 3-9. Relative changes in rice yields at ecoregion level when canal conveyance efficiency changes from a) 30% to 50% and b) 30% to 70% in the near and far future. SSP1, SSP3 and SSP5 represents Shared Socioeconomic Pathway with radiative forcing level of 2.6 W/m², 7.0 W/m² and 8.5 W/m²

The increase in rice yield shows a clear spatial variation, with the tropical Terai region experiencing the most percentage increase (Fig. 3-9, Table 3-5, Table 3-6). When

CCE is enhanced from 30% to 50%, yield increases range from 2 to 15% (Fig. 3-9a), and 6 to 31% with a CCE improvement from 30% to 70% (Fig. 3-9b). These findings underscore the importance of prioritizing CCE upgrades to 70% in the Terai region. By the century's end, the Terai could see a yield increase ranging from 7 to 42% with a 50% CCE, and from 14 to 77% with a 70% CCE, suggesting a substantial benefit from investing in CCE improvements to 70%. In contrast, the Western and Middle Hill regions witness smaller yield increases, ranging from 1 to 6% with an improvement from 30% to 50% CCE, which then slightly increases to 3 to 14% with a CCE improvement from 30% to 70%. By the century's end, yield increases in the Hill regions range from 1 to 13% with a 50% CCE, and from 1 to 15% with a 70% CCE. This indicates that investing in CCE improvements in the Hill regions, especially beyond 30%, is not as high a priority as it is in the Terai. The Mountain region and Eastern Hill region consistently demonstrate negligible changes across all future scenarios, suggesting that enhancing the CCE to 30% would sufficiently support agriculture in these areas. However, upgrading the CCE to 50% in the Middle Hill region could offer benefits in the future.

The increase in maize yield is noticeable across all ecoregions (Fig. 3-10, Table 3-7, Table 3-8). The tropical Terai region witnesses the highest percentage increase in yield. When CCE is enhanced from 30% to 50%, yield increases range from 7 to 27%, which further climbs to 11 to 28% with an improvement in CCE from 30% to 70%. This underlines the need to prioritize increasing the CCE to 70% in the Terai. Moreover, by the century's end, the yield increase in the Terai is projected to be 7 to 21% with a 50% CCE, and 10 to 38% with a 70% CCE, indicating that investments in advancing conveyance efficiency to 70% will have significant benefits for maize production even in future. In the hill regions, yield increases from converting CCE from 30% to 50% are observed within the range of 3 to 14%, which remains the same with a CCE change from 30% to 70%. By the century's end, the yield increase in the hill regions is expected to range from 1 to 15% with a 50% CCE and from 8 to 25% with a 70% CCE. This suggests that while benefits from increasing CCE to 70% will be moderate in the near future, they will be substantial in the far future. Thus, a long-term investment in CCE would pay off with better yields at the century's end in the hill regions. At the century's end, the yield increase in the mountain regions ranges from 1 to 14% with a 50% CCE and from 1 to 21% with a 70% CCE. This indicates that investing to increase CCE to 50% is sufficient for Maize production in the Mountain regions.

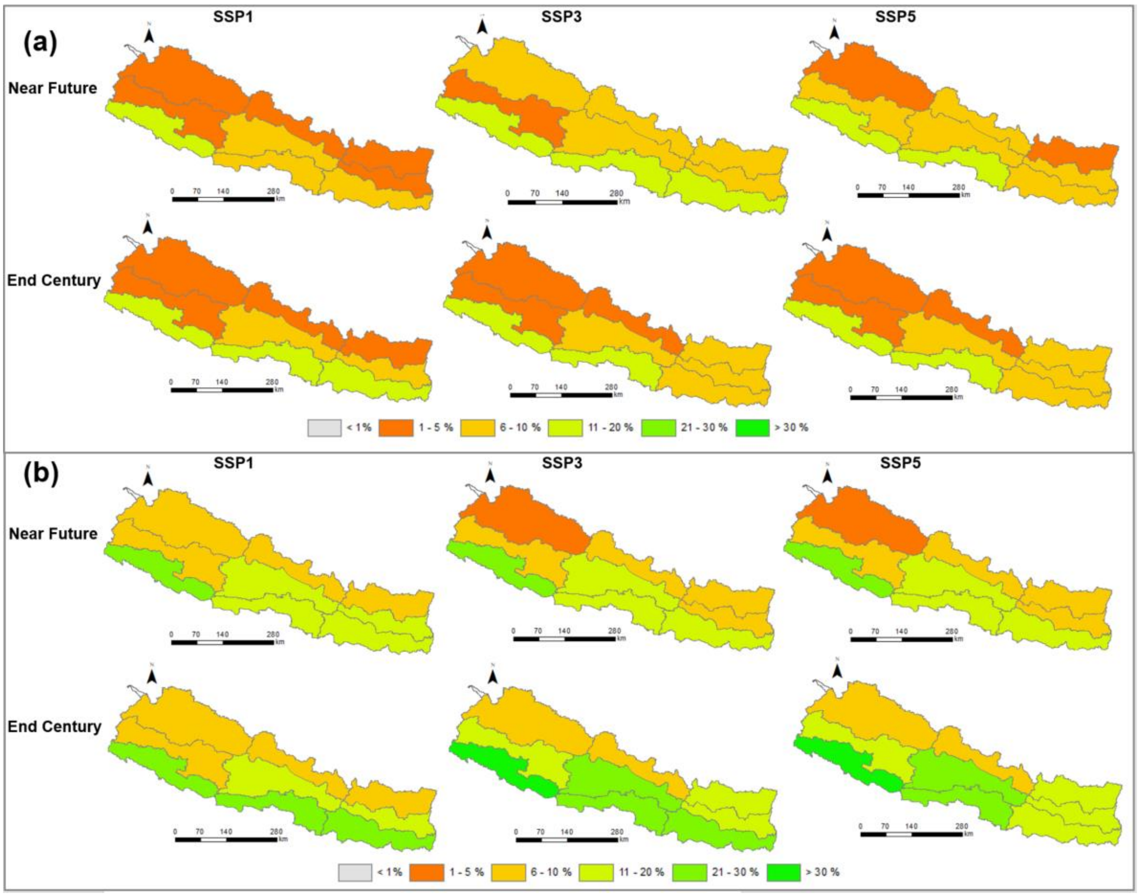


Figure 3-10. Relative changes in maize yields at ecoregion level when canal conveyance efficiency changes from a) 30% to 50% and b) 30% to 70% in the near and far future. SSP1, SSP3 and SSP5 represents Shared Socioeconomic Pathway with radiative forcing level of 2.6 W/m², 7.0 W/m² and 8.5 W/m².

For wheat enhancing canal conveyance efficiency (CCE) from 30% to 50% leads to a marginal increase in yields across all ecoregions (Fig. 3-11, Table 3-9, Table 3-10). Specifically, in the tropical Terai and hills, a slight yield increase of up to 4% is recorded under a scenario transitioning from 30% to 50% CCE, pertinent only to projections for the end of the century. When CCE is further boosted to 70%, the yield improvements in the Terai and hills regions could reach up to 10% by the century's end. In the mountain region, adopting a 70% CCE can lead to yield increases of up to 12% in the near future and 25% in the distant future. This suggests that endeavours to enhance CCE will likely yield significant benefits in mountainous areas in the far future. Nevertheless, the general results suggest that elevating conveyance efficiency to 30% will be adequate for wheat production across all ecoregions.

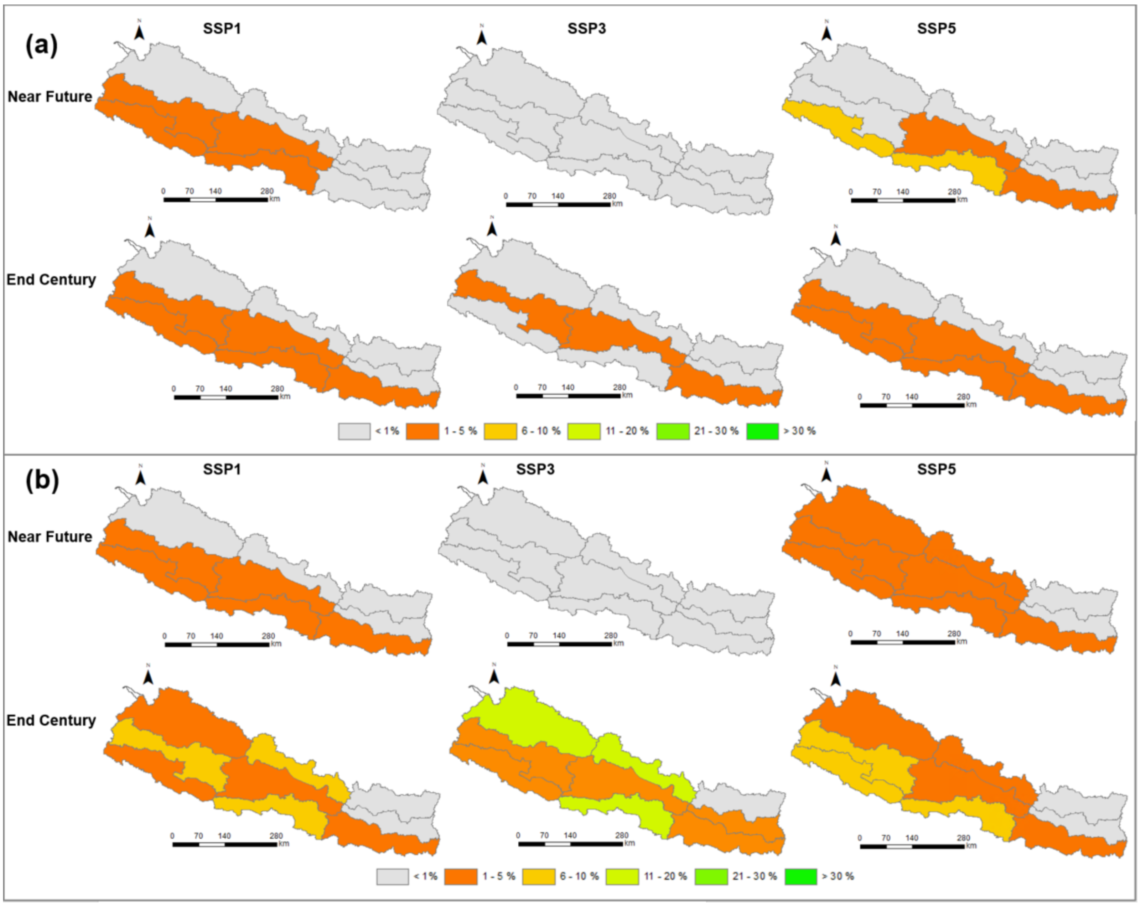


Figure 3-11. Relative changes in wheat yields at ecoregion level when canal conveyance efficiency changes from a) 30% to 50% and b) 30% to 70% in the near and far future. SSP1, SSP3 and SSP5 represents Shared Socioeconomic Pathway with radiative forcing level of 2.6 W/m², 7.0 W/m² and 8.5 W/m².

3.3.4 Implications for fertilizer use

In Nepal, the current utilization of fertilizers is low across all crops (Table 3-4, "current"), as fertilizers are often difficult to purchase for farmers in sufficient quantities (Basukala and Rasche, 2022; Takeshima, 2019). However, to reach the growth potential offered by higher rates of irrigation, the crops demand more nutrients in the CCE scenarios. Rice may require an increase in nitrogen fertilizer of 200-250% from current rates in the near and far future, and double the rate of phosphorous fertilizer. The fertilizer requirements of maize are even higher with an increase of 300-350% of nitrogen and 500% of phosphorous fertilizer. Wheat, lastly, may require an increase of roughly 340% in the near, and only 250% in the far future compared to current nitrogen fertilization rates, and an increase of 50% to 75% of phosphorous fertilizer in the near and far future, respectively. The results show that fertilization rates need to increase considerably if the yield potential is to be met. Results also show that an increase from a canal conveyance efficiency of 30% to 70% does not markedly influence fertilization rates, and that nutrient requirements will not change noticeably between the near and far future, except for nitrogen fertilizer for wheat.

Table 3-4. National Level fertilizer requirements under different scenarios and in different periods.

		Nitrogen fertilizer [kg/ha]			Phosphorous fertilizer [kg/ha]		
Period	Scenario	Rice	Maize	Wheat	Rice	Maize	Wheat
Current	Current	37	36	35	12	9	8
Near future	CCE30	135	154	153	24	50	12
	CCE50	111	164	153	24	54	12
	CCE70	114	166	154	24	56	12
Far future	CCE30	128	146	121	23	51	14
	CCE50	106	155	122	23	56	14
	CCE70	110	160	124	24	59	14

3.4 Discussion

Climate change projections indicate that climatic and hydrological extremes and overall variations may increase in Nepal (Bhattarai et al., 2023b). Hydrological fluxes for example may change by −26% to +37% (Palazzoli et al., 2015). Shifts in climate and hydrology will in turn affect crop productivity, both in positive and negative directions. Simulations project potential changes of crop production in the range of −36% to +18% for wheat, −17% to +4% for maize, and −17% to +12% for rice (Palazzoli et al., 2015), and -60% to +20% for wheat and rice (Shrestha and Shrestha, 2017). A study conducted in the middle hill region of Nepal demonstrated that the decrease in rice yield is mainly due to temperature stress (Shrestha and Shrestha, 2017). Similarly, globally, each degree Celsius of warming may reduce yields of maize by 3.4%, wheat by 2.4% and rice by 0.3% (Deng et al., 2023). Building and maintaining sustainable irrigation practices in Nepal is thus essential for the stability of the agricultural sector. In this paper, we could show that increasing the conveyance efficiency of canals can lead to substantial yield benefits, especially in the Terai ecoregion, which is in line with the findings of similar studies looking at water management for rice (Boonwichai et al., 2018; Houma et al., 2021; Rajwade et al., 2018; Shrestha et al., 2017; Wu et al., 2018). Likewise, the efficient supplementation of irrigation is expected to boost maize yields in the coming decades (Liao et al., 2024; Quan et al., 2022; Sen, 2023).

Expanding and maintaining irrigation infrastructure is expensive, and priority regions with the highest potential return on investment should be identified. Our results show that the subtropical Terai region should be a priority for investments, especially for the crops rice and maize. Irrigated area should be expanded and it should be ensured that a CCE of at least 50% is maintained. Agriculture in the hill regions would also benefit from a higher CCE, but resulting yield increases are projected to be lower, meaning that a moderate expansion of irrigated area and maintaining a CCE of 30% to 50% may be the most financially viable solution. In the mountain regions, investments should be sparse due to the considerably lower return on investments. Our findings also indicate that middle Nepal consistently demonstrates superior crop yields across all scenarios and crop types compared to both the eastern and western regions. An analysis based on CMIP6 climate models data for Nepal showed that the western and eastern parts of Nepal have high projected changes in hydro-climatic extremes and rising trends in mean annual maximum temperature and minimum temperature (Bhattarai et al., 2023b), which may explain the lower yields in these regions.

For wheat, a different strategy is needed. Our results show that supplemental irrigation does not improve yields markedly. A study conducted in the Koshi basin of Nepal also showed that wheat was more vulnerable to climate change than maize or rice (Palazzoli et al., 2015), and further studies have similarly predicted no change or even a decrease in wheat yields even with supplemental irrigation (Bouras et al., 2019; Chattaraj et al., 2014; Mirgol et al., 2020; Vollset et al., 2020; Yuan et al., 2016). The authors of the studies argue that increased temperatures reduce the length of the growth phases of wheat, resulting in early maturity and a lower water demand.

With a higher water availability, nutrient requirements of the plants increase as well (Gao et al., 2023; Wang et al., 2023). Appropriate fertilizer applications are needed to promote root development, enhance soil moisture and input absorption, and boost crop yield (Jiang et al., 2017). According to our simulations, especially nitrogen fertilization rates need to be increased drastically if the potential yield increases due to higher CCE are to be realized. Once local potential yields of a certain crop and variety are reached, adding more fertilizer does not increase yields further (Wang et al., 2021). It should therefore be a priority for the Nepalese government to ensure a steady and sufficient supply of affordable fertilizer and to develop efficient organic fertilization schemes (cf. Basukala and Rasche, 2022) along with investing in additional irrigation infrastructure projects on a larger scale.

We have shown that expanding irrigation and improving its efficiency can benefit farmers in Nepal. Currently many irrigation schemes in Nepal, including those managed by farmers, agencies, jointly, or privately, rely on gravity-based surface irrigation with low canal efficiency, resulting in significant water loss before reaching the farms. These schemes encounter difficulties in maintenance, water allocation, distribution, and scheduling, which impede the optimal use of water. Understanding the efficiency of canal irrigation systems is crucial for assessing their crop yield—which is vital for future plans concerning irrigation expansion, agricultural intensification, and crop productivity increases in Nepal. This knowledge allows planners and decision-makers to take the necessary steps to address these issues. Improvements in irrigation can be achieved through proper canal linings, infrastructure upgrades, and agronomic support, enhancing irrigation services. Effective irrigation planning, operation, and management should be conducted within the context of river basins, considering hydrological boundaries as the most appropriate units for planning efforts. Additionally, implementing water measurement structures is crucial for accurately determining water allocation and diversion by irrigation systems. This facilitates an easy assessment of Canal Conveyance Efficiency (CCE) and the overall efficiency of irrigation systems. By monitoring CCE, water losses can be identified, and corrective measures can be swiftly implemented. The adoption of new irrigation technologies will also promote the sustainability of agricultural irrigation and water resource management.

Furthermore, strengthening coordination among water users' associations, district irrigation development offices, and district agriculture development offices is essential. As outlined in the Irrigation Master Plan 2019, enhancing the capacity of central authorities, state governments, local municipalities, water user associations, and potentially farmer cooperatives is crucial. This enhancement involves providing both on-the-job and formal training programs focused on irrigation service development and management. Seasonal climate forecasts may aid farmers in making informed irrigation decisions, positively influencing irrigation scheduling. With support from water users' associations and district irrigation development offices, farmers can use various irrigation scheduling tools to improve irrigation management.

This analysis demonstrates the crucial role of improved irrigation efficiency in enhancing future agricultural productivity under changing climate conditions and emphasizes the strategic necessity of advancing irrigation practices to boost crop yields across Nepal. As a caveat, we want to mention some inherent constraints. The compilation of data on agricultural productivity, resource utilization, and management in Nepal was challenging due to the limited availability of aggregated and integrated data, necessitating reliance on diverse sources of varying quality. We thus adopted uniform management assumptions across different districts and diverse eco-regions, simplifying the complex decision-making processes of individual farmers and overlooking external constraints. Further, to accurately model microclimatic variations in Nepal and simulate crop yields precisely, climate and soil data of higher resolution are necessary. In scenarios involving irrigation, we assumed that an expansion was always possible and that CCE could be improved, whereas in many regions, there are constraints that limit the expansion of irrigation systems and the improvement of conveyance efficiency. Moreover, we presume that cropping schedules remain unchanged annually across all scenarios, disregarding the dynamic nature of agricultural practices. While farmers often practice intercropping to optimize land use, our model, EPIC, typically simulates the growth of only one crop at a time for each simulation unit.

3.5 Conclusions

In this study, we assess the impact of expanded irrigation and varying canal conveyance efficiencies (CCE) on the production of key agricultural crops—rice, wheat, and maize—under shifting climatic conditions across Nepal's diverse landscapes. Understanding the nuances of irrigation efficiency and its effects on crop yields is crucial for the effective management of irrigation water. We show that the benefits of improved irrigation efficiency vary by location, affecting crop yields differently across regions. Our findings underline the importance of not only constructing new irrigation projects but also rehabilitating existing irrigation schemes and upgrading infrastructure to enhance efficiency. Nationally, expanding irrigation and improving CCE to 30% can significantly boost rice, wheat and maize yields by more than 3 t/ha, making it a highly recommended strategy for all regions. In the Terai region, elevating CCE to 70% would further substantially increase crop yields, whereas in the hills, a CCE improvement to 50% is sufficient. These insights can inform decision-makers in optimizing the expansion of irrigation by ensuring the appropriate CCE in Nepal's canal systems for crops like rice, maize, and wheat in various ecoregions. Future research in the field of irrigation should explore the social, cultural, economic, and agronomic factors that influence farmers' decisions regarding irrigation, offering a deeper understanding of the intricacies involved.

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Chapter 4

4 Effect of Alternate Wetting and Drying (AWD) and Continous flooding in Rice production in Terai Nepal.

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Abstract: The cultivation of rice is a significant contributor to greenhouse gas (GHG) emissions, primarily due to the conventional practice of continuously flooded (CF) irrigation practices, which entails substantial water usage. In response to this challenge, alternate wetting and drying (AWD) irrigation has emerged as a water-saving alternative. This study examined the impact of AWD irrigation compared to CF control on rice yield, irrigation water use, and methane (CH4) emissions in the southern agriculture region Terai of Nepal. Results showed that AWD treatments drastically reduced CH4 emissions by 27% to 30% and irrigation water requirements by 28% to 48%. A further 2% to 19% increase in rice grain yield was achieved when AWD was used instead of CF control. AWD irrigation displayed the promising potential for efficient water resource utilization and GHG emissions mitigation in rice cultivation within the study area, presenting a viable alternative to continuous flooded irrigation.

Keywords: Alternate wetting and drying, Greenhouse gas emissions, Methane (CH4), GHG mitigation, Water management, Grain yield

4.1 Introduction

Rice serves as a number one food for over half of the worldwide population and contributes significantly to global food security (Shekhar et al., 2024). It is the primary staple food in Asia imparting 35–60% of the dietary energy consumed by over three billion humans (Qi et al., 2020). However, rice stands out as one of the most significant irrigation water users and ranks among the leading sources of strong greenhouse gas methane (CH4) (Echegaray-Cabrera et al., 2024). The production of CH4 in paddy soils occurs under strictly anaerobic conditions by methanogenic Archaea, while aerobic methanotrophic bacteria are chiefly responsible for methane oxidation inside rice paddies (Conrad, 2007). To mitigate GHG emissions from rice production and ensure food security while safeguarding natural resources, developing practices that reduce emissions is imperative.

Improved water and rice management are essential sustainable agricultural practices influencing GHG emissions (IPCC, 2023). Continuous flooding (CF) irrigation, a traditional and popular method in many rice-growing regions, contributes to CH4 emissions due to anaerobic degradation by methanogens (Hoang et al., 2023; Islam et al., 2020). Therefore, modifying current cropping techniques could offer a pathway to reduce GHGs emitted from rice soil. One effective method for suppressing CH4 emissions involves intermittent drainage and flooding of the rice field (Dahlgreen and Parr, 2024; Hua et al., 2024). Intermittent flooding enhances soil permeability and increases soil redox potential, reducing CH4 emissions (Tyagi et al., 2010). In this regard, alternate wetting and drying (AWD) irrigation, established by the International Rice Research Institute, has been introduced as an efficient and productive strategy for rice farming, particularly in South and Southeast Asia (Dahlgreen and Parr, 2024). AWD involves reduced water application, and proper nutrient management is also emphasized as one of its fundamental principles (Menete et al., 2008). This method, involving cyclic drying of fields to maintain a shallow soil water ponding, offers potential water savings without compromising yields under optimal management conditions (Lampayan et al., 2015; Yang and Zhang, 2010).

In Nepal, rice is the primary cereal crop, cultivated across 1.48 million hectares annually, yielding 5.13 million tons (MoALD, 2023). CH4 contributes 75% to agricultural GHG emissions, reflecting the sector's significance (International Centerfor Tropical Agriculture; World Bank; CGIAR Research Program on Climate Change Agriculture and Food Security; Local Initiatives for Biodiversity Research and Development, 2017). Despite ranking nineteenth globally in rice cultivation area, Nepal ranks 59th in production, indicating productivity challenges (FAOSTAT, 2022). As a result, Nepal's rice imports have increased annually by 24.48% in quantity and 38.11% in value, while domestic production growth is below 2% (Gairhe et al., 2021). To tackle this challenge, the Nepalese government has prioritized boosting domestic rice production to mitigate the annual import expenditure (Choudhary et al., 2022). Despite numerous plans and programs to strengthen the rice sector, Nepal has not yet achieved the policy goal of national self-sufficiency in rice production. Nepal has the potential to attain self-sufficiency in rice, but this requires significant productivity increases and closing yield gaps (Basukala and Rasche, 2022).

Primary irrigation practices in rice cultivation in Nepal are done with continuous flooding, which requires excessive irrigation water. These challenges make transitioning from continuous flooding (CF) to water-saving irrigation practices imperative. Various methods, such as the system of rice intensification, bund plugging, aerobic rice systems, raised beds, and alternate wetting and drying (AWD), have emerged as viable alternatives (Uprety, 2016). AWD, in particular, has gained widespread adoption as a water-saving practice. Unlike continuous flooding, AWD involves intermittent flooding and drying of fields, with the decision on soil dryness thresholds determined by factors like crop variety, growth stage, soil type, and weather conditions (Dahlgreen and Parr, 2024). Studies have shown that fields can be left without ponding water for 1 to 10 days, depending on these variables (Dahlgreen and Parr, 2024; Norton et al., 2017). Notably, AWD conserves irrigation water and enhances root length, plant growth, and yield (Yang et al., 2012). Despite alternate wetting and drying (AWD) benefits, its formal adoption among farmers in various rice-producing regions, including Nepal, has been limited. One of the primary barriers to widespread AWD adoption is the variability in its impact on yield, influenced by factors such as soil type, climate, cultivars, and management practices (Khanal, 2021; Uprety, 2016). Additionally, AWD may not be suitable for specific soil conditions, such as sandy soils where water drainage is rapid or heavy clays with shallow water tables (Alauddin et al., 2020). Socio-economic, cultural, and political factors also play a significant role in farmers' reluctance to adopt new irrigation technologies, especially without evidence of success from local field trials (Arai et al., 2021). Crop modeling presents a promising avenue for addressing these gaps, offering a cost-effective and efficient means of determining AWD irrigation practices' threshold values without the need for expensive and time-consuming field experiments. Despite the vital role rice cultivation plays in Nepal's agriculture sector, the AWD system has not been extensively evaluated, and there is a lack of research focusing on biophysical crop modeling studies incorporating AWD in Nepal's rice cultivation. Existing studies typically involve controlled small-field trials where they compare AWD with traditional irrigation practices to assess their impacts on crop yield, water use efficiency, and greenhouse gas emissions (Banjade et al., 2023; Niraula and Karki, 2023; Rajbhandari, 2007; Raut et al., 2020; Uprety, 2016). Additionally, there are social studies regarding the adoption of AWD by farmers (Howell et al., 2015; Khanal, 2021). Against this backdrop, our study aims to advance this discourse by utilizing the IPCC Tier 1 technique of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories emissions from rice-based cropping systems in Nepal. Additionally, we conduct scenario simulations to evaluate the adoption of AWD in the entire southern Plain Terai region, probing its suitability and mitigation potential as a field management technique. We are answering the following research questions with this study:

- What will be the effect of alternate wetting and drying of rice fields on crop yields and water use under climate change?
- What will be the effect of continuous flooding on rice yields and water use under climate change?
- How will these methods affect methane emissions?

4.2 Materials and Methods

4.2.1 Study area

We considered the whole Terai region of Nepal as the study area. The Terai region of Nepal spans approximately 34,019 square kilometers, representing approximately 23% of Nepal's total land area. This region is situated at an elevation of 67 to 300 meters (Bhuju et al., 2007). The Terai region of Nepal is a fertile plain situated in the southern part of the country, extending from east to west all along the Indian border (Shrestha et al., 2013). With its productive agricultural lands and diverse ecosystems, the Terai is a vital agricultural area, producing various crops, including rice, wheat, maize, sugarcane, and fruits. With a population of approximately 15.6 million, half of Nepal lives here (CBS, 2011). The Terai region of Nepal encounters a tropical savanna climate characterized by dry winters and hot summers. The mean annual temperature varies from 20 to 28°C. Annual rainfall averages between 1,600 and 1,800 mm in the west and 2,500 to 3,000 mm in the central and eastern parts (Karki et al., 2017a). The spatial distribution of annual precipitation typically follows the monsoon pattern (Department of Hydrology and Meteorology (DHM), 2015). In this study, we categorized the Terai region into three sub-regions based on longitude (Figure 4-1).

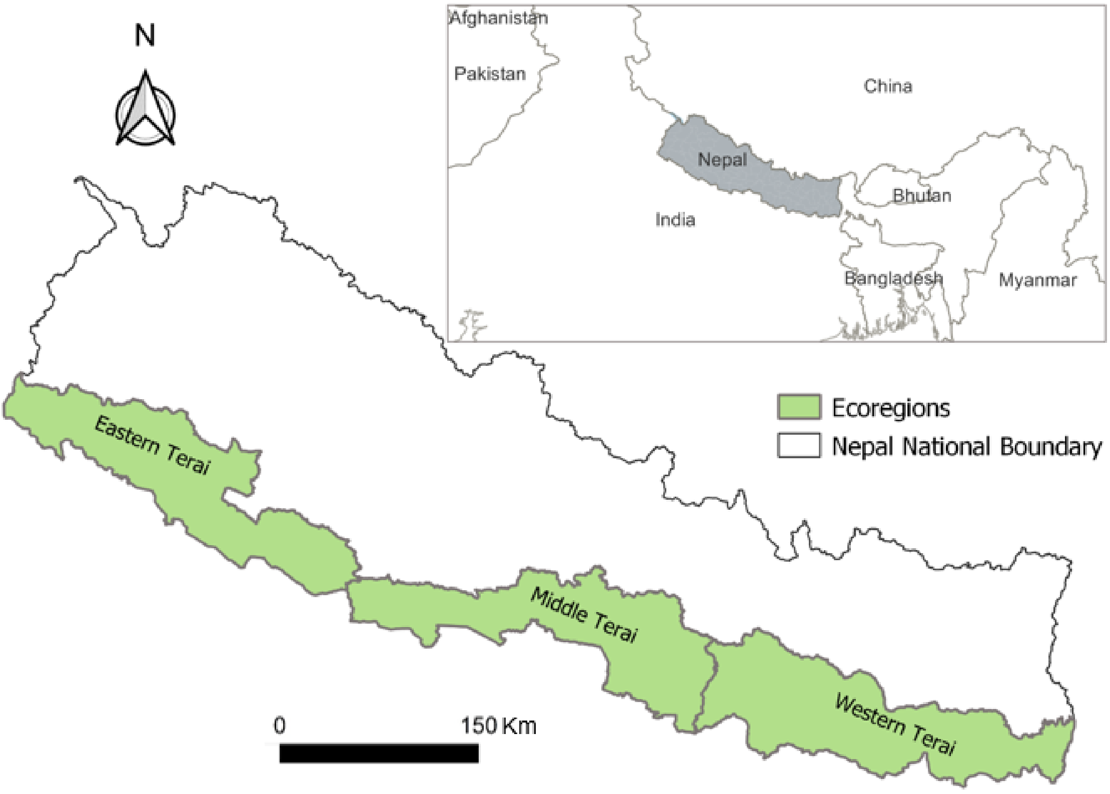

Figure 4-1. The three different agro-ecological zones of Terai, Nepal. The enclosure at the top right shows the location of Nepal in South Asia with neighboring countries.

4.2.2 Homogenous response units and simulation units delienation

To implement crop growth simulations with a field-unit-based EPIC crop model at Terai's diverse agriculture landscape region, we simplify the representation of spatial heterogeneity and climatic conditions by creating Homogenous response units (HRUs) for more accurate analysis and simulations. We adhered to the methodology outlined in constructing the HRUs in the Global Earth Observation – Benefit Assessment (GEOBENE) database (Skalský et al., 2008). The classification process entailed partitioning the territory into three elevation categories, seven slope categories, and ten soil classes, as delineated in Table 4-1. This approach was crucial to maintain a uniform and standardized representation for simulation purposes.

Table 4-1. Slope, elevation, and soil texture classes utilized to delineate the homogeneous response units (HRUs) in this study.

Elevation classes		Slope classes		Soil typological units	
Elevation [m]	Classification (Barnekow Lillesø, 2005)	Class	Slope [%]	Class	Dominant soil
< 300	Lower Tropical	1	< 3	1	Eutric Cambisols (Be)
300 - 1000	Upper Tropical	2	3 - 6	2	Eutric Fluvisols (Je)
1000 - 2000	Subtropical	3	6 - 10	3	Calcic Cambisols (Bk)
		4	10 - 15	4	Dystric Regosols (Rd)
		5	15 - 30	5	Dystric Cambisols (Bd)
		6	30 - 50	6	Humic Acrisols (Ah)
		7	> 50	7	Humic Acrisols (Ah)
				9	Rankers (U)
				10	No soils (RK2)
				11	Lithosols (I)

We further subdivide HRU units based on district boundaries, land use and land cover data, and climate data raster. This subdivision allowed for a more detailed and localized analysis, considering variations in land characteristics and climate conditions within each HRU. District boundaries were sourced from the Global Administrative Areas database (GADM, 2018). The land use layer was retrieved from the "Land Coverage of Nepal 2010" dataset that was developed by the International Center for Integrated Mountain Developments (ICIMOD)(Uddin et al., 2015). The climate grid of spatial resolution of 0.44 degrees used was generated from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) climate datasets. In the final stage, we utilized the land use mask to distinguish between cropland and non-cropland areas, including only those units containing cropland in our list of simulation units. As a result, the total count of simulation units reached 289 simulation units (Figure 4-2).

4.2.3 Slope, elevation, soil, and climate Data

The digital terrain information for the study region was acquired from the NASA Shuttle Radar Topographic Mission (SRTM) 90m Digital Elevation Database (v4.1), accessible through the Consortium for Spatial Information (CGIAR-CSI) affiliated with the Consultative Group for International Agricultural Research (CGIAR). This resource offers a spatial resolution of 90m at the equator (Jarvis et al., 2008). Soil typological units (STUs) were delineated from the globally dominant soil typological units outlined in the GEOBENE database (Skalský et al., 2008). These units furnish essential data on the analytical characteristics of soil required by biophysical models, furnishing insights into distinct soil types characterized by attributes delineating their properties and characteristics (Jones and Thornton, 2015). We incorporated daily climate datasets encompassing precipitation, relative humidity, maximum and minimum temperatures, solar radiation, and wind speed for two distinct timeframes: a baseline period spanning from 2015 to 2021, and a near-future period from 2022 to 2050. Future climate projections were derived from three scenarios based on phase 6 of the Coupled Model Intercomparison Project (CMIP6), covering low-end (SSP126), medium-high (SSP370), and high-end (SSP585) future forcing pathways. These projections were derived from bias-corrected and statistically downscaled climate data sourced from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) (Lange, 2019). We utilized data from three CMIP6 models: GFDL-ESM4, MPI-ESM1-2-HR, and IPSL-CM6A-LR, with a spatial resolution of 0.44 degrees. The ISIMIP3b climate data were accessed via the ISIMIP repository (https://data.isimip.org/search/).

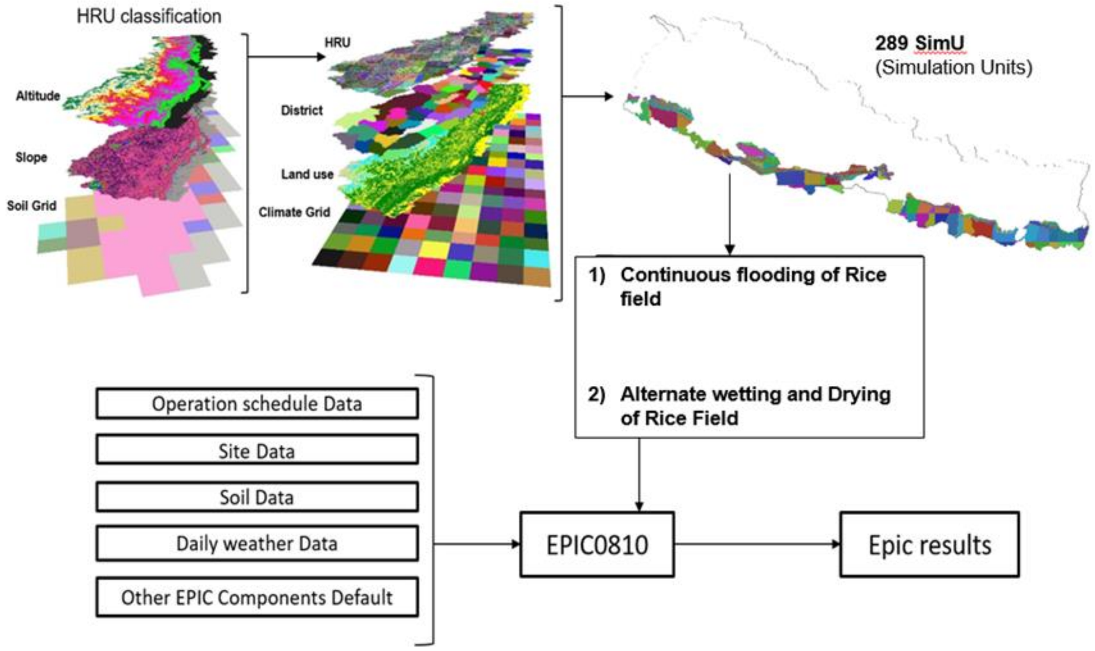

Figure 4-2. Flow diagram of the methodological outline used for the irrigation management for rice crop in Terai, with homogeneous response unit (HRU) and simulation unit demarcation, applied scenario, and input data to the EPIC crop model.

4.2.4 EPIC crop model:

EPIC is a complex biophysical process-based simulation tool, which operates on a daily time step to simulate various processes, including plant environmental control, yield, water balance, greenhouse gas emission, weather patterns, hydrology, soil erosion caused by wind and water, nutrient cycling, tillage practices, crop management strategies, and crop growth dynamics (Williams et al., 1989). The embedded processes allow for a detailed analysis of agricultural systems, facilitating informed decision-making and management practices at the field level (Di Bene et al., 2022; Gaiser et al., 2010; Williams et al., 1989). EPIC combines meteorological data, soil information, and crop-specific parameters to simulate various aspects of agricultural processes. The model provides choices for predicting crop yields using various potential evapotranspiration equations, making it adaptable to different environments (Balkovič et al., 2013). It also offers management options such as tillage methods, irrigation schedules, fertilizer application rates, and timing.

EPIC uses general plant growth model with crop specific parameters to simulate growth. Potential biomass in EPIC is computed daily based on photo-synthetically active solar radiation and radiation-use efficiency. This potential biomass undergoes adjustments to actual biomass daily, accounting for stresses like extreme temperatures, water scarcity, nutrient deficiencies, or inadequate aeration. Crop yield estimation employs the harvest index principle, where the harvest index rises nonlinearly with accumulated heat units from zero at planting to the optimal value at maturity (Zhang et al., 2018). However, high temperatures, low solar radiation, or water stress during critical crop stages can diminish the harvest index (Yang and Zhang, 2010). Managing yield losses due to nutrient stress involves a broad range of nutrient supply strategies through crop management. Water stress is effectively addressed through careful soil water balance management, a sensitive process especially influenced by the chosen PET method (Roloff et al., 1998), along with supplementary irrigation when required. We chose to employ the EPIC model for this study due to its proven reliability across various environments (Wang et al., 2022b), particularly in handling the complex environmental conditions found in Nepal for crop simulations. The outputs produced by the EPIC model provide extensive insights into crop growth, water dynamics, nutrient interactions, and carbon fluxes at daily, monthly, and yearly intervals. In this research, we focus on crucial parameters such as estimated annual yield (Yd, t/ha), growing season evapotranspiration (GSET, mm), and annual irrigation water supply (IR, mm).

The greatest challenge in implementing EPIC for paddy simulation lies in the fact that EPIC plots are not coded to permit ponding conditions caused by flooding water. Therefore, water table-based forced operations are incorporated in operation files to accommodate water ponding conditions with diking, no drainage, and outlet controls. Three operation files for three Terai regions are created manually and were used for all Simulation Units (SimUs) lying in the respective regions. Irrigation is added once the water table layer of the first soil layer is diminished below 0 mm. If there is extra precipitation, no irrigation is applied. Irrigation and drainage timing are carried out based on the water table of the first soil layer. Water is drained if there is ponding water for more than a week by drainage, destroying bunds and opening outlet controls. For creating continuous flooding conditions, no drainage of the field is carried out, and if needed, irrigation is done to maintain constant water flooding.

4.2.5 Model calibration

The calibration of the rice crop model was conducted for the years 2015-2021 with current management practices for rice cultivation in Terai. The preliminary crop parameters values were sourced from the standard set in the EPIC crop database file. We focussed on crop parameters such as potential heat units, radiation use efficiency, harvest index, optimal temperature, and base temperature for calibration. The model was ran for rice crop, and the simulated yields were then compared with the district-level rice yield data provided by the Ministry of Agricultural Development (MOAD), Nepal, from 2015 to 2021. Through iterative adjustments, the crop-specific parameters were fine-tuned to minimize discrepancies between the simulated and actual yields, adhering to constraints that prevented deviations of more than 20% from initial values or beyond the feasible range outlined in the EPIC user guide. This process enabled the calibration of the model to accurately reflect the characteristics of local rice varieties across different districts. Since a universal set of parameters for all simulations unit was not feasible, unique parameter sets were established for each of the districts in the Terai region of Nepal. Evaluation of the model's performance during calibration employed four statistical metrics: Nash-Sutcliffe Efficiency, correlation coefficient, relative error, and percent bias.

Nash-Sutcliffe efficiency (NSE) quantifies the agreement between observed and simulated data, providing a measure of model accuracy, with values ranging from -∞ to 1. Higher values indicate better model performance in replicating observed data.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i - \bar{Y}_i)^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2} \qquad (1)$$

The percent bias (PBIAS, Eq. 1) identified the average tendency of the simulated data to be larger or smaller than the observed data. When values are positive, it suggests that there has been an underestimation; negative values imply an overestimation bias, while a value of zero indicates no bias whatsoever. Generally, PBIAS values 0-10 are considered very good, 10-15 good, 15-25 fair, and values >25 unsatisfactory (de Salis et al., 2019).

$$PBIAS = 1 - \frac{\sum_{i=1}^{n}(Y_i - \mathrm{X_i}) * 100}{\sum_{i=1}^{n} Y_i} \tag{2}$$

where X_i is the reported crop yield in district i, Y_i simulated crop yield in district i and n is the total number of districts.

The correlation coefficient is a statistical measure that assesses the strength and direction of the linear relationship between two variables. It ranges from -1 to 1, with a positive value indicating a positive correlation, a negative value indicating a negative correlation, and 0 indicating no linear correlation. It's commonly used to gauge the degree of association between variables in data analysis and modelling

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{\mathrm{X}})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{\mathrm{X}})^2 \ \sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \tag{3}$$

where $\bar{\mathrm{X}}$ is the simulated crop yield mean and $\bar{Y}$ is reported crop yield mean.

We also calculated the relative error RE (Eq. 2) to observe systematic errors in the simulated data. Considering the versatility of agro-ecological zones and the scale of this study, we assume an RE of ≤ 30% to be an acceptable result, whereas RE > 50% should be considered to be extreme errors (Balkovič et al., 2013; Niu et al., 2009).

$$\mathrm{RE_i} = \frac{(\bar{\mathrm{Y}}_\mathrm{i} - \mathrm{X_i})}{\mathrm{X_i}} \cdot 100 \tag{4}$$

where X_i is the reported crop yield in district i, Y_i simulated crop yield in district i, and $\bar{Y}_i$ is the simulated average crop yield in district i.

4.2.6 Crop simulation scenarios

Apart from three different Shared Socioeconomic Pathway with radiative forcing level of 2.6 W/m², 7.0 W/m² and 8.5 W/m² (SSP1-2.6, SSP3-7.0, and SSP5-8.5), a total of two different management scenarios have been simulated for complete areal extent of Terai region. Our two scenarios are:

(i) Continous flooding of rice field

(ii) Alternate Wetting and Drying of rice field

The additional fertilizer applications in both scenarios were triggered automatically during the simulation if the plant experienced moderate nutrient stress on a specific day (a stress factor higher or equal to 15%). Stress-triggered mineral phosphorous, a maximum annual 300 kg of mineral nitrogen per hectare is applied. Each scenario was run for all 289 simulation units covering Terai Nepal from 2015 to 2050 (Figure 4-1).

4.2.7 Estimation of Methane Emission

We applied the IPCC Tier 1 technique of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for estimating methane emissions from rice fields (IPCC, 2019). Specific thresholds of emissions factors for fundamental categories of sources are used for rice cultivation methods and crop calendars to compute methane emission scaling factors. Adjusted daily emission factor (EF) calculated for South Asia of value 1.48 kg CH4 ha-1 d-1 for irrigated continuously flooded rice fields were used whereas 0.81 kg CH4 ha-1 d-1 for irrigated with multiple drainage periods rice fields were used (IPCC, 2019). As shown in the following equation, we multiply the emission factor by the cultivated area and cropping duration to derive the methane emission rate for each rice field method. Subsequently, it is multiplied by the cultivated rice area and cultivation duration for each cultivation type to get emission values for the district and eco-region. The Tier 1 technique provides a standardized emission factor applicable across various sources, conditions, countries, and regions.

$$CH4\ rice = EFi \times T \times A \times 10^{-6} \qquad (5)$$

CH_4 rice = CH_4 emission from rice cultivation in a region or country annually (Gg CH_4 yr^{-1})

EFi = Daily emission factor

T = Period of cultivation

A =Harvested area of rice (annual)

4.3 Results

4.3.1 Calibration of crop yields

Crop yields were simulated under reported management practices from 2015 to 2021 across all simulation units. Crop yields at the district, ecological, and national levels were calculated by adding the simulated outputs from all individual simulation units within those geographic limits. The simulated mean crop yields at the Terai were within the same range as the reported mean crop yields: rice yielded 3.7 t/ha versus the reported 3.4 t/ha. At the district level, simulated rice yields were, in some instances, slightly higher than reported yields, yet overall they remained comparable. The Nash-Sutcliffe efficiency (NSE) value was 0.59 for rice. These values indicate that the simulation model performed more effectively in predicting crop yields compared to a simple average of the observed yields across all crops. The percent bias (PBIAS) between reported and simulated mean annual yields was -7.2% for rice. The correlation coefficient r was 0.83 for rice, which indicates a strong positive linear relationship between reported and simulated rice yield. The degree of agreement, as measured by the index of agreement, is 0.85 for rice, indicating a high level of consistency between the compared data sets. The relative error (RE) values spanned from -35.02% to 31.07% for rice. These values represent the accuracy of the numerical approximations compared to the reported and simulated values. Based on the statistical indicator values, the calibration of rice can be considered satisfactory. The scatterplot illustrates that our calibrated EPIC model slightly overestimated the average rice yield in Terai Nepal (Fig. 4-3).

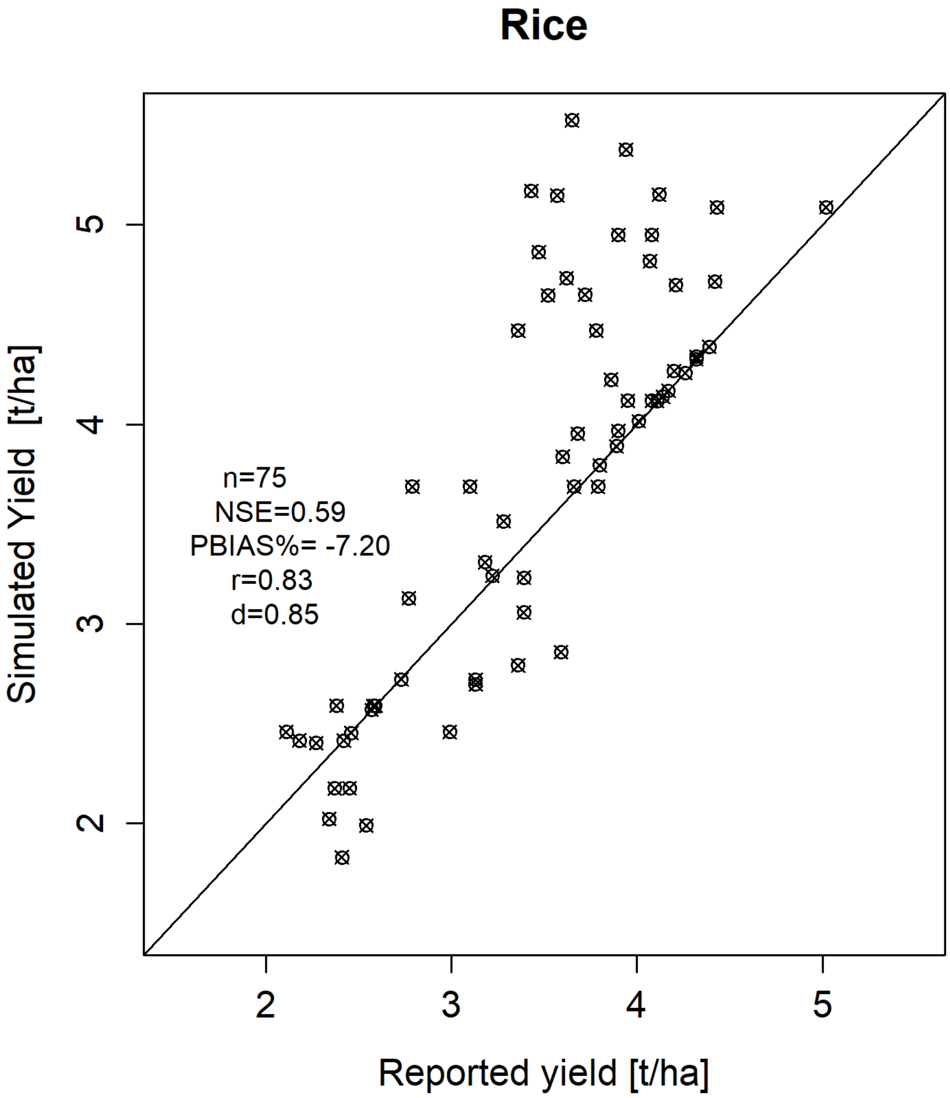

Figure 4-3. Comparison of district level mean simulated rice yields and mean reported crop yields published by the Ministry of Agriculture Development (MOAD) Terai Nepal. Each data point represents a long-term average yield (from 2015 to 2021). The line indicates x = y (perfect agreement). NSE represents Nash-Sutcliffe efficiency; PBIAS represents percentage bias, n the number of districts, r the Pearson correlation coefficient and d the degree of agreement.

4.3.2 Effect of Irrigation managements on Rice Yield

In the near future, the mean crop yield for different eco-regions under the Alternate Wetting and Drying (AWD) and Continuous Flooding (CF) scenarios are presented in Figure 4-4. In the scenario of continuous ponding of water, the aggregated rice yield in the Eastern Terai region is 6.7 tonnes per hectare (t/ha). With the implementation of the Alternate Wetting and Drying (AWD) method in rice farming, the yield increases to 7.4 t/ha, indicating an increase of 0.7 t/ha. In the Western Terai region, under the Alternate Wetting and Drying (AWD) method of rice farming, the rice yield is 8.9 t/ha. However, under the continuous ponding rice farming method, the yield decreases to 7.5 t/ha, indicating a 1.4 t/ha decrease. In the Middle Terai region, under the Alternate Wetting and Drying (AWD) method, the rice yield is 9.8 t/ha. However, under the continuous ponding (CF) scenario, the rice yield decreases to 9.6 t/ha, resulting in a 0.2 t/ha decrease. These values indicate that under the continuous ponding (CF) scenario, there is a decrease in mean crop yield compared to the Alternate Wetting and Drying (AWD) scenario in all three eco-regions.

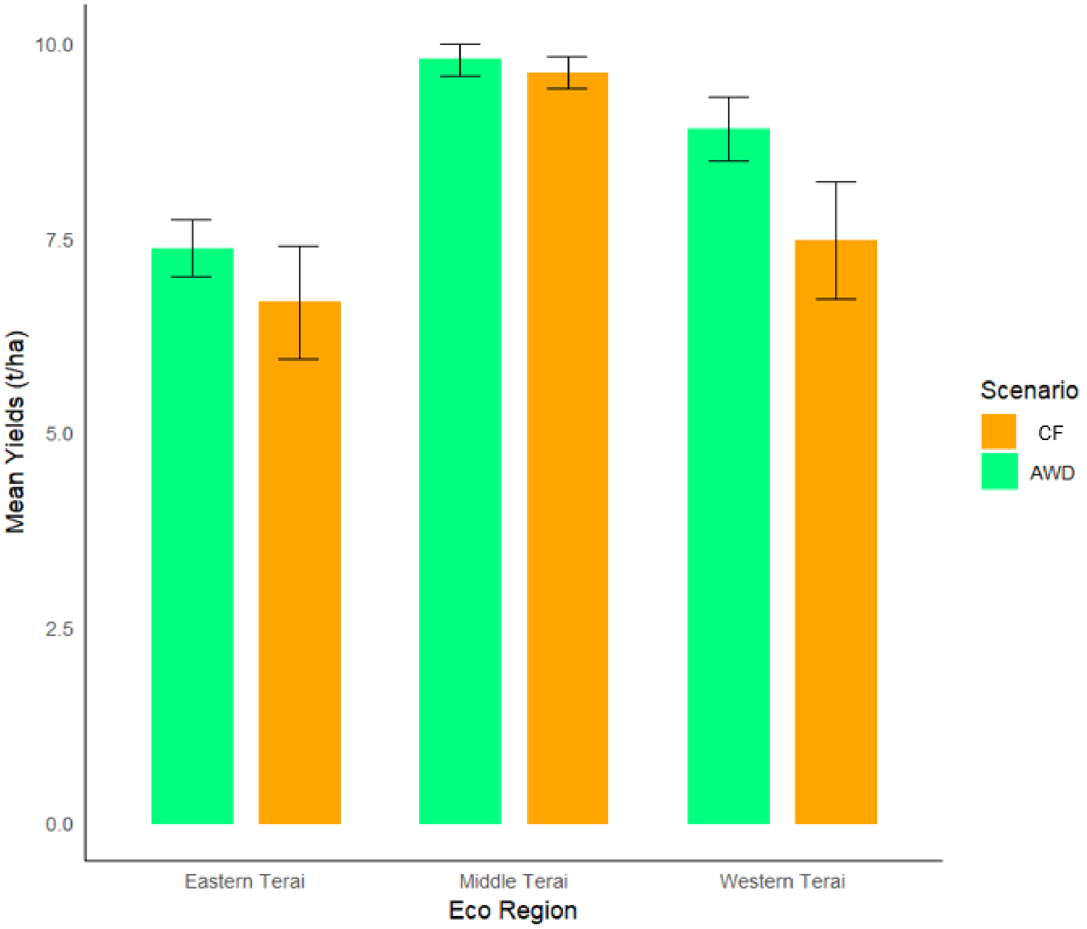

Figure 4-4. Effect of Alternate Wetting and Drying (AWD) and Continuous Flooding (CF) irrigation managements on crop yield in three Terai eco regions for the near future period (2023 - 2050). The whisker shows the standard deviation of yield with three climate models.

4.3.3 Effect of Managements on Irrigation Water Requirement

Irrigation water use in different eco-regions while using different rice cultivation practices is presented in Figure 4-5. The Eastern Terai region utilizes 497 millimeters (mm) of irrigation under the Alternate Wetting and Drying (AWD) scenario. However, in the Continous Flooding (CF) scenario, the irrigation increases substantially to 946 mm. In the Middle Terai region, the irrigation requirement under the AWD scenario is 864 mm, which rises to 1214 mm under the CF scenario. Similarly, in the Western Terai region, irrigation measures 555 mm under the AWD scenario, while it escalates to 1025 mm under the CF scenario. These figures emphasize the significant difference in irrigation demands between the AWD and CF scenarios across the Eastern, Middle, and Western Terai regions, indicating varied water management strategies and their implications for rice cultivation in each eco-region.

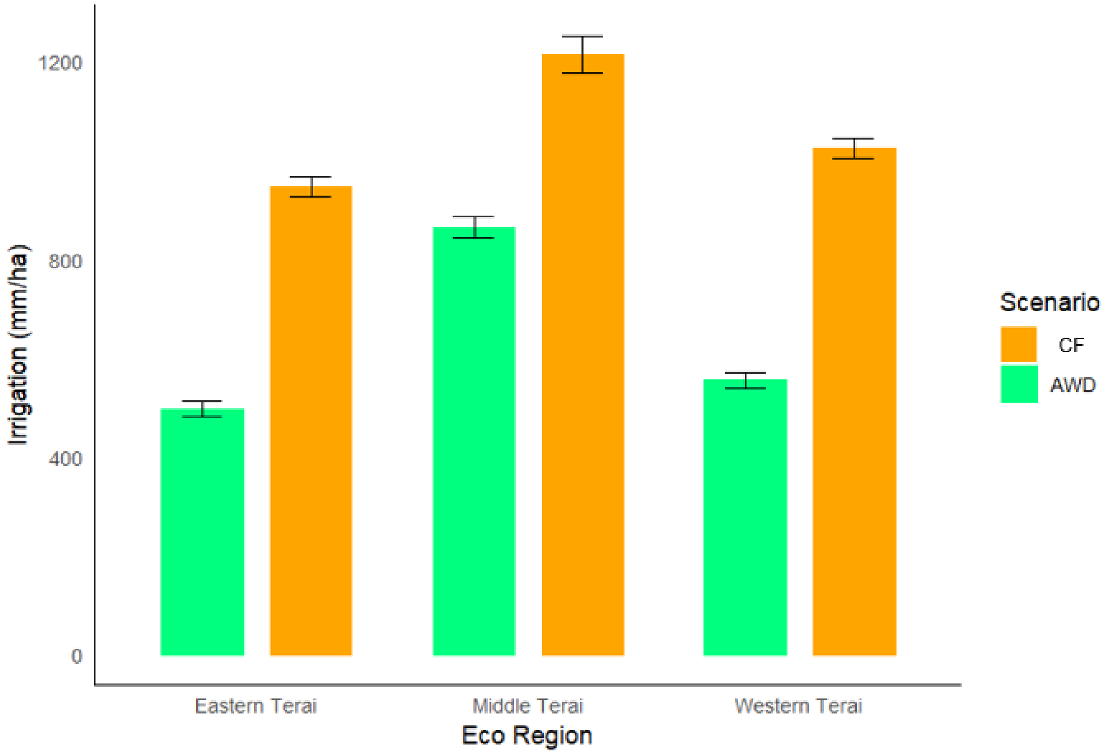

Figure 4-5. Effect of Alternate Wetting and Drying (AWD) and Continuous Flooding (CF) irrigation managements on irrigation water consumed in mm in three Terai eco region for near future period (2023 - 2050). The whisker shows the standard deviation with three climate models.

4.3.4 Effect of Managements on Methane Emissions

Methane emissions in gigagrams of CH4 per year (Gg CH4 yr-1) vary across eco-regions and scenarios, as shown in Figure 4-6. In the Eastern Terai region, under the Continuous Flooding (CF) scenario, methane emissions measure approximately 58.84 Gg CH4 yr-1, while under the Alternate Wetting and Drying (AWD) scenario, emissions decrease to about 32.20 Gg CH4 yr-1. Similarly, in the Middle Terai region, methane emissions amount to roughly 54.22 Gg CH4 yr-1 under the Continuous

Flooding scenario and decrease to around 29.68 Gg CH4 yr-1 under the AWD scenario. In the Western Terai region, methane emissions reach approximately 50.77 Gg CH4 yr-1 under the CF scenario and decrease to about 27.79 Gg CH4 yr-1 under the AWD scenario. These values highlight the significant impact of irrigation management practices on methane emissions across the eco-regions, with the AWD scenario generally resulting in lower emissions than the CF scenario.

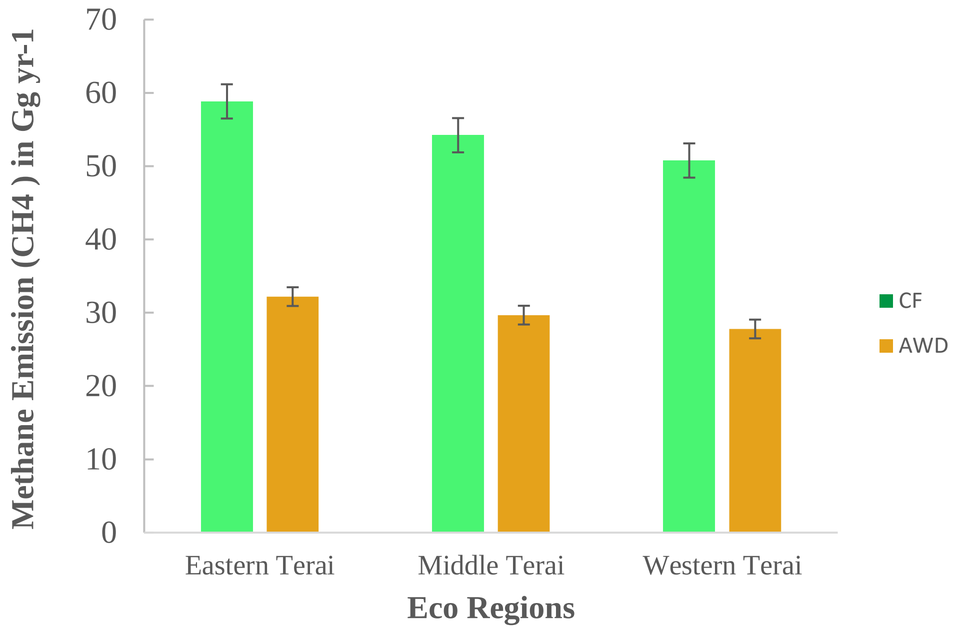

Figure 4-6. Effect of Alternate Wetting and Drying (AWD) and Continuous Flooding (CF) irrigation managements on methane emissions in Gg yr-1 in three Terai ecoregion for near future period (2023 - 2050).

4.4 Discussion

In this study, AWD demonstrated a reduction in water usage while maintaining increased yield levels. This result aligns with studies indicating that AWD can reduce water use inputs by approximately 25–70% without compromising crop yield (Ishfaq et al., 2020; Loaiza et al., 2024). The reduced irrigation water required under AWD compared to CF can be attributed to decreased non-productive water losses through evaporation, seepage, and percolation, which can account for 15–48% of the total water applied (Dossou-Yovo and Saito, 2021). Recent research conducted on a global scale identified that the duration of unflooded days during rice cultivation is also a crucial factor affecting rice yield, along with soil and climate variables (Bo et al., 2022). Root biomass and Root Oxidation Activity (ROA) are vital traits for nutrient and water absorption and aboveground biomass (Yang et al., 2012). Alternate Wetting and Drying (AWD) improves rice yields by encouraging more profound root growth and better nutrient uptake. Improved root-shoot interactions under AWD contributed to higher grain yield (Liu et al., 2013). AWD promotes nutrient translocation, increasing grain yield despite reducing straw and aboveground biomass (Arai et al., 2021). This is why, in our study, despite applying over 50% less water, the AWD treatment maintained a similar crop yield to that of CF. Conversely, studies showed continuous flooding and excessive nitrogen can lead to excessive vegetative growth, delayed ripening, underdeveloped roots, unhealthy canopy structure, and lower harvest index (Arai et al., 2021; Yang and Zhang, 2010).

Our results are also aligned with the experimental research carried out in Agyauli Village, a place in the central Terai region of Nepal where AWD consumes 57% less water than CF plots while maintaining similar rice yields (Howell et al., 2015). An experimental study at Dhauwadi, Nawalparasi Terai, revealed that AWD-incorporated SRI resulted in a higher grain yield of 5.29 t/ha compared to conventional continuous flooding practices, resulting in 4.29 t/ha (Dhakal et al., 2017). This study also showed that cultivars did not impact grain yield, signifying that AWD could be a practical adaptation approach for achieving higher grain yield in Terai Nepal and analogous agro-climatic regions. Our results demonstrate that implementing AWD alone can enhance rice grain yield, aligning with findings from prior studies (Arai et al., 2021; Hua et al., 2024; Oo et al., 2018; Setyanto et al., 2018). This might be due to the improved air exchange into the soil, which helps provide adequate oxygen supply to the root system. This condition promotes the mineralization of soil organic matter, enhancing soil fertility (Oo et al., 2018). The AWD irrigation method was devised to conserve water in irrigated rice fields, predominantly utilized in regions facing water scarcity. Research by Liu et al. (2013) indicated water savings of 23–27% with a yield increase of 12–15%, while Lampayan et al. (2015) reported water savings of 43–54% without yield loss. These results are also in line with our results.

Our outcomes also showed a reduction in methane (CH4) emissions by more than half compared to continuous ponding rice farming systems. Experimental analysis conducted on similar terrain in India has also shown comparable results of CH4 emission reduction by 18% to 82% in AWD when compared to CF (Cowan et al., 2021; Gupta et al., 2016; Kumar et al., 2016; Mohapatra et al., 2023). In the AWD method, rice is cultivated in moist soil rather than flooded fields, with intermittent flooding during the rice-growing period (Ishfaq et al., 2020). Aerating the soil through intermittent flooding enhances methane oxidation, decreasing methane formation. This practice also improves oxygen supply to the roots, leading to healthier root systems capable of better nutrient uptake (Hoang et al., 2023). Furthermore, water management plays a decisive role in methane emission regulation by influencing the two microbial communities, methanogens and methanotrophs, involved in the methane cycle in the soil (Alauddin et al., 2020; Echegaray-Cabrera et al., 2024; Phungern et al., 2023). Therefore, the AWD system represents a sustainable option for rice production that reduces global warming potential and contributes to climate change mitigation while addressing the needs of the growing population (Raut et al., 2020). Based on the previous discussion, our estimated values align well with those reported in the literature, confirming the reliability of our research methods. This shows the potential of upscaling the onsite experimental setup to regional and national scales with the help of process-based crop modelling.

The EPIC model does not estimate methane (CH4) emissions; therefore, CH4 estimations must be done through extensions or modifications incorporating methane-related processes. We used the IPCC's Tier 1 methodology for estimating methane emissions, a simple and broadly applicable method. However, it relies on default emission factors and general data, and it overlooks local variations and specific crop management (Nikolaisen et al., 2023). Well established process-based biogeochemical models such as the Denitrification-Decomposition (DNDC) Model and Daily Century (DAYCENT) models are the best options for understanding and mitigating the environmental impacts of agricultural practices in intensive rice cultivation systems (Guo et al., 2023).

4.5 Implication in Nepalese Agriculture

Even there are proven experimental setups and research support the benefits of alternate wetting and drying in rice cultivation, this method has not become widely popular among farmers in Nepal. Farmers are reluctant to adopt this water-saving technique due to fears of reduced yields and the challenges of managing water levels precisely. In reality, rice requires increased water supply only during critical growth stages such as vegetative, panicle initiation, and grain filling. Limited awareness and knowledge about AWD technology among farmers pose additional barriers to its adoption. To address this, it is crucial to leverage local agricultural extension agencies to provide accurate information and guidance on implementing AWD effectively. Another barrier to AWD adoption is it requires controlled water sources. For this, irrigation authorities need to train and help enforce the use of alternate wetting and drying. Over time, as farmers become more familiar with AWD, combining it with participatory irrigation management can make it a more practical and accepted practice. Weeds pose another constraint to rice production, necessitating effective management strategies. This is the main reason continuous flooding is considered in rice farming. A study showed that weed biomass was lower in AWD fields when specific management practices were followed: maintaining flooding for the first ten days after transplanting (DAT), performing the first weeding before 24 DAT to reduce weed establishment, and conducting weed removal between 51 and 60 DAT during the panicle initiation phase (Dossou-Yovo and Saito, 2021). Considering, these weeding days, making a friendly, efficient mechanical weeder to enhance mechanical weeding will be an option for Nepal. Integrating mechanical weed management practices with suitable options like herbicide application could be a preference for Nepal's weed management efforts (Niraula and Karki, 2023).

Adopting the AWD management practice could serve as a practical adaptation approach for achieving higher grain yield in Nepal's Terai and similar agro-climatic regions. Therefore, the Nepalese government's foremost action should be promoting innovative climate practices that conserve water, decrease emissions, and increase crop yields. The insights from this analysis can help policymakers focus on further research in rice cultivation in Nepal

4.5 Conclusion

Adopting the alternate wetting and drying (AWD) method in the Terai region in the near future has resulted in significant improvements across multiple fronts. First, rice yields have increased due to the implementation of AWD practices, indicating that AWD has the potential to enhance rice productivity and contribute to food security in the region. Additionally, the reduced irrigation amounts required for rice cultivation under the AWD method suggest improved water management practices, resulting to more efficient use of water resources and potential savings in water usage. Furthermore, the considerable decrease in methane emissions in the Terai region in 2050 with AWD demonstrates the environmental benefits of this approach. AWD contributes to mitigating greenhouse gas emissions and addressing climate change concerns by reducing methane emissions. Overall, the findings suggest that adopting AWD in the Terai region offers a promising pathway toward sustainable agriculture, with positive outcomes for agricultural productivity and environmental conservation.

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Chapter 5

5 Discussion and Conclusion

In this dissertation, I explored questions focused on realizing the present and forthcoming food security from the national perspective of Nepal. Additionally, I examined the implications for achieving food security with reference to fertilizer application, irrigation water usage, and greenhouse gas (GHG) emissions. My primary research question was, "How can both current and future food security in Nepal be effectively ensured while concurrently mitigating the environmental impacts of agriculture with efficient use of water and mineral fertilizer?" In exploring the above research question, my thesis provided the following insights into the agricultural sector in Nepal:

1. Given the constraints of limited cultivable land and existing crop yield disparities in Nepal, a comprehensive examination of the potential for agricultural intensification to meet national demand for primary cereal crops rice, wheat, maize, barley, and millet is essential. The average yield gaps were in the range of 3.0 t/ha (wheat), 2.7 t/ha (rice), 2.9 t/ha (maize), 0.4 t/ha (barley), and 0.5 t/ha (millet) were found for Nepal. Addressing yield gaps through intensified agricultural practices can achieve both present and future food self-sufficiency at local, regional, and national levels. This process will definitely result in increased agricultural emissions due to higher levels of input use in Nepal. However, it will reduce reliance on international trade for food security, decrease associated transport emissions by food import, and reduce indirect land-use management emissions related to imported food production. This shift will help to secure a more sustainable food system in the country.

2. This dissertation methodically pinpointed the necessary strategies for closing yield gaps by estimating the required amount of mineral fertilizer input and

irrigation water. Further, the location-specific mineral nitrogen, phosphorous, and irrigation water requirements were calculated, addressing the nutrient and water-based biophysical obstacles restricting yields. Results showed that the mineral N up to 260.5 kg/ha, mineral P up to 69.7 kg/ha and irrigation up to 958 mm were needed on district level annually. The priority regions with the highest potential return on investment in terms of crop intensification were identified.

3. This study provides an essential contribution by evaluating the effect of irrigation expansion on agriculture crop production, taking into account climate change issues for rice, wheat, and maize in the complex landscapes of Nepal. The dissertation also highlighted that various locations can have different benefits in terms of crop yield. Further, it is also stressed that improving canal conveyance efficiency by rehabilitation of canal conveying infrastructures is also equally important to increase water availability along with irrigation expansion. This study also determined that on a national scale, yields for Maize, Rice, and Wheat can be increased up to 3.1 t/ha with a significant reduction in water usage by increasing efficiency from 30% to 50% and 70%. These findings showed the importance of efficient irrigation as a reliable adaptive strategy for addressing future climate change conditions.

4. This dissertation also highlights that future crop productivity must increase with sustainable climate-friendly practices by comparing climate-friendly alternate wetting and drying (AWD) practices to conventional continuous flooding (CF) practices in rice cultivation. The results indicate that under the AWD rice farming practice, there is an increase in mean crop yield of up to 19% compared to CF practices. Further, AWD practice results in less than one-third of the methane (CH4) emissions and over half the irrigation water demand compared to continuous flooding of rice farming systems across the eastern, middle, and western Terai regions. Therefore, the AWD system represents a sustainable option for rice production that reduces global

warming potential, consumes less water, and contributes to climate change mitigation while addressing the needs of the growing population.

Using the approach detailed in this thesis, increasing cereal productivity and contributing to food security in Nepal are viable. However, this requires the implementation of proper management practices and adaptive measures. The articles within this thesis, found in Chapters 2–4, provide further insights into addressing food demands, expanding efficient irrigation, and adopting climate-smart rice farming techniques (as discussed in Sections 2.4, 3.4, and 4.4). This chapter offers explicitly detailed answers to the research questions presented in Section 1.3. It shows the critical contributions of this work to the ongoing dialogue on sustainable food sovereignty strategies in Nepal, both now and in the future.

5.1 Strategies to Close Yield Gaps and gaining food self-sufiecíency:

The Food and Agriculture Organization (FAO) reported that the global food import bill would reach USD 1.94 trillion in 2022 (FAO, 2023). This food import raises serious concerns regarding food security, as it suggests that importing countries like Nepal are struggling to cover the increasing international costs, indicating that their ability to withstand higher global prices is diminishing. In 2020, Nepal imports rice valued at USD 232 million, wheat valued USD 38.4 million, and maize valued USD 90.8 million (FAOSTAT, 2020). One potential solution to this challenge is to increase local production by closing the yield gaps with sustainable extensive agriculture. However, achieving this objective entails deploying more fertilizer inputs and more irrigation water, which are scrutinized to address the three research questions of Chapter 2 of this thesis: RQ 1: “How large is the current yield gap for the five vital arable crops grown in the country (rice, wheat, maize, millet, and barley)?”, RQ 2: “How much fertilizer is needed to close the yield gap, and where should it be applied?”, and RQ3: “How much irrigation water is required to close the yield gap, and which are the priority regions where irrigated areas should be increased?”.

Responding to RQ 1, it becomes evident that there is considerable yield gap in cereal crops and closing yield gaps is imperative for mitigating present food deficits and enhancing food self-sufficiency, as discussed in Chapter 2. Results showed average yield gaps of 3.0 t/ha (wheat), 2.7 t/ha (rice), 2.9 t/ha (maize), 0.4 t/ha (barley), and 0.5 t/ha (millet). The pathways to narrow down this Specifically in Section 2.3.4, I have demonstrated that with enhanced fertilizer and irrigation applications, Nepal has the potential to produce an additional 4,316.85 metric kilotons of rice, 2,625.30 metric kilotons of wheat, 2,870.30 metric kilotons of maize, 110.96 metric kilotons of millet, and 8.19 metric kilotons of barley. This output is sufficient for Nepal to attain self-sufficiency in these crops, improving food security. Responding to RQ 2 and RQ 3, this thesis also delineates location-specific agricultural inputs and management strategies essential for closing yield gaps, including the requisite quantities of fertilizers. Closing yield gaps mandates an extra increase in mineral nitrogen (N) and mineral phosphorus (P) fertilizer application compared to business-as-usual scenarios levels (refer to Section 2.3, 2.4, Appendix)). The mineral N requirements to achieve attainable yields vary from 12.1 to 205.2 kg/ha for rice, from 30.5 kg/ha to 260.5 kg/ha for maize, from 0 to 245.4 kg/ha for wheat, from 39.3 to 239.85 kg/ha for millet, and from 0 to 218.75 kg/ha for barley. The mineral P requirement to achieve attainable yields varies from 1.75 to 31.2 kg/ha for rice, from 6.4 to 69.7 kg/ha for maize, from 0 to 24.57 kg/ha for wheat, from 10.4 kg/ha to 34.4 kg/ha for millet, and from 0 to 5 kg/ha for barley. Additionally, a surplus amount of irrigation water requirement must be addressed (refer to Section 2.3, 2-4, Appendix). The irrigation requirement varies for crops and ecoregions. On average, the tropical Terai regions require 785 mm of irrigation, the subtropical hill regions 540 mm, and the mountain areas 384 mm annually. Barley and millet are source of food security in the rural mountainous and hilly areas of Nepal. The climatic conditions limit yields of these crops, which is why additional fertilizer and irrigation water applications do not increase yields in my simulation results signifying need of development of new varieties to improve productivity in these areas.

Stressing that agricultural intensification must be done in an eco-friendly way, I proposed using organic manure to improve nutrient management for farmers in Nepal. In section 2.2.4, I have discussed integrating nutrient management through organic compost manure usage by improving the quantity and quality of current organic farmyard manure fertilizers. Organic compost manure could be also produced from biodegradable waste collected from households, as successfully done in Bhaktapur city, and could be implemented by other big cities of Nepal (Ranjit et al., 2019). A recent study on adopting improved organic manure practices in Nepal revealed a 17% increase in crop yield. As a result, it is essential to prioritize policies and initiatives that promote and expand the use and impact of these improved organic manure practices in Nepal (Dhakal and Escalante, 2022). However, if Nepal's government wants to close yield gaps using chemical fertilizers, it must address the significant hurdle of fertilizer availability. Nepal relies entirely on imports for its chemical fertilizers, as no domestic production industry exists. The imported quantities are often delayed and consistently fall short of actual demand, leading to frequent shortages and failing to meet farmers' needs during critical crop seasons (Uprety, 2016). The formal supply system only meets 60% of farmers' demand (Gautam et al., 2022). Some of the demand for chemical fertilizers is met through informal sourcing from an unreliable black market across the open border with India, which discourages private sector investment in fertilizers despite the high demand (MoAD, 2014).

Coordinated efforts are needed to ensure Nepalese farmers receive the required amount of fertilizer in a timely manner. Policy reforms and investments are critical, with the government needing to allocate a higher percentage of the national budget to agriculture, specifically for the procurement and distribution of fertilizers. International collaboration through bilateral agreements with neighboring countries, especially India, to curb the black market and seek aid from international organizations can help secure a steady supply of fertilizers. Strengthening distribution networks through supporting agricultural cooperatives and establishing agro-input centers in rural areas can provide reliable sources of fertilizers. Additionally, utilizing digital solutions like e-governance to monitor and manage fertilizer distribution and developing mobile applications to inform farmers about availability, location, and prices are essential. If possible, the government of Nepal should invest in the domestic production industry of chemical fertilizers to reduce dependency on imports.

Furthermore, many poor farmers do not have the financial means to buy the necessary quantities of fertilizer due to their limited purchasing power. Providing subsidies or financial assistance can make fertilizers more affordable to these marginal poor farmers (Thapa et al., 2023). Additionally, capacity building and awareness should be enhanced by conducting training programs that educate farmers on efficient fertilizer use. By implementing these strategies, Nepal can improve the availability and timely distribution of fertilizers, thereby enhancing agricultural productivity and overall food security.

5.2 Role of Irrigation Expansion and Improving Canal Conveyance Efficiency:

As mentioned in the previous subsection, expanding irrigation within current rainfed areas and improving irrigation conveyance efficiency are essential strategies for increasing water availability and crop productivity under changing climatic conditions in Nepal. My fourth research question (RQ 4) aims to investigate the potential of crop productivity via expanding irrigation for rice, wheat and maize: “How will a change of current management scenario to potential irrigation expansion with 30% CCE affect future crop yield?”. Addressing RQ 4., I found that, across all ecoregions, transitioning from current management practices to the adoption of irrigation expansion with a 30% conveyance efficiency (CCE) leads to an increase in rice, wheat, and maize up to 3.1 t/h (Section 3.3.2 in Chapter 3). This increased crop yield, with amplified irrigation water and fertilizer application, will improve food security in Nepal in the future.

However, the expansion of irrigation must be implemented sustainably to preserve river water flows and consider the water needs of other sectors such as drinking water supply, hydroelectric power, and industry. Studies showed that water resources might exist for expanding irrigation in perennial mountain snow-fed rivers in the future, but the timing of sufficient water availability often does not coincide with the periods when irrigation is needed (Baniya et al., 2024; Mishra et al., 2018; Pandey et al., 2023; Shrestha et al., 2016). The situation worsens in rainfed rivers and springs, particularly in semi-urban areas where river flow rates will decline (Chauhan et al., 2023). Due to these reasons, water availability and water saving will be critical issues, and it is essential to minimize water conveyed to irrigation schemes from rivers by reducing water losses while conveying to fields. To address this issue, the effect of increasing canal conveyance efficiency to 50% is investigated to answer the fifth and sixth research questions of this thesis: RQ 5: “How will a change in canal conveyance efficiency from 30% to 50% influence crop yields – under current to near-future climate conditions?”, and RQ 6: “How will a change in CCE from 30% to 50% influence crop yields - under climate conditions at the end of the century?”. Addressing RQ 5 and 6, the results showed a yield increase of up to 1 t/ha for maize, up to 0.3 t/ha for wheat, and up to 2.13 t/ha for rice in future. The results signify improved crop yields with enhanced CCE with efficient water use (Appendix and Section 3.2.6).

I further increased the CCE to 70% and tried to answer the seventh research question (RQ7): “How large are the benefits in terms of crop yield with an increase to 70% CCE?”. The results showed an increase in rice yield up to 2.13 t/ha, maize yield up to 1.2 t/ha, and wheat yield up to 0.3 t/ha. The impact of advancing irrigation technology and expanding cropland while enhancing canal conveyance efficiency indicate that improvements in irrigation efficiency not only lower irrigation water loss up to 320 mm but also elevate agricultural production, thereby reducing reliance on runoff from natural sources in the context of a changing climate.

Further, I identified the locations and crops where irrigation expansion yields the highest return on investment in Nepal (Chapter 3 Section 3.3.3). The results suggest prioritizing investments in the subtropical Terai region, especially for rice and maize, focusing on expanding irrigated areas with CCE of at least 50%, ideally reaching 70%. Moderate expansion and a CCE of 30% to 50% may be most viable for hill regions, while investments in mountain regions should be limited due to lower returns.

Irrigation schemes in Nepal predominantly use gravity flow canal systems with water sourced from rivers. These schemes are supply-oriented to distribute water to as many farmers as possible, often with low design capacities. These schemes frequently overestimate water availability and expand command areas beyond capacity due to social and political pressure, leading to an inability to meet the necessary water supply

(Paudel, 2010). This result in water scarcity, constrained irrigated agriculture, reduced cropped area, altered water demand, and lowered crop yields. Additionally, high sedimentation, insufficient maintenance, and lining of canals make these systems unreliable. To address these challenges, proposed solutions include dredging large main canals to improve conveyance performance, constructing new regulator intakes to maintain required high water levels, proper canal lining, infrastructure upgrades, agronomic support, and enhancing irrigation services on branch and tertiary canal networks (Abd-Elaty et al., 2022; DoWRI, 2019; El-Molla and El-Molla, 2021; ElGamal et al., 2019; Paudel, 2010).

Irrigation systems management in Nepal requires significant improvements, focusing on four key thematic areas: system modernization, management improvement through irrigation management transfer, on-farm water management, and enhanced maintenance and Irrigation Service Fee collection (DoWRI, 2019). Modernization efforts should focus on rehabilitating and modernizing a major portion of existing farmers, agencies, and jointly or privately managed irrigation systems, improving the efficiency and coverage of irrigation while transferring the management of central systems to suitable entities. Management transfer is essential as it reduce the government’s financial burden by involving water users in system performance and maintenance. Various entities could take on these, including local governments for systems within their jurisdiction, private operators for large systems under contract, water users group (WUA) for small-scale systems, and the Department of Irrigation and WUA joint management for large, complex systems. Implementing these transfers requires modernizing systems and enhancing the capacity of Water Users’ Associations (DoWRI, 2019). In the case of joint management, the persistence of dual management systems must be addressed by actively involving farmers and water users in decision-making activities like water scheduling and enhancing the upkeep and maintenance of irrigation canals.

In summary, this chapter models the irrigation techniques in enhancing water availability with improved canal conveyance and minimizing water losses, thereby contributing to agricultural productivity in Nepal. Further, on a larger watershed basin scale, water management focused on the rehabilitation of water sources, water conservation, inter-basin transfer programs (Bhattarai et al., 2023a), construction of rainwater harvesting structures (e.g., water impounding project) could contribute to flood mitigations downstream and water availability during the dry season (Duwal et al., 2023).

5.3 Role of Alternate wetting and drying in Rice in improving yield:

In the former subsections, I have shown that subsistence low-input agriculture and conventional practices are inadequate to meet national food demands. However, excessive and inefficient input-based intensified agriculture is also associated with land, soil, and water pollution, degradation, and biodiversity loss (Mueller et al., 2012; Pradhan et al., 2015; Senapati et al., 2022). Thus, continuing traditional intensive way to close yield gaps will not be sustainable. My research questions eight, nine, and tenth explore sustainable agriculture intensification to increase rice yield while mitigating the environmental consequences of its cultivation in Terai, Nepal. The research questions are as follows: RQ 8: “What will be the effect of alternate wetting and drying of rice fields on crop yields and water use under climate change?”, RQ 9: “How will continuous flooding affect rice yields and water use under climate change?”, and RQ 10: “How will these methods affect the methane emission?”. Rice is prioritised because it is the primary food crops in the country, covering about 31% of the total harvested area, and contributing 7.5% to the national GDP (International Centerfor Tropical Agriculture; World Bank; CGIAR Research Program on Climate Change Agriculture and Food Security; Local Initiatives for Biodiversity Research and Development, 2017).

Addressing RQ 8, 9, and 10, AWD shows increased crop yield compared to CF by 2% to 19% (Chapter 2, section 4.3.2). Additionally, AWD uses less irrigation water, which is lower by 28% to 48% compared to CF (Chapter 2, section 4.3.3). Finally, AWD substantially reduced cumulative CH4 emissions by 44.8 to 54.7% compared to CF (Chapter 2, section 4.3.4). Our findings suggest that implementing AWD can serve as a climate-resilient, low GHG emission practice for rice farmers in Nepal, ensuring yield stability, food security, and enhanced water use efficiency across both dry and wet seasons. Studies have also shown that in AWD practices combining organic manure and fertilizers produces higher average yields than using them separately (Gairhe et al., 2021; Khanal, 2021; Linquist et al., 2015; Uprety, 2016). This demonstrates the complementary effect of organic manure and fertilizers; manure improve soil structure and supplement parts of nutrients to the plants, while mineral fertilizers supply required nutrients in bulk for quick response (Su et al., 2024). Therefore, future policy and research should focus on integrated nutrient management, combining organic farmyard manure with mineral fertilizers for increasing productivity in Nepal.

In the Terai region and Nepal, the direct application of AWD faces limited effectiveness due to various agro-ecological and socio-economic constraints, such as livelihood strategies, water reliability, land type, distance of fields from residences, land ownership status, increased weed, and access to training (Uprety, 2016). These challenges have led to the continued use of traditional low-yield rice cultivation practices and hence needed to be addressed. The ways to increased water reliability had already been discussed in chapter 3 and previous subsection 5.2. In context of weed management, maintaining flooded condition in initial ten days after transplant (DAT) of rice, early weeding in AWD fields before 24 DAT and between 51 - 60 DAT had shown very effective results and must be used for weed management in Nepal (Dossou-Yovo and Saito, 2021). The maintenance of initial days flooded conditions minimized weed germination (Rodenburg and Johnson, 2009), early weeding reduce weed establishment and infestation, and post weeding reduce weed competitiveness (Rao et al., 2017). However, there is need of using more efficient and user-friendly mechanical weeders and applying selective and non-selective herbicides are needed in Nepal, shifting labour-intensive manual weeding.

Along with alternate wetting and drying measures, additional effective climate-friendly agricultural research development and extension strategies are essential for transforming agriculture in Nepal. Current agricultural research in Nepal follows a top-down approach driven by the research interests of research institution, but it must instead prioritise farmers' priorities and demands (Khanal, 2021). Further, Nepalese agricultural research, development and extension agencies should facilitate the dissemination of research results and technology effectively to farmers. There should be a good provision of proper training to farmers' regarding implementation of climate friendly measures rather than merely instructing farmers treating them as unreceptive beneficiary. Although the Government of Nepal (GON) has sought to promote private sector involvement in R&D, progress has been limited due to weak coordination. There is need of efficient linkage mechanisms for supporting public-private partnerships (Ghimire et al., 2021; Khanal, 2021; Uprety, 2016). Last but not the least, to achieve sustainable impacts, it is vital to enhance the capabilities of both government and private sector actors through proactive policies and program interventions that facilitate functional participation and collaboration.

In summary, implementing the recommended reforms and strengthening research and extension systems while promoting connections among various actors, service providers, and stakeholders within Nepal's federal system will be critical to achieving the desired outcomes and ultimately transforming the agricultural sector.

5.4 Limitations and Directions for Future Research

The process-based EPIC crop model was utilized in this dissertation to simulate different fertilizers and irrigation management strategies under climate change conditions. Despite its robustness and widespread use for simulating agricultural production and assessing environmental impacts, EPIC has limitations. EPIC requires extensive input data for accurate simulations, including detailed weather, soil, and management practice data. The climate data used in this study, with a resolution of 0.44 degrees, is too coarse to accurately cover all microclimatic conditions in Nepal. A higher resolution of climate data is needed for more accurate simulations, as climate projections' uncertainties also affect the results of EPIC simulations.

Another major limitation is the unavailability of detailed soil data in Nepal, which is crucial for accurate simulations. For EPIC, the required soil database includes depth of soil layer, bulk density, sand content, soil water content at wilting point, silt content, soil water content at field capacity, clay content, organic nitrogen concentration, pH, sum of bases, organic carbon concentration, cation exchange capacity, soluble Nitrate concentration, electrical conductivity (Williams et al., 1989). Due to the lack of this in-depth soil data, the study had to rely on the GEOBENE Global database, which does not account for the small-scale soil variability necessary for precise agricultural planning of Nepal. Integrating GEOBENE data with other datasets is also challenging due to discrepancies in formats, scales, and temporal resolutions. Soil data with accurate information on soil properties will simulates crop growth, development, and yield accurately.

The district-level average yields reported by the Ministry of Agriculture in Nepal were used for calibration. The data provides broad spatial and temporal coverage, enabling assessments across diverse regions and management practices. Yet, they lack precise and detailed insights into crop responses under controlled conditions and are prone to inaccuracies, posing challenges for model calibration (NPSC, 2015). Further, aggregated results on a regional scale tend to reduce farm-scale variability (Eini et al., 2023; Villani et al., 2024; Wang et al., 2017). Due to these reasons, combining these with controlled experimental data, despite its resource intensity, along with remote sensing and expert knowledge, can enhance crop model accuracy and reliability.

I used the IPCC Tier 1 methodology for estimating methane emissions, which offers a more straightforward, generalized approach using default emission factors based on general conditions and average practices (IPCC, 2019). Although this method is more accessible to apply and requires less specific data, it carries higher uncertainty due to its broad assumptions and lack of site-specific adjustments (Nikolaisen et al., 2023). Process-based biogeochemical models such as the Denitrification-Decomposition (DNDC) Model and Daily Century (DAYCENT) models can be used for future research for the assessment of methane emission from different rice cultivation practices (Gao et al., 2023).

This thesis addresses increased crop yields, considering only mineral fertilizer and irrigation water use. However, apart from agricultural inputs, it is imperative to emphasize new current and future technological advancements rather than focus solely on one or two measures. Likewise, this thesis does not address the effect of weeds, pests, diseases, micronutrient, shifts in cropping patterns over time, and intercropping of multiple crops due to their complexity (Liu et al., 2014). Despite these limitations, the overall performance of the EPIC crop model was reasonable based on the performance criteria selected for this research. However, further studies can be carried out addressing the issue mentioned above and taking into account a detailed analysis of the trade-offs associated with various measures to close the yield gap and sustainable intensification.

5.5 Conclusion:

In conclusion, with detailed methodology, this thesis identified multiple challenges and opportunities for the underperforming agriculture sector in Nepal. Using a biophysical crop model for simulating the transition from conventional low-input agriculture to input-intensified irrigated agriculture, I have suggested solutions to increase crop yields under current and future conditions. My findings emphasized the importance of efficient fertilizer and water use in closing yield gaps and achieving food self-sufficiency in Nepal. Apart from yield gaps quantification; I assessed the potential benefits of additional irrigation and fertilizer application. The results showed the considerable potential of crop yield increment in agriculture to contribute to food security and GDP in Nepal.

Additionally, my analysis showed the potential impact of expanding irrigated areas and enhancing canal conveyance efficiency on crop productivity under various climate change scenarios. Improving canal conveyance efficiency, coupled with expanded irrigated areas, could substantially boost crop yields across the country, particularly in the Terai and Hill region. The results demonstrated that improving canal conveyance efficiency positively affects the Nepalese agriculture sector, resulting in less water loss, efficient water use, and high crop yield.

Furthermore, I emphasized adopting climate-friendly, water-conserving measures, such as Alternate Wetting and Drying (AWD) methods for rice cultivation in the future intensified agriculture of the Terai region. This approach aims to increase crop yields to meet future food demand while mitigating the environmental consequences of intensified agriculture. AWD adoption in the region showed a promising pathway toward sustainable agriculture, yielding positive outcomes such as improved rice yield, reduced irrigation water use, and decreased methane emissions.

Overall, this thesis contributes to the continuing discourse on enhancing food security and self-sufficiency in Nepal through domestic production. The pathways identified include closing yield gaps through efficient fertilizer and water use, expanding irrigated areas, enhancing canal conveyance efficiency, and adopting climate-smart practices. The results of this study might be helpful for policymakers and development agencies in making well-informed decisions to identify sustainable pathways to increase agricultural productivity, enhance food security, and sustainably transform the agricultural sector in Nepal. The methodology applied in this study can also be relevant to other regions facing similar challenges.

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Appendix

Table 2-5. District-wise simulated (Sim.) and reported (Rep.) crop yields (t/ha) for rice, maize, wheat, barley, and millet. The reported crop yields were provided by the Ministry of Agriculture Development Nepal. The data were used to evaluate the quality of the crop model calibration.

	Rice		Maize		Wheat		Barley		Millet	
District	Sim.	Rep.	Sim.	Rep.	Sim.	Rep.	Sim.	Rep.	Sim.	Rep.
Achham	1.86	2.13	1.07	1.61	0.98	1.49	1.31	1.09	1.35	1.17
Arghakhanchi	2.25	2.20	2.14	1.99	0.89	1.61	0.26	1.03	1.05	1.07
Baglung	1.98	2.62	2.61	2.20	1.37	1.73	0.58	1.44	1.06	1.17
Baitadi	1.65	1.96	0.75	1.64	1.26	1.37	0.04	0.91	1.22	1.14
Bajhang	1.95	1.91	1.48	1.45	0.84	1.48	0.74	1.00	0.72	0.95
Bajura	2.11	1.86	1.63	1.72	1.68	1.39	1.1	1.04	1.14	0.95
Banke	3.03	2.77	2.12	1.87	0.57	2.42				
Bara	3.09	3.75	2.37	2.60	0.63	2.89				
Bardiya	3.24	3.12	2.30	1.93	0.43	2.47				
Bhaktapur	2.33	5.74	2.70	3.31	1.04	2.93	0.74	1.23	1.07	1.27
Bhojpur	2.2	2.45	1.92	2.10	1.56	1.95	0.23	1.14	1.21	1.03
Chitawan	3.79	3.07	2.02	2.50	0.62	2.45				
Dadeldhura	1.83	2.31	0.87	1.71	1.27	1.37		0.97	1.18	0.88
Dailekh	1.81	2.45	1.07	1.88	1.03	1.54	1.06	1.01	1.38	1.19
Dang	3.2	3.19	2.81	2.01	0.37	2.18				
Darchula	1.03	2.03	0.96	1.73	0.48	1.40	0.44	0.84	0.53	0.82
Dhading	1.72	2.71	0.94	1.90	0.97	1.82	2.03	0.91	1.28	0.96
Dhankuta	1.96	2.60	1.73	2.00	1.47	1.95	0.1	1.13	1.18	1.00
Dhanusha	2.73	2.68	2.81	2.54	0.69	2.03				
Dolakha	2.17	2.19	2.17	1.93	1.59	1.50	0.92	0.81	1.02	1.11
Dolpa	1.12	1.57	0.88	1.71	1.42	1.48	0.93	0.97	0.86	0.81
Doti	1.82	2.43	0.73	1.71	0.99	1.67	0.51	0.95	1.03	1.10
Gorkha	2.09	2.71	1.39	2.20	0.74	1.81	0.67	1.13	0.82	1.06
Gulmi	1.73	2.34	1.80	1.80	0.88	1.69	0.25	1.11	0.63	1.19
Humla	1.94	1.42	0.69	1.52	2.06	0.91	1.22	0.92	1.26	0.85
Ilam	1.85	2.49	1.39	2.16	1.13	2.03	0.32	0.74	0.90	0.99
Jajarkot	1.73	2.23	1.14	1.73	0.84	1.18	1.34	1.16	1.50	1.38
Jhapa	2.66	3.31	2.47	2.30	0.53	2.47				
Jumla	2.38	1.58	1.64	1.44	2.36	1.09	1.17	1.07	1.42	1.38
Kabhrepalanchok	2.13	3.06	1.99	2.25	0.88	1.92	0.52	1.02	0.94	1.01
Kailali	3.35	2.67	2.35	1.68	0.29	2.11				
Kalikot	2.1	1.69	2.37	1.58	1.74	1.30	1.12	1.08	1.30	1.20
Kanchanpur	3.42	2.61	2.58	1.78	0.35	2.10				
Kapilbastu	2.81	2.43	1.93	2.18	0.66	2.20				
Kaski	1.18	2.88	1.77	2.25	0.84	1.97	0.19	1.17	0.59	1.21
Kathmandu	2.26	5.36	2.69	2.99	1.01	2.37	0.75	1.00	1.04	1.00
Khotang	2.04	2.21	2.07	2.03	1.61	1.67	0.39	0.97	1.27	1.00
Lalitpur	1.73	5.05	1.68	2.45	0.71	2.44	0.01	1.51	0.86	1.21
Lamjung	2.06	2.35	1.37	2.18	0.88	1.95	0.88	0.91	0.87	1.00
Mahottari	2.82	2.37	2.77	2.16	0.66	1.91				
Makawanpur	2.98	2.97	2.20	2.28	0.34	2.30				
Morang	2.87	3.21	2.71	2.27	0.54	2.16				
Mugu	2.22	1.85	1.11	2.14	2.12	1.34	1.17	0.92	1.39	1.66
Myagdi	1.42	2.66	1.30	2.30	2.64	1.78	1.46	1.20	1.00	1.02
Nawalparasi East	3.6	3.29	1.93	2.43	0.55	2.40				
Nawalparasi West	3.3	3.29	2.29	3.67	0.55	2.40				
Nuwakot	1.61	3.14	0.82	2.12	1.10	2.21	2.2	0.94	1.36	1.35
Okhaldhunga	1.84	2.42	2.08	1.87	1.65	1.61	0.53	0.97	1.34	1.29
Palpa	2.15	2.69	1.88	2.03	0.64	1.93		1.06	0.65	1.04

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Panchthar	2.3	2.13	1.40	1.56	1.43	1.68	0.62	0.91	1.09	1.45
Parbat	1.31	2.35	1.77	2.07	0.98	1.69	0.26	0.94	0.60	0.91
Parsa	3.08	3.58	2.63	3.04	0.67	2.67				
Pyuthan	1.86	2.24	0.86	1.53	0.76	1.78	0.27	1.81	1.18	1.08
Ramechhap	1.81	2.23	1.98	2.12	1.47	1.76	0.63	0.81	1.19	1.08
Rasuwa	2.8	2.22	0.56	1.74	1.23	1.75	2.29	1.10	1.02	1.02
Rautahat	3.19	2.61	2.52	2.05	0.62	2.18				
Rolpa	1.78	2.18	1.27	1.68	0.92	1.65	0.54	1.10	1.54	1.01
Rukum East	1.81	2.53	1.44	1.71	0.59	1.58	2.21	1.01	1.69	1.19
Rukum West	1.79	2.53	1.32	1.71	0.63	1.58	1.9	1.01	1.58	1.19
Rupandehi	3.34	3.28	2.26	2.40	0.58	2.60				
Salyan	1.74	2.60	1.24	1.93	1.00	1.64	0.46	0.96	1.39	1.15
Sankhuwasabha	2.26	1.95	1.89	1.73	1.29	1.83	0.37	0.96	1.01	1.01
Saptari	2.8	2.53	2.99	2.17	0.73	2.17				
Sarlahi	2.95	2.60	2.80	2.63	0.64	2.09				
Sindhuli	2.49	2.35	2.75	2.24	0.62	2.02				
Sindhupalchok	2.82	2.34	2.10	2.10	0.98	1.55	0.95	1.16	0.92	1.12
Siraha	2.78	2.39	2.66	2.27	0.68	1.99				
Solukhumbu	1.97	1.99	1.58	1.99	1.57	1.45	1.29	1.06	1.12	1.17
Sunsari	2.93	3.02	2.75	2.42	0.58	2.36				
Surkhet	3.02	2.79	2.95	2.21	0.22	1.96				
Syangja	1.65	2.89	1.70	2.55	0.62	1.97	0.1	1.02	0.56	1.22
Tanahu	2.01	2.89	1.71	2.49	0.68	1.84	0.05	0.80	0.55	1.06
Taplejung	2.49	2.09	1.70	2.02	1.52	2.76	0.54	1.08	0.99	1.16
Terhathum	2.27	2.10	1.60	1.68	1.54	1.66	0.28	1.03	1.12	1.09
Udayapur	2.49	2.78	2.82	1.99	0.61	2.04				

Appendix

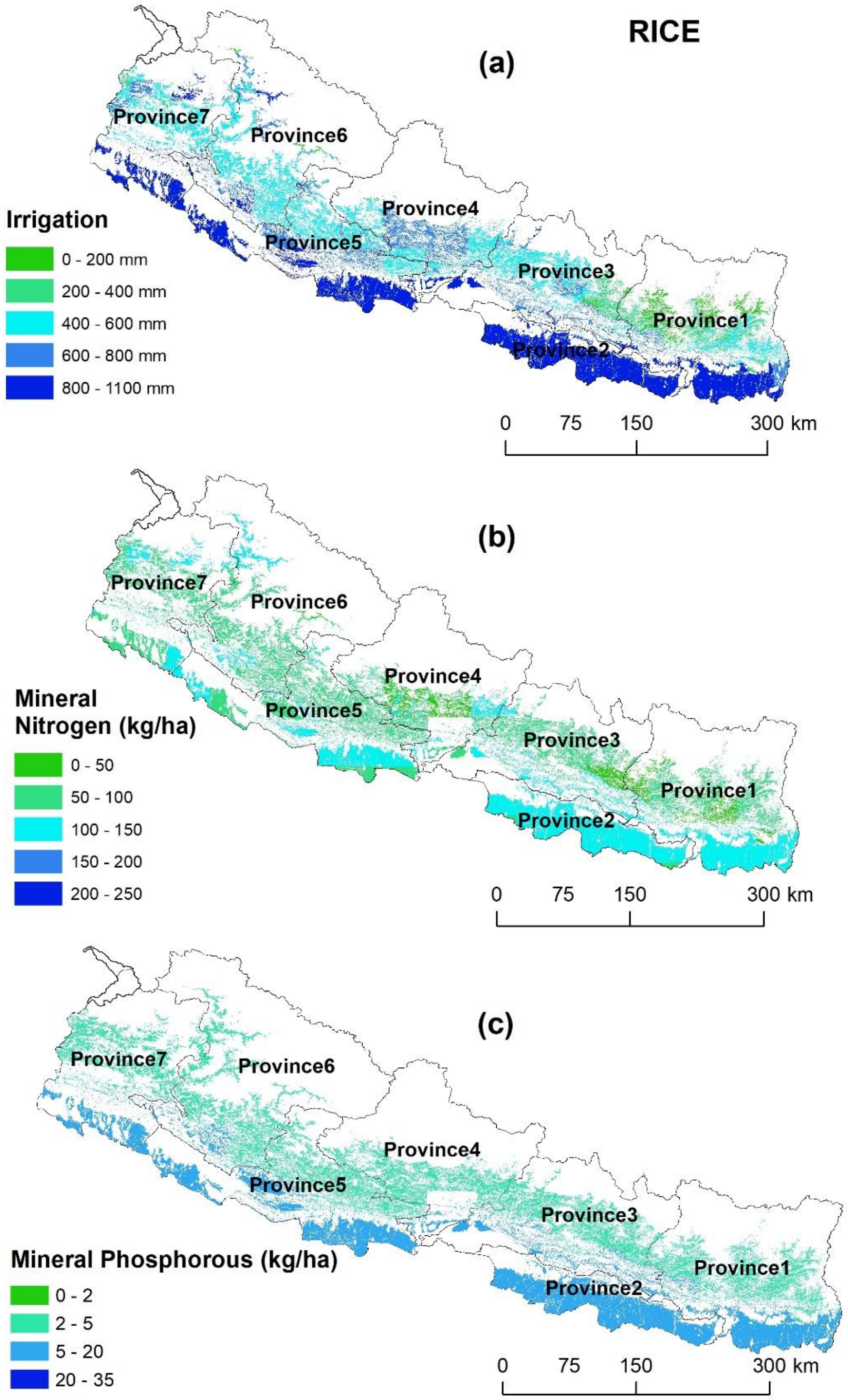

Figure 2-8. (a) Annual irrigation (mm), (b) maximum mineral nitrogen (kg/ha), and (c) maximum mineral phosphorous (kg/ha) fertilizer requirements to achieve attainable yields at simulation unit level for rice.

Appendix

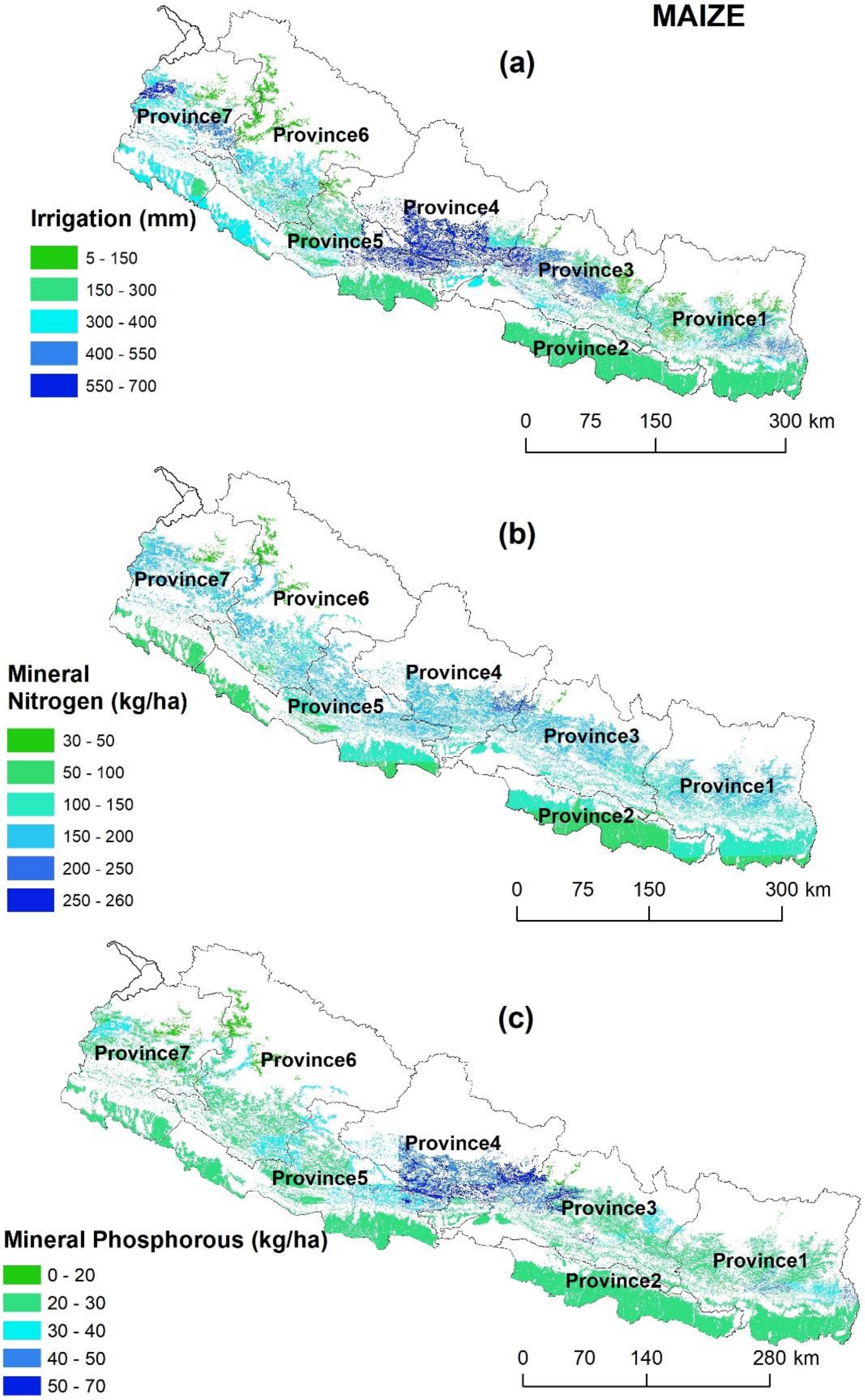

Figure 2-9. (a) Annual irrigation (mm), (b) maximum mineral nitrogen (kg/ha), and (c) maximum mineral phosphorous (kg/ha) fertilizer requirements to achieve attainable yields at simulation unit level for maize.

Appendix

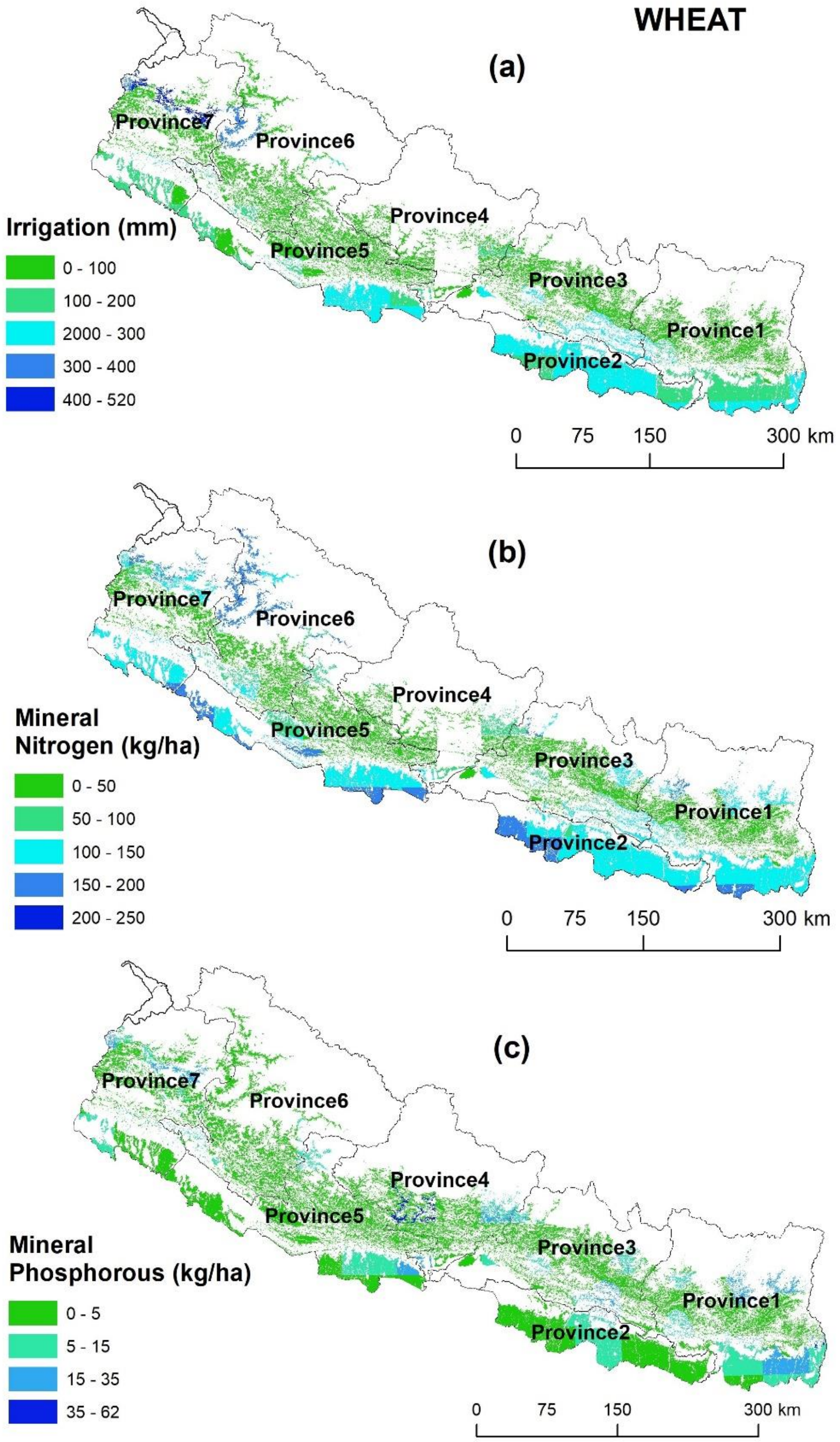

Figure 2-10. (a) Annual irrigation (mm), (b) maximum mineral nitrogen (kg/ha), and (c) maximum mineral phosphorous (kg/ha) fertilizer requirements to achieve attainable yields at simulation unit level for wheat.

Appendix

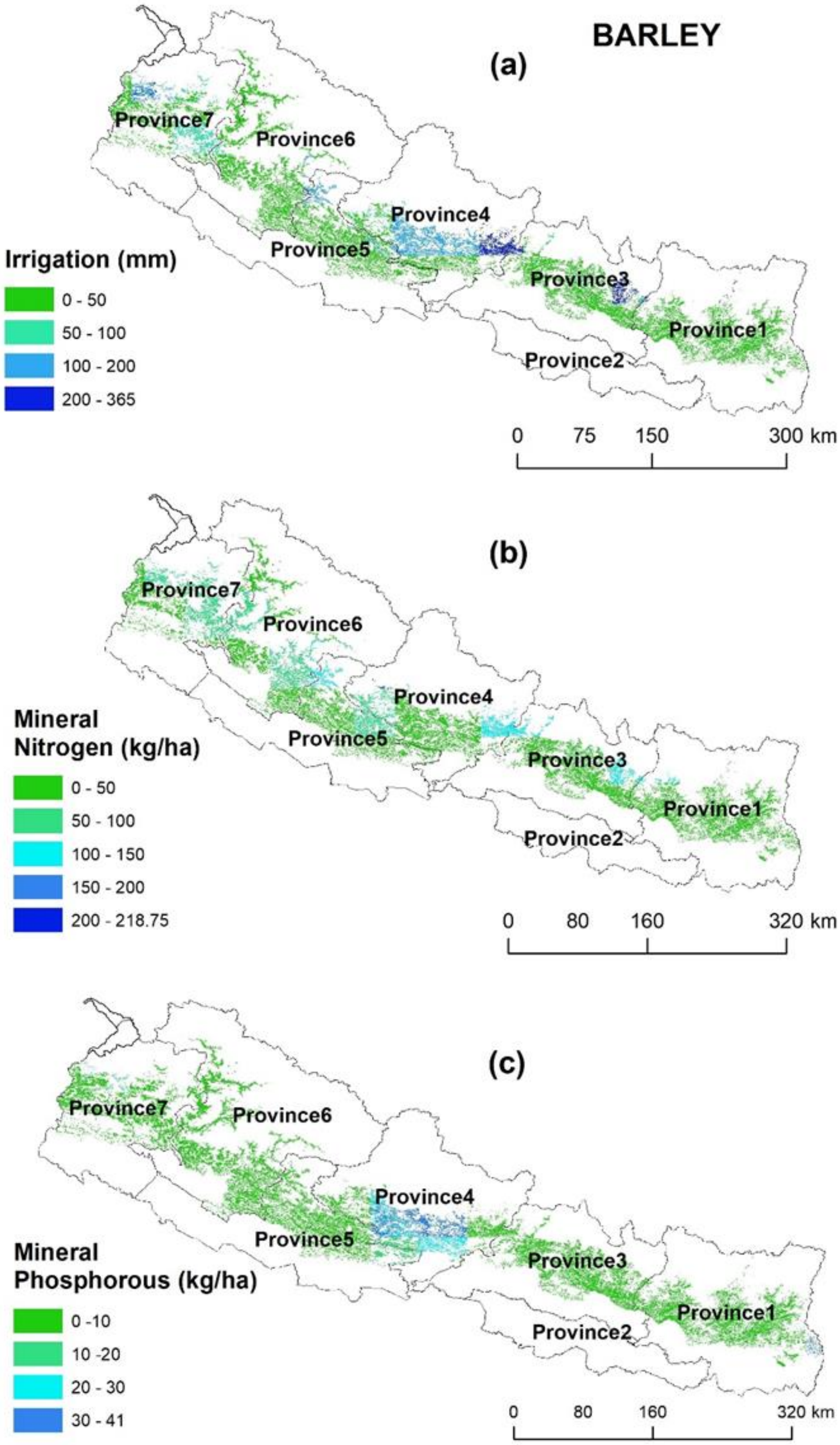

Figure 2-11. (a) Annual irrigation (mm), (b) maximum mineral nitrogen (kg/ha), and (c) maximum mineral phosphorous (kg/ha) fertilizer requirements to achieve attainable yields at simulation unit level for barley.

Appendix

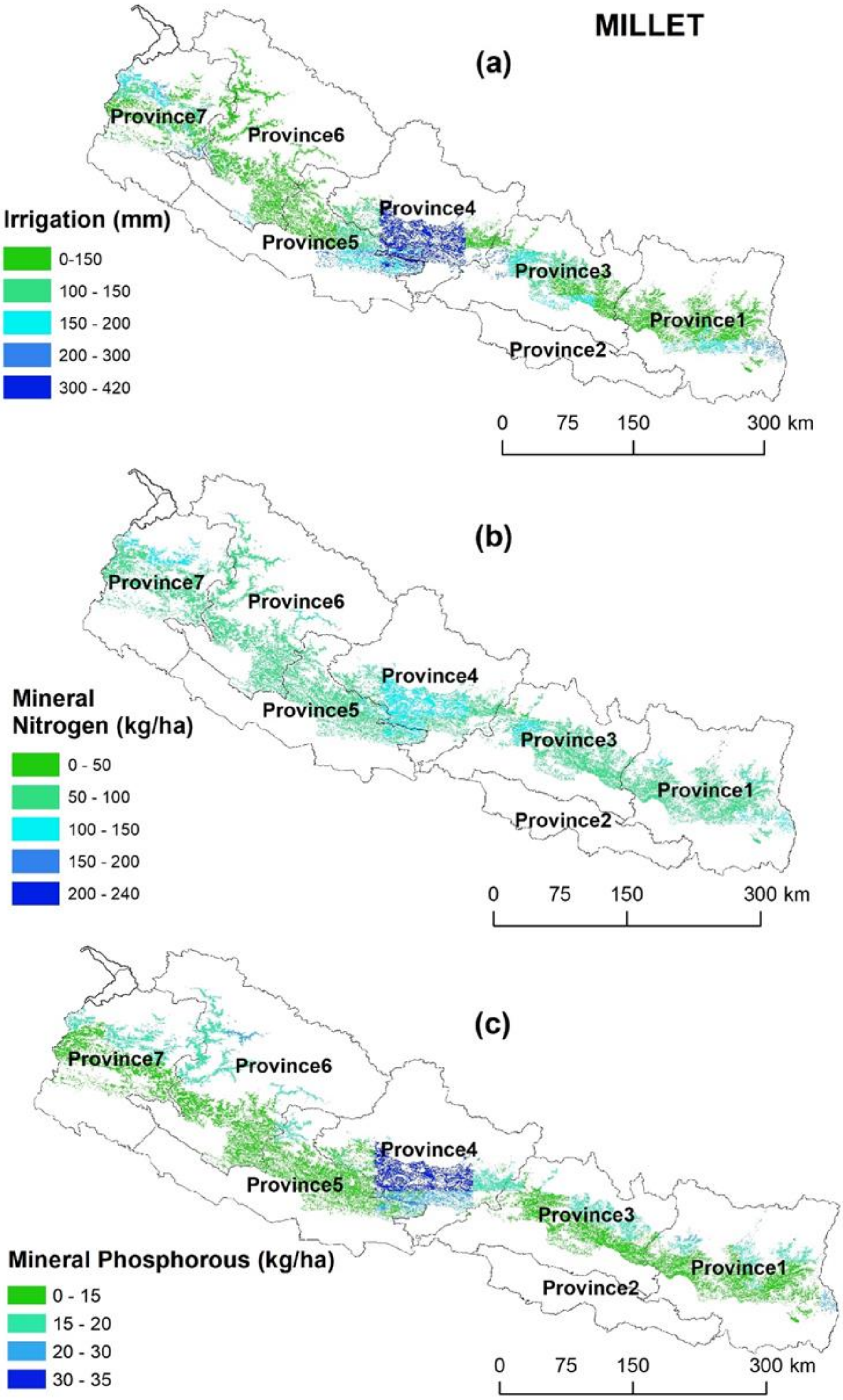

Figure 2-12(a) Annual irrigation (mm), (b) maximum mineral nitrogen (kg/ha), and (c) maximum mineral phosphorous (kg/ha) fertilizer requirements to achieve attainable yields at simulation unit level for millet.

Appendix

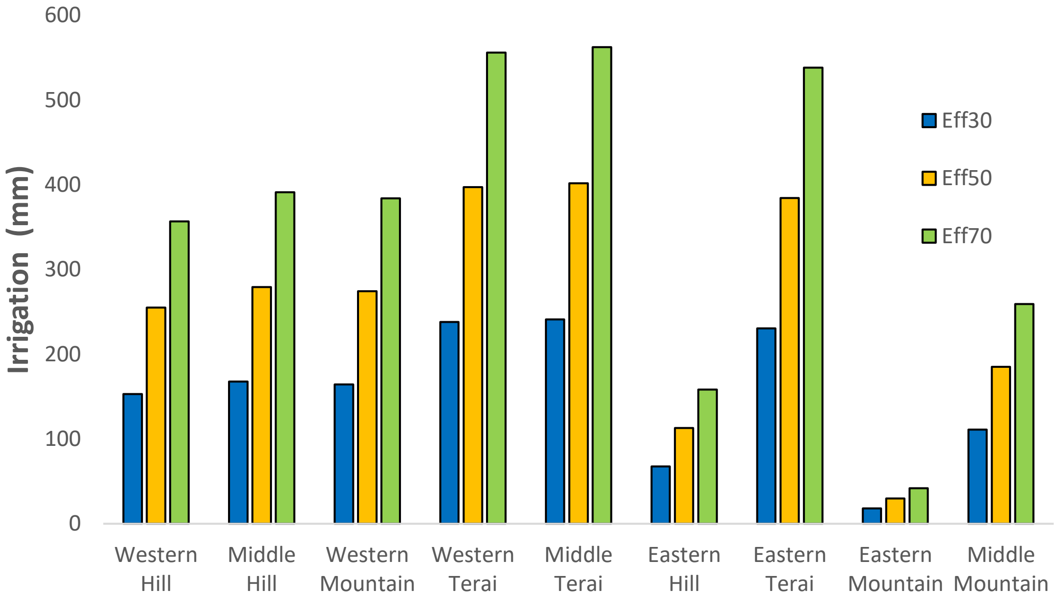

Figure 3-12. Different amounts of irrigation water conveyed to rice crops based on the canal efficiency.

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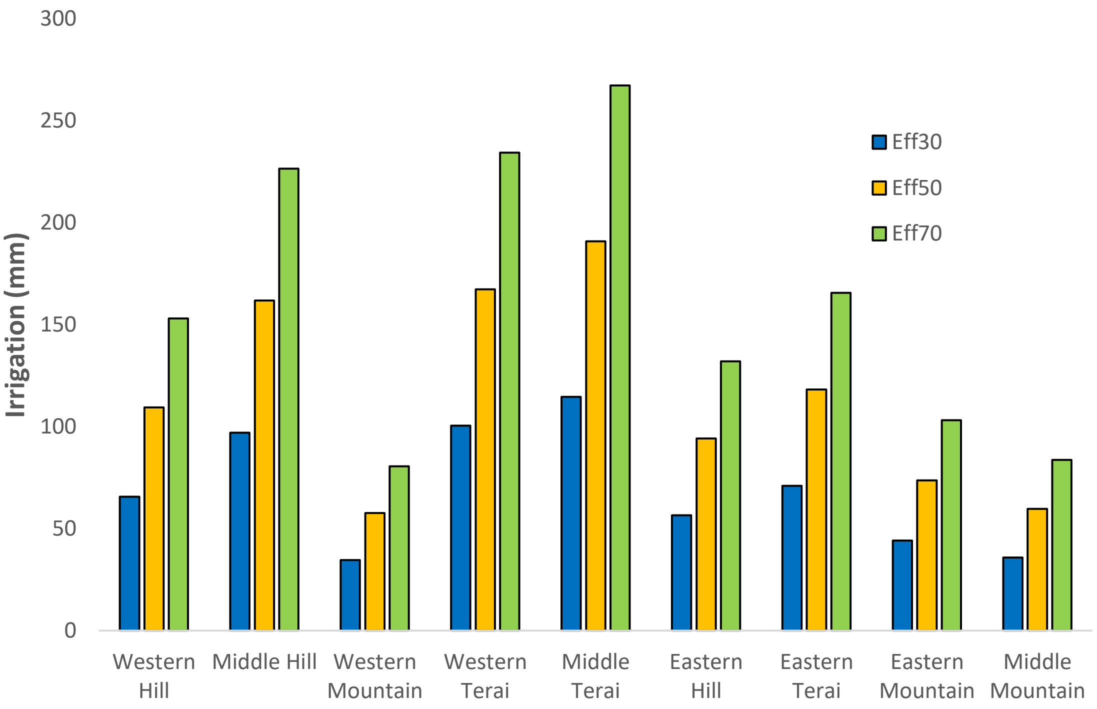

Figure 3-13. Different amounts of irrigation water conveyed to maize crops based on the canal efficiency.

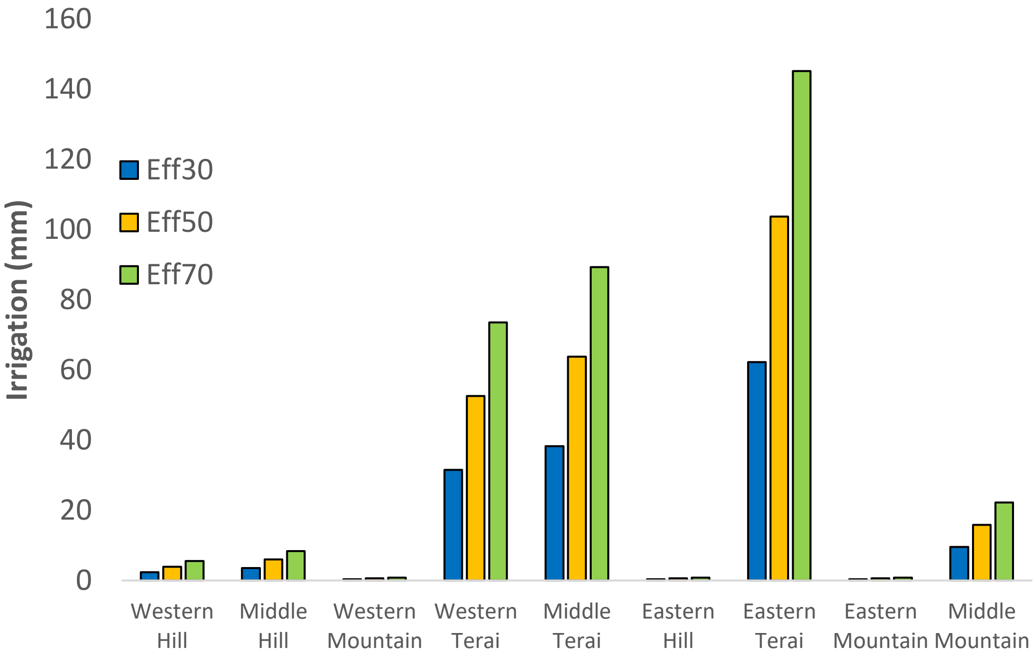

Figure 3-14. Different amounts of irrigation water conveyed to wheat crops based on the canal efficiency.

Appendix

Table 3-5. Aggregated rice yield changes across nine ecological regions in Nepal, showing the percentage change in yields when canal conveyance efficiency is improved from 30% to 50%, for both near future and end-of-century. SSP1_2.6, SSP3_7.0, and SSP5_8.5 represent the Shared Socioeconomic Pathways with radiative forcing levels of 2.6 W/m², 7.0 W/m², and 8.5 W/m², respectively

		Near Future			**End Century**		
		SSP1-2.6	**SSP3-7.0**	**SSP5-8.5**	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**
Terai	East	6 – 10%	4 – 8%	2 – 7%	7 – 14%	10 – 12%	12 – 14%
	Middle	8 – 15%	7 – 12%	4 – 11%	11 – 24%	20 – 37%	23 – 42%
	West	8 – 14%	5 – 11%	4 – 12%	12 – 19%	17 – 26%	18 – 25%
Mountain	East	0%	0%	0%	0%	0%	0 – 1%
	Middle	0 – 3%	0 – 1%	0%	0 – 6%	3 – 6%	3 – 6%
	West	0%	0%	0%	0%	0%	0%
Hill	East	0%	0%	0%	0%	0%	0%
	Middle	4 – 6%	3 – 5%	2 – 6%	5 – 7%	4 – 11%	6 – 13%
	West	0 – 2%	0 – 2%	0 – 2%	1 – 4%	2 – 6%	3 – 5%

Table 3-6. Aggregated rice yield changes across nine ecological regions in Nepal, showing the percentage change in yields when canal conveyance efficiency is improved from 30% to 70%, for both near future and end-of-century. SSP1_2.6, SSP3_7.0, and SSP5_8.5 represent the Shared Socioeconomic Pathways with radiative forcing levels of 2.6 W/m², 7.0 W/m², and 8.5 W/m², respectively

		Near Future			**End Century**		
		SSP1-2.6	**SSP3-7.0**	**SSP5-8.5**	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**
Terai	East	12 – 25%	9 – 19%	5 – 15%	14 – 30%	23 – 31%	25 – 32%
	Middle	14 – 31%	12 – 22%	8 – 20%	18 – 43%	40 – 74%	44 – 77%
	West	11 – 26%	7 – 16%	6 – 20%	16 – 34%	27 – 45%	26 – 43%
Mountain	East	0%	0%	0%	0%	0%	0%
	Middle	2 – 9%	0 – 5%	0 - 2%	3 – 12%	8 – 16%	15 – 10%
	West	0%	0%	0%	0%	0 – 2%	0 – 1%
Hill	East	0%	0%	0%	0%	0%	0%
	Middle	10 – 16%	10 – 12%	7 – 13%	12 – 17%	12 – 26%	18 – 33%
	West	2 – 8%	2 – 6%	1 – 6%	5 – 12%	9 – 17%	10 – 16%

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Table 3-7. Aggregated maize yield changes across nine ecological regions in Nepal, showing the percentage change in yields when canal conveyance efficiency is improved from 30% to 50%, for both near future and end-of-century. SSP1_2.6, SSP3_7.0, and SSP5_8.5 represent the Shared Socioeconomic Pathways with radiative forcing levels of 2.6 W/m², 7.0 W/m², and 8.5 W/m², respectively

		Near Future			**End Century**		
		SSP1-2.6	**SSP3-7.0**	**SSP5-8.5**	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**
Terai	East	9 – 10%	8 – 15%	7 – 15%	12 – 14%	11 – 14%	7 – 11%
	Middle	8 – 10%	8 – 16%	7 – 22%	9 – 12%	11 – 13%	10 – 14%
	West	13 – 15%	11 – 13%	11 – 27%	15.5 – 16%	15 – 20%	13 – 21%
Mountain	East	3 – 4%	3 – 10%	2 – 9%	3.5 - 4%	5 – 21%	5 – 17%
	Middle	4 – 5%	4 – 11%	3 – 10%	5 - 6%	5 – 15%	0 – 7%
	West	3.5 – 4%	3 – 14%	2 – 10%	3 - 4%	3 – 16%	4 – 8%
Hill	East	4 – 6%	4 – 13%	3 – 12%	6 – 8%	5 – 15%	5 – 10%
	Middle	7 – 8%	7 – 8%	6 – 14%	9 – 10%	5 – 13%	6 – 13%
	West	4 – 5%	3 – 9%	3 – 11%	4.5 – 5%	2 – 7%	1 – 8%

Table 3-8. Aggregated maize yield changes across nine ecological regions in Nepal, showing the percentage change in yields when canal conveyance efficiency is improved from 30% to 70%, for both near future and end-of-century. SSP1_2.6, SSP3_7.0, and SSP5_8.5 represent the Shared Socioeconomic Pathways with radiative forcing levels of 2.6 W/m², 7.0 W/m², and 8.5 W/m², respectively.

		Near Future			**End Century**		
		SSP1-2.6	**SSP3-7.0**	**SSP5-8.5**	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**
Terai	East	15 – 19%	14 – 18%	11 – 17%	22 – 27%	17 – 24%	10 – 23%
	Middle	15 – 21%	15 – 17%	13 – 18%	19 – 25%	21 – 26%	23 – 29%
	West	22 – 28%	18 – 23%	19 – 24%	29 – 31%	28 – 35%	30 – 38%
Mountain	East	7 – 9%	6 – 8%	5 – 7%	9 – 10%	11 – 12%	11 – 13%
	Middle	7 – 10%	6 – 7%	5 – 7%	8 – 11%	9 – 10%	9 – 13%
	West	6 – 7%	4 – 5%	4– 6%	6 – 7%	5 – 7%	6 – 8%
Hill	East	9 – 12%	8 – 11%	6 – 10%	13 – 17%	12 – 15%	9 – 14%
	Middle	14 – 17%	13 – 14%	11 – 14%	17 – 20%	18 – 25%	19 – 24%
	West	7 – 9%	6 – 7%	5 – 8%	8 – 10%	8 – 13%	9 – 14%

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Table 3-9. Aggregated wheat yield changes across nine ecological regions in Nepal, showing the percentage change in yields when canal conveyance efficiency is improved from 30% to 50%, for both near future and end-of-century. SSP1_2.6, SSP3_7.0, and SSP5_8.5 represent the Shared Socioeconomic Pathways with radiative forcing levels of 2.6 W/m², 7.0 W/m², and 8.5 W/m², respectively

		Near Future			**End Century**		
		SSP1-2.6	**SSP3-7.0**	**SSP5-8.5**	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**
Terai	East	0 – 1%	0%	0%	0 – 1%	0 – 2%	1.5– 2%
	Middle	0 – 2%	0%	0%	2.5 – 3%	0 – 3%	3 – 4%
	West	0 – 2%	0%	0%	2.5 – 3%	0 – 2%	2 – 4%
Mountain	East	0%	0%	0%	0%	0%	0%
	Middle	0%	0%	0%	0%	0%	0%
	West	0%	0%	0%	0%	0%	0%
Hill	East	0%	0%	0%	0%	0%	0%
	Middle	0 – 2%	0%	0%	2 – 3%	0 – 3%	2.5 – 3%
	West	0 – 2%	0%	0%	2 – 5%	0 – 4%	3.5 – 4%

Table 3-10. Aggregated wheat yield changes across nine ecological regions in Nepal, showing the percentage change in yields when canal conveyance efficiency is improved from 30% to 70%, for both near future and end-of-century. SSP1_2.6, SSP3_7.0, and SSP5_8.5 represent the Shared Socioeconomic Pathways with radiative forcing levels of 2.6 W/m², 7.0 W/m², and 8.5 W/m², respectively

		Near Future			**End Century**		
		SSP1-2.6	**SSP3-7.0**	**SSP5-8.5**	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**
Terai	East	0 – 3%	0%	0 - 3%	1 – 4%	3 – 6%	4 – 5%
	Middle	0 – 8%	0%	0 - 7%	3 – 9%	0 – 15%	8 – 10%
	West	0 – 5%	0%	0 - 5%	3 – 6%	0 – 9%	5 – 9%
Mountain	East	0%	0%	0%	0%	0%	0%
	Middle	0 -	0%	0 -	0 - 16%	0 - 15%	0 - 3%
	West	0 - 6%	0%	0 - 5%	0 - 6%	0 - 25%	5%
Hill	East	0%	0%	0%	0%	0 - 3%	0%
	Middle	0 – 4%	0%	0 - 4%	3 – 4%	4 – 5%	5 – 6%
	West	0 – 7%	0%	0 - 7%	5 – 8%	4 – 7%	7 – 9%

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.

I hereby declare upon oath that I have written the present dissertation independently and have not used further resources and aids than those stated.

Amit Kumar Basukala

Wedel, June 4th, 2024